AlGaN Metal-Semiconductor-Metal UV Photodetectors

by

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Dedication

For the golden days at Rochester
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Biographical Sketch

Yiming Zhao was born in Yuzhou, Henan province of China in 1990. He attended Central South University at Changsha, Hunan in 2008 and graduated with a Bachelor’s Degree of Materials Science and Engineering in 2012. During the time at CSU, he was selected for the Talent Program of Physics and received extensive physics education. He also carried out research on the metal/carbide interface properties using first-principle calculations in Professor Yong Jiang’s group.

He joined the University of Rochester in 2012 to pursue the doctoral degree in Materials Science. He became a member of Laboratory for Laser Energetics in the Plasma and Ultrafast Physics Group in 2013 and started research in ultrafast UV photodetectors based on AlGaN under the direction of Professor William Donaldson. He received the Frank J. Horton fellowship for five years and held several appointments as a teaching and research assistant. His research interests fall into the area of ultrafast photodetectors, electric-optical materials and devices.
Acknowledgements

My deepest gratitude belongs to, of course, my advisor, Professor William R. Donaldson. I would not have completed the research on AlGaN UV photodetectors and fabricated these high-performance devices without his guidance and support. He is always able to help and gives me enough freedom at the same time. I have learned so much from him and will continue to be inspired by his insightful way of thinking for the rest of my life. I also want to thank Professor Roman Sobolewski and Professor Gary Wicks for their helpful advices and resources during my thesis work.

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Last, I want to say my gratefulness to my parents, for their unconditional love for me all my life and to their tremendous support not only in my life but also in my soul.

I want to put my love, Jingjing, in the end, for the infinite happiness brought to me.
Abstract

Semiconductor devices based on III-Nitride have been studied for years and research has been carried out on many different types of devices. Among them, photodetectors based on AlGaN ternary alloy show good potential for solar blind UV photodetectors and metal-semiconductor-metal structures enables temporal response in picosecond level with very low dark current. In this thesis, the practical applications of the photodetectors on AlGaN have been studied in the areas of both device physics and materials. Different structures and materials layout of the devices were designed and fabricated. The device performance including the I-V property and temporal response under different circumstances were both simulated by APSYS and tested experimentally. Various parameters including device layout, bias voltage, incident power, operating temperature, beam size and focusing location were varied to demonstrate their influence on the device performance. The fluctuation in the percentage of Aluminum (denoted as Al %) was investigated from the materials perspective and its influence on the device performance was investigated both theoretically and experimentally. The metal-semiconductor contact nature was studied by applying a pulsed-voltage measurement, and the PPC phenomenon found in the device temporal response was investigated and methods to reduce it were tried out.

To achieve faster device response and lower dark current, second generation devices were fabricated on better quality wafers with improved device designs. Within the different doping profiles and contact materials of the second-generation devices, the best devices
showed a fast response time of below 20 ps and dark currents below 10 pA. The devices showed excellent response linearity with the bias voltage and the laser energy.

The PPC effects and high dark current are also observed on P-doping devices and the reason for this is investigated from the perspective of materials properties. The results showed that the macroscopic defects (cracks and voids in the AlGaN thin film), rather than the microscopic defects (point defects, dislocation), are likely the major reason causing the extremely slow decay of the response time. There are also carbon segregation layers found on in the P-doping materials, which is likely to be connected with the PPC effects and high dark current of the devices.
Contributors and Funding Sources

This work was supported by a dissertation committee consisting of my advisor, Professor William Donaldson and Professor Roman Sobolewski of the Department of Electrical and Computer Engineering, and Professor Gary Wicks of the Institute of Optics. All the devices described in Chapter 4 were fabricated at the Semiconductor & Microsystems Fabrication Laboratory (SMFL) at Rochester Institute of Technology (RIT) with the help of their staff. All the devices described in Chapter 7 were fabricated at the URnano facilities with the help of Brian McIntyre and James Mitchel. The X-ray photoelectron spectroscopic measurements were carried out with the help of Wenchuan Ma in Professor Alexander Shestopalov’s group. The X-ray diffraction measurements were carried out with the help of Christine Pratt. The focused ion-beam measurements were done by the guidance of Ralph Wiegandt. The ORIGAMI laser setup was helped by Joseph Katz.

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<tr>
<td>AlGaN</td>
<td>Aluminum Gallium Nitride</td>
</tr>
<tr>
<td>BBO</td>
<td>Beta barium borate</td>
</tr>
<tr>
<td>CW</td>
<td>continuous wave</td>
</tr>
<tr>
<td>DG</td>
<td>delay generator</td>
</tr>
<tr>
<td>DPRA</td>
<td>diode-pumped regenerative amplifier</td>
</tr>
<tr>
<td>EDS</td>
<td>Energy-dispersive X-ray spectroscopy</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FHG</td>
<td>forth harmonic generation</td>
</tr>
<tr>
<td>FIB</td>
<td>Focused Ion Beam</td>
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<td>FWHM</td>
<td>full width half magnitude</td>
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<tr>
<td>HF</td>
<td>high frequency</td>
</tr>
<tr>
<td>HMDS</td>
<td>Hexamethyldisilazane</td>
</tr>
<tr>
<td>HTS</td>
<td>Hardware Timing System</td>
</tr>
<tr>
<td>MOCVD</td>
<td>metal-organic chemical vapor deposition</td>
</tr>
<tr>
<td>MSM</td>
<td>metal-semiconductor-metal</td>
</tr>
<tr>
<td>ND</td>
<td>netral density</td>
</tr>
<tr>
<td>NEP</td>
<td>noise-equivalent power</td>
</tr>
<tr>
<td>OD</td>
<td>optical density</td>
</tr>
<tr>
<td>PCB</td>
<td>printed circuit board</td>
</tr>
<tr>
<td>PPC</td>
<td>persistent photoconductivity</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
<td>-------------</td>
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<tr>
<td>ps</td>
<td>pico-second</td>
</tr>
<tr>
<td>PVD</td>
<td>physical vapor deposition</td>
</tr>
<tr>
<td>RIE</td>
<td>reaction ion etching</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>SCR</td>
<td>space-charge regions</td>
</tr>
<tr>
<td>SEM</td>
<td>scanning electron microscope</td>
</tr>
<tr>
<td>SMFL</td>
<td>Semiconductor &amp; Microsystems Fabrication Laboratory</td>
</tr>
<tr>
<td>THG</td>
<td>Third harmonic generation</td>
</tr>
<tr>
<td>URnano</td>
<td>Integrated Nanosystems Center</td>
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<tr>
<td>UV</td>
<td>Ultraviolet</td>
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<tr>
<td>XPS</td>
<td>X-ray photoelectron spectroscopy</td>
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<td>XRD</td>
<td>X-ray diffraction</td>
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Chapter 1 Introduction

1.1 Review of research on AlGaN MSM UV photodetectors

Research on III-nitride materials had been going on since the first synthesis of AlN, InN and GaN in 1907 [1], 1910 [2], and 1932 [3] respectively. III-nitride materials have many advantages such as the ideal spectral selectivity with wide direct bandgaps from the deep UV to the infrared region, high breakdown field, high thermal stability, radiation hardness, and expected high responsivity [4]. However, the materials were initially polycrystalline and were of little value for semiconductor applications. It was not until the late 1980’s that the research in this area was booming, when two major breakthroughs were made on the thin film materials growth technology: the development of buffer layer techniques to obtain smooth and crystalline films and the demonstration of p-type doping. With the breakthrough of the epitaxy technique for GaN film by metal-organic chemical vapor deposition (MOCVD) in the 1990s, the first GaN-based UV photoconductor was developed by Khan et al. in 1992 [5]. Shortly after, the first AlGaN based solar-blind photodetectors were demonstrated in 1996 [6,7]. Following the first reports on photoconductive devices, Schottky [12-14], p-i-n [15-17], MSM [18,19], and avalanche photodiodes [20,21] have successfully been demonstrated. Ever since, research in III-nitrides photodetection devices gradually turned into a specialized field, whereas it used to be part of the wide bandgap semiconductor field.

Among the III-nitride materials, the ternary materials systems of Al<sub>x</sub>Ga<sub>1-x</sub>N have attracted world-wide attention and have seen tremendous development in recent years. One of the most attractive features is a wide range of bandgap from the binaries GaN with 3.5eV to
AlN with 6.2 eV [8] that covers cut-off band edge range between 360 nm and 200 nm, providing a full UV region photodetection [9,10]. Also, Al$_x$Ga$_{1-x}$N alloys with x higher than 40% are considered to be among the best candidates for solar-blind detection. Besides, the material exhibits high chemical, thermal stability and radiation hardness, contributing to the driving force of research in high-temperature and high photon energy detection, and applications to harsh working environments like outer space [11].

The AlGaN photodetectors have wide range of applications from UV astronomy, UV curing of different materials, water purification, flame detection, bio-sensors to more advanced applications including missile plume detection, combustion engine control, and secure space-to-space communications [44]. A good example is the detection for missile plume and other launching actions, which need a good blindness against a daylight background within the earth’s atmosphere. In the very harsh environment of laser induced fusion system, this kind of device is a good candidate for characterization and diagnostic of the ultrafast ignition laser system. The AlGaN material bears the possibility to design the spectral properties of a photodetector accordingly, and it is also desirable to fabricate an array of fast devices across a designed Al composition gradient to give high speed and variable spectral sensitivity [46].

1.2 Major challenges on AlGaN photodetectors

During the decades of AlGaN photodetector development, several major difficulties have been heavily discussed and still need more research to make further improvement.
• **Materials defects**

Due to the large lattice and thermal mismatch between AlGaN thin film and the substrate (most commonly sapphire or SiC), tensile strain commonly occurs and limits the heteroepitaxial growth of the AlGaN directly on GaN/sapphire template to a maximum Al% of 30%, otherwise cracking of the layer would happen. [22] The AlGaN films grown on sapphire often see many fine mosaic blocks (such as hexagonal shaped structures), and the coalescence of these block will also result in cracks. Material defects, such as atomic vacancies, stacking faults, threading dislocations and grain boundaries are commonly seen in these materials and are usually known to deteriorate the device performance [44]. For example, the cracks can cause high dark current in the μA or mA range, a low UV-visible rejection ratio and restrict the performance of the UV devices [23]. Several approaches to improve the quality of AlGaN materials have been reported. In 1992, M. Asif Khan et al. proposed a novel way of atomic layer epitaxy of GaN over sapphire by the method of switched metalorganic chemical vapor deposition [24]. Then in 2002, J Blasing et al. put forward the stress reduction method by employing low-temperature AlN [25]. Other approaches include superlattices development of GaN/Al, GaN/AlGaN [45] layers and different epitaxial lateral overgrowth techniques like [26] in 2009 and [27] in 2012. The best performance of the AlGaN photodetectors ever reported was on a GaN template used the Schottky structure, and showed a dark current of 9 nA at −5 V, and UV/visible rejection ratio of $10^4$. [31] After all of these advances, the achievement of crack-free AlGaN thin film with high materials quality is still very difficult and expensive. More researches are still needed.
Al% inhomogeneity

Al% inhomogeneity has also been reported by several groups and is believed to be detrimental to device performance, such as ultrafast photon detection. Local, in-plane compositional inhomogeneities were reported by Min Gao et al, demonstrating the existence of phase segregation in AlGaN alloys [28]. They concluded that the phase segregation has a strong dependence on the relative diffusion lengths of Al and Ga on the growth surface, and a small variation of 20~30 °C temperature across the growth surface plays a very significant role in controlling the nature and magnitude of the alloy modulation amplitude. This illustrated one way to explain the Al% inhomogeneity in the AlGaN thin film. Similar effect was observed by Collins et al., who reported that compositional inhomogeneities can be generated when limiting the surface mobility of the Al atom by appropriate growth parameters. [29] The work of P. Pramanik et al.[30] also demonstrated this effect in 2017, and further identified two types of compositional inhomogeneities in the AlGaN thin film. One occurs under stoichiometric conditions due to the limited mobility of Al atoms and the other occurs under Al/Ga rich conditions, where the surface is coated with a metallic layer and rich with the active nitrogen. They also concluded that the inhomogeneity makes very significant changes to the values of both the dark current and the photocurrent. It can also influence spectral dependence of the photodetector, with sharp exciton-related peaks observed under Al/Ga rich conditions and long band-tails observed for stoichiometric conditions. However, as to the influence of the inhomogeneity on the device temporal response as well as responsivity, especially under illumination of ultrafast pulsed laser, there is still no systematic study. Part of this work is going to focus on this regime.
• PPC effects

Partly because of the above two major materials problems, the AlGaN thin film show a high density of deep-level defects compared to the conventional semiconductors [32] [33]. The defects degrade the device performance by introducing a sublinear dependency of the photocurrent on the incident power, a low UV/visible contrast, and persistent photoconductivity (PPC) effects [34]-[36], which is especially unwanted for ultrafast UV photodetector applications. A large amount of research dealing with the extremely long rise and fall time of optically excited III-nitride devices have been published, and many different models have been proposed to explain the origin of PPC.

There have been investigations both theoretically and experimentally considering macroscopic potential barriers at surfaces, interfaces, grain boundaries and doping or material inhomogeneities that hinder the recombination process in order to explain the long decay time (~10^3 s) and huge photoconductive gain (~10^3) observed in GaN photoconductors.[37] For example, A. Carbone’s work [38] believed that the long decay time is caused by the high density of dislocations and grain boundaries in the materials, which act as massive traps that captured the free carriers. The positively charged traps captured holes act as a barrier for the photo-excited holes, thus significantly slowing down the recombination process, elongating the decay time of the device. [38] [39]

However, the majority of research tried to explain this in microscopic way like trapping of free carriers at localized defects. Earlier studies by Park et al. put forward the theory that the bi-stability of nitrogen vacancy (VN) accompanied with a change in the charge state is the major reason causing the PPC in Mg-doped GaN.[40] Ursaki et al. built up a mechanism related to the broad distribution of electron traps located 2.2 eV below the
conduction band, which caused PPC in their Si-doped GaN materials. [41] They also believed that the gallium vacancy V$_{\text{Ga}}$ or the gallium antisite N$_{\text{Ga}}$ may be the possible origin of PPC. Katz et al. considered the electron re-occupation of the filled hole traps at the semiconductor-metal interface after the termination of illumination, which causes a gradual recovery of the Schottky barriers [42]. However, the controversy over the reason of PPC still has not been settled.

Researches about methods to reduce the PPC effects have also been carried out, and most recent results include the work M Hou et al. at 2017, in which they successfully suppressed the decay time from 39 hours to 24 seconds by using an in-situ heating method on the device and increased the device temperature to ~ 270 °C. [43]

However, there is little research about the PPC effects in AlGaN devices with ultrafast UV laser incidence. With a more transient incident process and much fewer photons injected than the CW laser, the PPC phenomenon and its origin mechanism may be different. Also, there is no systematic study on the influencing factors over the decay time on the ultrafast AlGaN photodetectors. This work in the following chapters will delve into these topics.

**References**


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Chapter 2 Basic principles and device design

2.1 Basic principles for MSM photodetectors

The Metal-Semiconductor-Metal photodetector is a planar device, consisting of two back-to-back connected Schottky diodes on a semiconductor layer. The metal structure is composed of two contact pads and interdigitated fingers, which form the active area of the device. Figure 2.1 showed the SEM image of a typical MSM photodetector active area fabricated with finger width of 3 μm.

![SEM image of a typical MSM photodetector active area](image)

*Figure 2.1 SEM image of a typical MSM photodetector active area*

The MSM photodetectors have several advantages like fabrication simplicity, low dark current, the potential to achieve high quantum efficiency, low internal gain, and high bandwidth capability [1] [2]. Also, the lateral, planar structure of these devices allows extremely low capacitance, which matches the requirements of high-speed performance very well. What’s more, the fabrication for MSM photodiodes is comparably simple and it can be compatible with field effect transistors, which makes them suitable for integration in an optical detection and amplifier [3].
The device works by absorbing optical energy and converting a photon flux into a time-varying electrical signal. When incident photons have an energy higher than the semiconductor bandgap, electron and hole pairs are generated and these carriers are transported to the metal contact pads, producing a signal in the external circuit under the application of an external bias voltage.

**Energy band diagram**

The simplified band diagram of the MSM structure device with a 1-D approximation, as well as the electric field is shown in Figure 2.2. The electric field distribution and band diagram change accordingly with the increase of the bias voltage. The electrical field is the derivative of the potential in the diagram. The shaded areas in each band diagram represent the metal contacts.

When there is no bias voltage, for a thermal equilibrium condition a built-in voltage is established. The band diagram would be as Fig 2.1(a), where \( \varphi_n \) is the barrier height for the contact and the \( V_D \) is the build in voltage, and \( l \) is the finger spacing. \( V_D \) is given by

\[
V_D = \Phi_n - \frac{1}{q}(E_C - E_F)
\]

(2.1)

Where \( q \) is the elementary charge, \( E_C \) is the conduction band energy level and \( E_F \) the Fermi-level in the semiconductor. For a symmetrical MSM structure (both contacts are fabricated with the same size and metallization, thus the same barrier height), the \( V_D \) can also be given as

\[
V_D = \Phi_n - \frac{kT}{q} \ln \frac{N_C}{N_D}
\]

(2.2)

Where \( k \) is the Boltzmann constant, \( T \) the temperature and the depletion-layer width is defined as
\[ W = \frac{2\varepsilon_s\varepsilon_0}{qN_D} V_D \]  

(2.3)

where \( \varepsilon_s, \varepsilon_0 \) are the static dielectric constant of the semiconductor and permittivity of the free space respectively, and \( N_c \) is effective density of states at the conduction band, \( N_D \) is the doping density in the semiconductor.

When the bias voltage is applied to the diode, one of the contact turns to be forward biased and the other one reverse biased. And the space-charge regions (SCR) widths under the contacts increases with the increasing of bias voltage. When the bias voltage reaches the reach-through voltage, \( V_{RT} \), the two SCR touch together, causing the total of depletion regions to be same as the finger spacing. At this condition, the whole finger spacing areas are fully depleted and the band diagram as well as the electric field at this condition is shown in Fig. 2.2(b).

With the further increase of the bias voltage, the electric field goes to zero and the energy band becomes flat at the metal-semiconductor interface, the corresponding voltage is usually called the flat band voltage, \( V_{FB} \). For a symmetric MSM structure, the \( V_{FB} \) is given by

\[ V_{FB} = \frac{qN_D t^2}{2\varepsilon_s \varepsilon_0} \]  

(2.4)

And the corresponding band diagram is shown in Fig 2.2(c). For the case of the device of this thesis, an AlGaN MSM photodetector with 3 \( \mu \)m finger spacing and unintentionally doping \( (N_d \approx 10^{14} \text{ cm}^{-3}) \), the \( V_{FB} \approx 2.5 \text{ V} \). This is lower than any testing voltage used in this thesis, therefore all devices were tested in the flat band regime.
After the bias voltage exceeds the $V_{FB}$, the energy band is bent further downward and maximum voltage that can be applied on the contact, the breakdown voltage, is limited by the break down phenomena near the maximum field at the reverse biased contact.

Schottky Effect

The actual Schottky barrier height or the build in voltage of the Schottky contact is slightly lower than the value predicted by equation 2.1 and 2.2, which is due to the Schottky effect (as shown in Fig.2.2). Image charges build up in the metal electrode of a metal-semiconductor junction as carriers approach the metal-semiconductor interface. The potential associated with these charges reduces the effective barrier height, which is
called the Schottky effect. The lowering is even more significant when there is bias voltage applied on the Schottky barrier.

The barrier lowering is given by:

$$\Delta \phi = \sqrt{\frac{qE}{4\pi \varepsilon_s}}$$  \hspace{1cm} (2.5)

Where $\varepsilon_s$ is the semiconductor static permittivity and $E$ the electric field at the interface. This barrier reduction has a dependence on the applied bias voltage and tends to be rather small compared to the barrier height itself. Therefore, the Schottky effect is neglected in this thesis.

**Photocurrent and the responsivity**

For MSM photodetector under bias and illumination, the band diagram is shown in Fig 2.3. The diagram assumes front-illumination. The photocurrent depends on the light intensity and the optical properties of the thin film. With opaque metal contact, the metal fingers block out the light that shined on them. Assume $A_{\text{cont}}$, $A_{\text{act}}$ are the total areas of the metal contact and the active area, and $P_{\text{inc}}$ the power of the incident laser, the photocurrent of the MSM photodetector can be written as

$$I_{ph} = \frac{qP_{\text{inc}}\eta_i}{hv} \cdot \frac{A_{\text{cont}}}{A_{\text{act}}} (1 - R)(1 - e^{-\alpha d})$$  \hspace{1cm} (2.5)

*Fig 2.3 Energy band diagram of the MSM PD under bias and illumination*
Where \( R \) is the reflectivity of the thin film, \( \eta \) is the quantum efficiency, \( d \) the semiconductor thin film thickness and \( \alpha \) is the absorption coefficient.

And the responsivity of the photodetector can be defined as

\[
R(\lambda) = \frac{I_{\text{photo}}(\lambda)}{P_{\text{opt}}(\lambda)} = \eta(\lambda) \cdot \frac{q}{E_{\text{opt}}(\lambda)} \tag{2.6}
\]

Where \( I_{\text{photo}} \) is the response photo current, \( P_{\text{opt}} \) is the incident laser power, and \( \eta \) is the quantum efficiency at wavelength of \( \lambda \). This is the most fundamental figure-of-merit to describe a photodetector, the capacity to convert an optical signal measured in Watts into measurable signal for the oscilloscope. Typical example of my first-generation device gives an \( I_{\text{photo}} \) under 266 nm 38.4 \( \mu \)W (average power of the pulsed laser) laser incidence is 0.62 mA at a bias voltage of 30 V. By doing an integration of the current with the pulse period (6.7 ms), we get the average photocurrent of 1.55 \( \mu \)A. This gives a responsivity of 40.3 mA/W and a quantum efficiency of 18.7%.

**Rise and fall time**

Practically the rise time \( t_{\text{rise}} \) from the dark signal to the 90% of the maximum signal upon illumination and the fall time \( t_{\text{fall}} \) to the 10% are commonly used to characterize the temporal response of the photodetector. The intrinsic response time is the combined effect of the field-dependent carrier transit time \( \tau_{\text{tr}} \) and the diffusion time before recombination \( \tau_{\text{diff}} \), and is also dependent on the device structure and materials properties [4]. They can be given by

\[
\tau_{\text{tr}} \approx 0.36 \frac{W_{\text{SCR}}}{\mu F} ; \tau_{\text{diff}} \approx \frac{w^2 \tau_{\text{REC}}}{2L^2} \tag{2.7}
\]
Where \( W_{SCR} \) is the width of the space charge region and \( \mu \) the carrier mobility, \( F \) the electric field strength, \( w \) the length of the field free region, \( L \) the corresponding diffusion length and \( \tau_{rec} \) the minority carrier lifetime.

However, the high-speed performance of the MSM diode can be degraded by the materials defects, combining the effects of the external circuit’s response time \( \tau_{cir} \) and the measurement package’s response time \( \tau_m \) such as the read-out circuit and the oscilloscope, the actual response time we got has the relationship

\[
t = \sqrt{\tau_{tr}^2 + \tau_{diff}^2 + \tau_{cir}^2 + \tau_m^2}
\]  

(2.8)

Therefore, if we want to examine the intrinsic response time of the PD, an ultrafast measuring method must be used to eliminate the effect of measurement system on the electrical pulse generated in the device. This can be accomplished with an electro-optic (EO) sampling experiment, which usually gives a sub-picosecond time resolution. However, the EO sampling measurement is very complex for operation and need very fine alignment of the optical system and does provide a practical data acquisition system for single shot event. For real-time, single-shot applications, a convenient timing instrument is desired to record the data, such as digital oscilloscope and read-out circuit. For this purpose, the device needs to be integrated into a circuit, which inevitably reduces the high-frequency performance of the entire system.

2.2 MSM photodetector device design

Device capacitance

Since the device geometry can influence the device performance as discussed in the previous part, it is very important to design the device structure as well as the external circuit to obtain an optimized device performance.
The Capacitance of the MSM structure is of critical importance to the device performance, and dominates the device high-frequency performance. Using a theoretical model based on the conformal mapping, the MSM capacitance is given by [5]:

\[
C = \frac{\varepsilon_0(1 + \varepsilon_r)K}{K'} \cdot \frac{A}{s + w}
\]

\[
K = K(k) = \int_0^{\pi/2} \frac{d\varphi}{\sqrt{1 - k^2 \sin^2 \varphi}}
\]

\[
k = \tan^2 \frac{\pi}{4} \cdot \frac{s}{s + w}
\]

\[
K' = K(\sqrt{1 - k^2})
\]

(2.9)

Where \( \varepsilon_0 \) is dielectric constant of vacuum, \( \varepsilon_r \) the relative effective dielectric constant of the semiconductor, \( s, w \) the finger spacing/width and \( A \) the active area size. Take the MSM AlGaN diode in the later part as an example, with \( s \) and \( w \) of both 3 \( \mu \)m and active area 50 by 50 \( \mu \)m\(^2\), the device will have a unit capacitance of 0.041 fF/\( \mu \)m and a total capacitance of 17.1 fF.

Based on these equations, decreasing the finger spacing will increase the device capacitance, while decreasing the carrier transit time. However, the dark current will be increased at the same time.

We can reduce the device capacitance by decreasing the size of the active region, but this requires tight focusing of the incident beam and leads to high incident optical energy density, and increases the operation complexity. What’s more, for a smaller active region, the dark current as well as the noise-equivalent power (NEP) will be higher. Plus the fact that the saturation level will get lower with a smaller active area, the dynamic range of the detector will be smaller.
As the capacitance is a complex function of finger spacing and width, which can also influence other device performances like dark current, it is well worth trying fabricating different device structures with finger width and spacing combinations and compare their actual performance.

**Transmission line and compensation pad design**

To better couple out the photo-generated impulse signal, the external circuit needs to be specially designed to match the MSM structure and reduce any discontinuity without degrading the overall bandwidth of the entire assembly.

The transmission-line properties of the parallel strips separated by a dielectric sheet can be found in [6]. To match the 50 Ω impedance of the measurement cable and the oscilloscope, the transmission line width is calculated to be 1.1 mm based on the equations in the reference [7]. As the designed active area is only 50 by 50 μm² and is much smaller than the size of the 1.1 mm wide transmission line, a compensation pad is needed between the active area and the transmission line. This pad has to be fabricated with the devices and it can also make it easier to couple the device into the outside circuit, either by wire bonding or by silver paste.

A compensation pad that can move the transmission line’s inherent capacitance gradually into fringing capacitance is designed by the following equation given by Hoefer [8]. By doing this, we kept the impedance constant until the step is complete [9].

\[
\frac{dy}{dx} = \pm \sqrt{\left(\frac{\eta_0 h \cdot \varepsilon_{e(2y)}}{2\gamma_{ref} Z_01(2y)} - 1\right)^2 - 1}
\]

where \(\eta_0\) is the characteristic impedance of free space (-377 Q); \(\varepsilon_e\) the effective relative dielectric constant of a microstrip line having width \(w\); \(Z_0\) the impedance of microstrip
line having width w and the dielectric replaced with air; y the distance from centerline of the microstrip line

![Diagram showing calculated compensation taper and 0.55 mm transmission line]

*Figure 2.4 The calculated compensation pad shape (only quarter showed)*

Beginning with y=w/2=25 μm and calculate the dy/dx with a step size of 0.0125 mm, we add the dy to the y value of previous step until the final width of 1.1mm/2 is reached. The taper calculated is shown in Fig. 2.4 and this is used directly as the compensation pad shape during the mask design and lithography pattern design in the later part.

### 2.3 Circuit design and SPICE simulation

To better couple out the photogenerated impulse signal, the external circuit needs to be specially designed to match the MSM structure and reduce any discontinuity without degrading the overall bandwidth of the entire assembly. We used a large bias resistor (1 kΩ) to isolate reflections from the charging circuit and prevent the circuit from recharging quickly. An ultra-broad-band (12 kHz to 1-GHz) optical capacitor (100 nF) is
added between the transmission line and the copper back board, in order to produce a high-speed electrical connection and prevent the bias portion of the line from discharging.

![Equivalent circuit of MSM photodetector under illumination](image)

Figure 2.5 Equivalent circuit of MSM photodetector under illumination

We used SPICE to simulate the entire assembly and see the influence of the circuit on the pulse shape. The equivalent circuit of the MSM photodiode with the parasitic circuit elements is as shown in Fig. 2.5. In the plot, R1 is the impedance of the digitizing oscilloscope, which is 50 Ω. L1 and L2 are the inductances caused by the transmission line on each side of the sample, V1 is the photocurrent source (defined as an electrical pulse with FWHM of 10 ps), R2 is the dark resistance of the AlGaN MSM device, C3 is the capacitance of the MSM structure, C1 and C2 are the capacitances between the fingers and the ground, R3 is the high speed bias resistor, and C4 is the ultrafast Optical-capacitor. All the elements have their values as indicated in the diagram. The probe point is set right above the oscilloscope impedance to emulate the real experiment condition. Given a Gaussian electric pulse with 10 ps FWHM, the simulation result gives a broadened impulse output about 16.9 ps, as shown in Fig. 2.6. We can therefore conclude
that the pulse broadening caused by the fast circuit is around 13.6 ps. The oscillations after the main peak are caused by the inductances (L1, L2 in Fig. 2.5) of the transmission lines beside the device. This inductive effect will be discussed more in Chapter 7. The simulation also produced the impulse output of the devices without the bias resistor and the optical-capacitor. The influences of these components can be easily seen as the device without the bias resistor showed extremely broadened shape, while the device without the optical-capacitor showed very bad reflection issues.

However, the SPICE simulation only gives a prediction of the circuit influence on the pulse broadening, and reveals nothing related to the optical electronic process in the semiconductor material. In order to simulate the optoelectronics process in the device, which is related to the behavior of the carriers, more sophisticated method is employed and will be explained specifically in next chapter.

![Figure 2.6 Simulated output pulse from SPICE with the equivalent circuit, and the circuit without opto-capacitor (C4) or high speed resistor(R3)](image_url)
References


Chapter 3  Device performance simulation by APSYS

3.1  Simulation theory introduction and model building

Prior to fabrication of the device, simulations of the device performance were done systematically with APSYS, a general-purpose 2D/3D modeling software program based on Finite Element Analysis. [1] (This program was temporarily purchased by the Laboratory for Laser and Energetics and the license is no longer available.) This software includes many advanced physical models including quantum tunneling, hot carrier transport and trap dynamics. The simulator solves interwoven equations including the basic Possion’s equation, the self-consistent hydrodynamic equations, the heat transfer equations as well as the conventional drift-diffusion current equation for electrons and holes based on the built-in materials properties data base [2].

The device layout is simplified to a 2-D model, with only two Schottky contact and the AlGaN thin film/sapphire substrate defined. The models are meshed with various sizes throughout the model, as shown in Figure 3.1. The interface regions and the edge region from the Schottky area to the illuminated area are defined with smaller mesh size, as the carrier activities in these regions are comparably more complex.

All of the simulations assumed that the incident UV pulse had a duration of 3 ps and a peak intensity of $5 \times 10^3$ W/m². The default bias voltage was set to be 5 V and photons energy roughly 1 eV above the absorption edge. Several device-models were built to investigate the influence of different parameters, like device layout, laser intensity and wavelength, on the device response behavior and I-V behavior. Although this is a very simplified model, and materials quality like dislocation density, defects density was set to
be ideal, the theoretical simulation can provide predictions on how these parameters can influence the device performance, giving guidance for the device design and testing.

### 3.2 Simulation results and discussion

We first checked the Al composition influence on the photocurrent. The detailed simulation results of the different Al% photodetectors are listed in Table 3.1.

<table>
<thead>
<tr>
<th>Al%</th>
<th>Rise Time (ps)</th>
<th>Peak Contact Current (μA/m)</th>
<th>Band Gap (eV)</th>
<th>Incident Photon Energy (eV)</th>
<th>Photon Energy Above the Edge (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.96</td>
<td>81.7</td>
<td>3.24</td>
<td>3.76</td>
<td>0.52</td>
</tr>
<tr>
<td>0.2</td>
<td>5.82</td>
<td>80.5</td>
<td>3.56</td>
<td>4.13</td>
<td>0.57</td>
</tr>
<tr>
<td>0.4</td>
<td>5.74</td>
<td>80.2</td>
<td>3.88</td>
<td>4.96</td>
<td>1.8</td>
</tr>
<tr>
<td>0.6</td>
<td>5.68</td>
<td>71.1</td>
<td>4.20</td>
<td>4.96</td>
<td>0.76</td>
</tr>
<tr>
<td>0.8</td>
<td>5.54</td>
<td>70.0</td>
<td>4.52</td>
<td>5.64</td>
<td>1.12</td>
</tr>
<tr>
<td>1.0</td>
<td>5.35</td>
<td>61.5</td>
<td>4.84</td>
<td>6.20</td>
<td>1.36</td>
</tr>
</tbody>
</table>

*Table 3.1. Detailed comparison of the simulation results for different Al% photodetectors from 0% to 100%*

Overall, the simulations show a 25% decrease in the sensitivity as the material progresses from GaN to AlN. This is somewhat surprising since an increasing Al composition should increase the UV light absorption, presumably resulting in a higher photocurrent. To further investigate this phenomenon, several simulations were done with incident photons 0.5 to 1.3 eV above the band edge. The photocurrent turned out to be a complex function of the energy above the band edge, where the band edge is dependent on the Al concentration. To give a rule of thumb for future prediction regarding the device performance with varying Al composition, a linear fit was done for ∆E (Photon energy
above the absorption edge) ~ I (peak of photocurrent) data points, as shown in Figure 3.2. This simulation indicates that, for a device fabricated in fluctuated Al composition wafer, a variance as much as 25% in the response current could be caused by the Al fluctuation with the same incident laser.

**Figure 3.1** The 2-D simplified model for APSYS simulation (a) and the mesh model (b). The metal contacts were defined only by the geometric region and the Schottky barrier height with no mesh set within them. The regions with more condensed mesh were set as there are more complex carriers behaviors.

**Fig. 3.2** Photocurrent versus ΔE (E_{incident laser} − E_g).
We also simulated the response curve of devices with different finger widths and spacings. The results are shown in Figure 3.3. The black curve describes the incident pulse and uses the left axis, the others are the response curves of devices with different geometry, which uses the right axis. The simulation works indicated the trend that bigger finger spacing will lead to longer response time, while lowering the responsivity. This can be partly explained by Equation 5.2 that we develop to describe the relationship between the device load voltage and the electrode gap/carrier density/carrier mobility.

![Figure 3.3. APSYS simulation for response curve of devices with different finger size](image)

*Figure 3.3. APSYS simulation for response curve of devices with different finger size*

The device response under different incident laser power is shown in Figure 3.4.
Increasing the incident laser power can increase the responsivity nearly by the same magnitude, but it can barely change the response time. The response signal decay time significantly increases when the incident power is above $5 \times 10^9 \text{W/m}^2$. Assume a 40 μm$^2$ beam size, a power of $5 \times 10^9 \text{W/m}^2$ is actually generating electron-hole pairs 94.2% of the atoms in the active area by theoretical estimation. This is saturating the device, thus the response voltage stops increasing after $5 \times 10^9 \text{W/m}^2$.

Consider the device as a simple slab of AlGaN material (the resistivity is $\rho$) with metal contact on both side (with a contact area of $A$), and the finger spacing be the length of the slab($l$). We can estimate the resistivity of the 2-D model (shown in Figure 3.1) by a very roughly estimation with Pouillet’s law:

$$ R = \rho \cdot \frac{l}{A} \quad (3.1) $$
So it is worthwhile to simulate how will the I-V behavior be influenced, when both the finger spacing (affecting l) and finger width (affecting A) increases. Simulated of the I-V curves with same finger width and spacing from 3 μm to 7 μm are shown in Figure 3.5.

It turned out that the device with bigger finger width/spacing would have lower dark current, and all the I-V relationship can be fitted with a third order polynomial function. Therefore, the finger spacing seems to play a bigger role in deciding the dark current than the finger width when increased for a same amount. The simulation predicts a much smaller dark current than the actual device, as the device we fabricated have bigger active area (roughly 0.5 mm² compared to 6 μm in two-dimensional scale) and the materials would be much more defective than the simulation assumes.

![Figure 3.5 Simulated I-V curves with different finger width and spacing.](image)

These simulations only describe the device behavior on the simplified 2-D sectional model of merely two fingers. The fabricated device has larger and more complex 3-D structures, a much larger compensation pad (roughly 0.5 mm²) and the materials properties would be significantly limited by the defects and dislocations (as proved in the
latter chapters). The measurement package, including the measurement cable, the laser pulse and the oscilloscope, would also cause the broadening of the response signal. Also, as shown in Chapter 2.3, the circuit can also cause the broadening of the response signal. Therefore, to get a more comparable simulation result to the experimental data obtained by the fast testing package, simulations with 3-D model based on the actual devices structures should be carried out with numerical simulation software. Also, the broadening effects caused by the measurement package and the circuit should be considered upon the simulation results.

Simulations based on 3-D models with the same structures as our actual devices had been tried out using COMSOL software package. However, as limited by the software computational capability, the simulations were not successful because that the mesh model was too complex. Other software with better computational capabilities is suggested to be used to do a more accurate simulation on the 3-D model of the device.

Reference

Crosslight Software Inc.

Chapter 4  AlGaN thin film Characterization and device fabrication

Prior to the fabrication of the AlGaN photodetector, the materials properties of the AlGaN thin film we were going to use were systematically examined, as described in this chapter. Afterwards, the processing recipe for the fabrication procedure was developed and elaborated in the later section. The investigation of the materials properties gave us better understanding on their influence on the device performance.

4.1  Chemical component investigation of AlGaN thin film

Although the thin film growth techniques have improved significantly over the past decade, the chemical component fluctuation problem, or Al% non-uniformity, had been a persistent problem affecting the material quality of AlGaN and other III-Nitride ternary systems. [1][2][3] Thus prior to the fabrication, it is worth checking the chemical uniformity of the AlGaN thin film, to better understand the materials quality and their influence on device performance.

Two-inch sapphire wafers with non-uniformly composed AlGaN thin film were bought from PAM-XIAMEN. The AlGaN thin film was deposited by Metal-Organic Chemical Vapor Deposition (MOCVD) process with a thickness of 300 nm, and the orientation of c-axis is (0001).

The surface morphology was investigated by scanning electron microscope (SEM), and hexagonal shaped islands with size around several microns were found throughout the wafer, typical example is shown in Figure 4.1(a). The element distribution was mapped by the technique of EDS Energy-dispersive X-ray spectroscopy (EDX). The measurement showed an obvious Al% fluctuation within a geometric scale comparable to the size of the hexagonal structures. An example of a 20 μm by 26 μm scanned regions is
shown in Figure.4.1 (b). The SEM surface morphology and the EDX mapping parallel 
with each other, indicating the Al% non-uniformity is possibly dependent on the 
hexagonal-shaped island.

**Figure.4.1 (a) Surface morphology of hexagonal structure on AlGaN wafer, (b) The 
corresponding EDX mapping of the hexagonal structure; (c) The Measured Al 
composition by XPS on 30 different positions, each position was measured 3 times with 1 
utm in separation, and the error bar represents the error of the 3 measurements.**

However, the EDX technique is not enough accurate in quantified analysis. Also, the 
measured thickness is in micron level, thus a portion of the signal count are from the 
Al₂O₃ substrate, making the non-uniformity of the thin film thickness another possible 
reason for the Al% fluctuation. To more precisely determine the Al composition at 
different areas, X-ray photoelectron spectroscopy (XPS) with a measurement depth of 
around 10 nm was used. The elemental percentage was decided by electron counts of 
each characteristic peak, and atomic sensitivity factor were used to scale the results. 
Thirty measurement points were randomly picked out throughout different parts of the 
wafer, and each point was measured three times with 1 µm spatial separation for 
averaging, the results are shown in Figure 4.1(c), and the error bar is obtained by 
calculating the error of the 3 measurements.
Within the 30 measured points, the Al% varied widely from 7% to 21%. There also exist several points where very similar Al% compositions were found. This might indicate that there exist relatively uniform small regions, like the hexagonal shape. In other aspects, the points with smaller error bars show better uniformity within the group of measurements, which may be taken within the hexagonal structure. And the points with larger errors may be taken around the edge of the hexagonal structure. However, as the XPS system does not feature a high magnification camera, we are not capable of demonstrating that the Al% varies by different hexagonal region.

4.2 Thin film defects research

Given the significant non-uniformity in Al%, it is reasonable to expect a high dislocation/defects density. The Al% fluctuation can cause the lattice mismatch between different Al composition regions, and the lattice mismatch between the AlGaN thin film and the sapphire substrate is also producing large amount of dislocations. It is thus necessary to check the dislocation density of the AlGaN thin film, which is usually an influential factor contributing to the dark current and elongated response time [4][5][6]. X-ray diffraction rocking curve was employed to calculate the dislocation density.

![Figure 4.2 X-ray rocking curve along the (0001) direction of the AlGaN thin film](image)

*Figure 4.2 X-ray rocking curve along the (0001) direction of the AlGaN thin film*
The measured FWHM for (0002) direction of the AlGaN thin film sample was 386.4 arcsec. The dislocation density was estimated based on the Hirsch model [7][8][9], with the equation as:

\[ \rho = \frac{\beta^2}{9b^2} \]

\[ \beta = 0.5H \times \sqrt{\frac{\pi}{\log_2}} \]  

(4.1)

where \( \rho \) is the dislocation density, \( \beta \) is the broadening of the rocking curve in radians, H the FWHM of the rocking curve and b the Burgers vector (a vector that represents the magnitude and direction of the lattice distortion resulting from a dislocation in a crystal lattice). It was found both experimentally and theoretically by T. Ward et al. [10] that dislocations in hexagonal systems are mostly sessile thread dislocations, relating to a burgers vector equal to the lattice constant a. The dislocation density of our AlGaN thin film was calculated to be \( 4.11 \times 10^8 \) cm\(^{-2}\), which means that there are about 4.11 dislocations in a 1 \( \mu \)m\(^2\) area (designated minimum illumination beam size in the later device testing) on average. This dislocation density is fairly large compared to the data of the best quality AlGaN thin films reported in the literature like [11] (\( 5 \times 10^7 \) cm\(^2\)) and [12] (\( 2 \times 10^7 \) cm\(^2\)).

Given the high Al% nonuniformity across the wafer, it is well worth investigating the uniformity of the dislocation distribution over the wafer. Since the XRD rocking curve measurements only acquire x-ray counts coming from a very small area (~1 \( \mu \)m\(^2\)), it is necessary to measure different locations on the wafer to check the uniformity of the dislocation density. We diced three pieces out from different parts of the wafer and measured the rocking curves respectively, which are shown in Figure 4.3. The three
rocking curves have curve width broadening of 399.6, 396, 358.6 arcseconds, giving a thread dislocation density of 4.47, 4.88, 4.31×10^8 cm^{-2} respectively. The dislocation density showed reasonable uniformity between different measurement locations. Additional information that can be determined from Fig. 4.3 is that there is an obvious shift for the positions of the rocking curves peaks (while no shift was observed from the substrate peak). As the peak location reveals information about the crystal orientation and the lattice constant, this is a good indication that the lattice constants between these measurement points are different, making another evidence for the non-uniformity of the Al composition.

![Figure 4.3 Rocking curves from three different measurement locations within one wafer](image)
To make a more thorough investigation on the material quality and get a visual impression, a cross sectional view of the AlGaN/substrate interface was acquired by drilling a hole using the Focused Ion Beam (FIB) capability of the SEM. Obvious crystal defects (roughly 10 nm to 100 nm in size) can be found throughout the SEM images of the interfaces, as shown in Fig. 4.4. As for the size of these defects, they are more likely the macroscopic defects such as cracks or voids. By calculating the average distance of the nearest features in the cross-sectional images, we roughly estimated the density of the crystal defects, which is \( \sim 4 \times 10^9 \text{cm}^{-2} \) and is even higher than the XRD prediction of dislocation density. These voids or cracks are very likely to degrade performance of the devices fabricated on top of these materials.

![Cross-sectional view of AlGaN/sapphire interface](image)

*Figure 4.4. The cross-sectional view of AlGaN/sapphire interface made by ion mill of SEM. Obvious dislocation-like features can be found throughout the interface.*

### 4.3 Optical property of the AlGaN wafer

The transmission curve of the AlGaN thin film was measured with a Lambda-900 spectrometer by scanning the wavelength from 200 nm to 1100 nm, and the result is shown in Figure 4.5. Three different locations were randomly taken at the wafer, and the corresponding transmission curves are shown in three different colors in Fig 4.5. The
curves showed a sharp cutoff wavelength from 312 nm to 328 nm, corresponding to a bandgap from 3.97 eV to 3.78 eV. The variation of the cutoff wavelength further proves the Al compositional fluctuation of the thin film, which is talked about in the previous part of this chapter. The oscillations are the result of the light interference in the AlGaN thin film, from which we can decide the thickness of the film, if the AlGaN refractive index of the measurement location is known. The result showed a visible to UV contrast of more than 4 decades.

Figure 4.5 Transmission curve of the AlGaN thin film, the three curves in different colors represents the spectrum measured at different positions within the wafer

Ambios Surface profiler was used to access the surface roughness of the wafer. Four linear measurements with length of 500 μm were taken, each of the measurement have 50 μm in separation. The measured results are shown in Figure 4.6. The peaks indicate features of more than 20 nm height and less than 10 μm in geometric scale. These are
most possibly referring to the hexagonal structures on the wafer surface, which is consistent with the SEM image of the surface morphology.

![Figure 4.6 The surface roughness measured with four linear runs. The x-axis has units of microns and y-axis is in Angstroms. The four different color curves represent each different lines of measurement.](image)

4.4 Device fabrication

The device fabrication was done after the systematic investigation on the AlGaN thin film properties, as the fabrication process may change the properties of the materials, and it would be difficult to do the measurement with the device on the AlGaN thin film. The photo lithography process is carried out by an Suss MA55 Contact Aligner. A 5-inch chrome/soda lime mask made by Photo Science Inc. was used to define the patterns, and the patterns on the mask were based on the device design described in Chapter 2.2. The finger spacing and width were chosen to be the same at 2 μm, 3 μm and 5 μm respectively, while another kind of device with 2 μm finger width and 5 μm finger
spacing was chosen for comparison. To make better use of the space on the 2-inch AlGaN wafer, all the four kinds of devices were repeated into an 8 columns and 9 rows matrix on the 5 inch mask. This gives a mass production of the devices, making it possible to do a statistical analysis of the device performances, and leaves better possibility to achieve a best performance device.

Gold was chosen as the metal contact of the device for its high work function (Φ=5.1 eV) [13] and chemical stability. Aluminum contact was chosen for comparison, since Al is part of the AlGaN ternary system while showing high work function of around 4.3 eV. Also, there is not enough research on Al as a contact for AlGaN photodetectors.

For both types of metal contacts, a thin layer (30 nm) of Titanium is deposited on the AlGaN thin film prior to Al or Au to assist their adhesion on AlGaN. There are also reports [14~16] showing that, if subjected to a short term anneal, the Ti layer tend to diffuse through the native oxide and reduce the surface oxide by consuming oxygen in the solid solution. Therefore, the adhesive Ti layer also helps reduce the problem of surface oxygen contamination. The gold layer was deposited by a plasma sputtering tool, while the Aluminum and Titanium layer was deposited by an e-beam evaporator.

The device fabrication process was mainly carried out at Semiconductor & Microsystems Fabrication Laboratory (SMFL), while the plasma sputtering process was carried out at Integrated Nanosystems Center (URnano). The detailed fabrication process was described as follows:

1. Mask making
Draw the device layout with Auto CAD, design the mask file with designed dye and pitch size. Decide the polarity and the mask material, then make the mask with commercial vendor.

2. Wafer cleaning
Immerse the sample into diluted HCl solvent overnight to remove dirt and oxide. Clean the wafer with DI water and dry with nitrogen air gun. Bake the sample under 190 °C for 1 min for dehydration.

3. Spin primer
Spin a thin layer of primer Hexamethyldisilazane (HMDS) to improve the photoresist wetting and adhesion. Use a spin speed of 4000 rpm and spinning time of 60 seconds. Bake for 1 min at 100 °C.

4. Spin photoresist
Spin LOR at 4000 rpm for 1 min and bake 5 min at 190 °C. Then use HPR-504 as the photoresist, spin at 4000 rpm for 1 min and bake at 100 °C for 1 min.

5. Write pattern with Contact Aligner
Suss MA55 Aligner is used to write the patterns. Put the wafer in the center of the vacuum truck and expose the wafer with a dose of 130 mJ broadband UV light (given by mercury arc ultraviolet light source) for 30 seconds. Take a post exposure bake at 100 °C for 1 min.

6. Sample develop
Immerse the sample into the developer CD-26 with tweezer and gently shake it for 1 minute. Take a hard bake afterwards at 120 °C for 1 minute.

7. Device pattern deposition
Use PVD-75 Lesker Hybrid Sputter-Evaporation Tool to deposit a layer of 30 nm Titanium at high vacuum level of $1 \times 10^{-6}$ Pa, with the e-beam deposition method. Then deposit another layer of 300 nm Au/Al with the plasma sputtering method.

8. **Lift-off**

For an ideal lift off result, soak the sample into PG remover, put the container into the ultrasonic bench with a 60 °C water bath.

The wafer is then dried with an air gun, and the fabrication is completed. The wafer was finally sent to outside dicing company (American Dicing Inc.) to get the separate devices, for the next step to couple the device into the measurement package, as discussed in the next chapter.

**Reference**


Chapter 5 Investigation on the device performance influenced by the Al compositional non-uniformity

Materials properties research in Chapter 4 revealed that the wafer we used for the initial set of fabrications had a 7% to 21% Al compositional fluctuation across the whole wafer region. Although a large amount of research has reported the fairly good performance of MSM photodetectors fabricated on AlGaN thin films [1–3], we are unaware of any research that explains how the Al% nonuniformity would influence the device’s performance. It is therefore of great importance to investigate the Al% fluctuation influence on the device performance.

The devices were fabricated with the recipe described in Chapter 4.4, and gold was chosen for the metal contact. The devices were then diced out and silver-epoxied to broad-band circuit with a transmission line to directly couple out the electrical pulse generated in the active area. The top view of this fixture as well as the active area structure is shown in Fig. 5.1. The backside of the circuit board is grounded. The transmission line width was designed to be 1.1 mm to match the 50- impedance of the 1.5 GHz oscilloscope. A large bias resistor (1 kΩ) was used to isolate reflections from the charging circuit and prevent the circuit from recharging quickly. An ultra-broad-band (12 kHz to 1-GHz) optical capacitor (100 nF) is soldered between the transmission line and the copper back board to produce a high-speed electrical connection and prevent the bias portion of the line from discharging.
5.1 Device testing equipment description

The test system consists of the laser source and the sample testing system. The two parts are both integrated on a bread board with the purpose of easy mount up, and it is easier to add different functions like temperature controlling without having to realign the system. Most of the tests were done with a CrystaLaser as the laser source. It is a 266 nm laser [4] with pulse duration of 20 ns. The laser wavelength is fourth harmonic generation of a Q-switched Nd: YAG laser, and the repetition rate can be adjusted internally or triggered externally. The average power reaching the detector is measured to be around 38.2 μW by a Thorlab PM200 Si photodiode, and most of the measurements were done with a repetition rate of 150 Hz.
The sample testing system is shown in Figure 5.2. The 40× microscopic system is designed to precisely focus the incident beam onto a specific position on the device, while relaying an image of the device on to a video monitor. This provides the visual feedback of the measured device structure, to get a better control of the beam pointing. The active area is illuminated by a collimated LED white light source. The microscope lens is designed with a working distance of 1 mm and a beam waist of 1 μm. The circuit board shown in Fig.5.1 with the photodetector was mounted on a three-dimensional translation stage and then plugged into a 1.5 GHz oscilloscope. The bandwidth of the oscilloscope was sufficient to see the anticipated 17-MHz features induced by the optical pulse. The translation stage enables beam scan in both transverse directions. Precise control of the beam size was achieved by adjusting the distance along the beam direction (Z direction). A GaAs MSM diode (purchased from Hamamatsu and packaged at the Laboratory for Laser Energetics) is used for reference.
**Beam size measurement**

After building the sample testing system, the size of the beam after the microscope lens is measured precisely.

![Beam size measurement at different distances from the microscopic lens focal position.](image)

*Figure 5.3 Beam size measurement at different distances from the microscopic lens focal position.*

The lines from left to right in different colors showed the measurement made 0 to 10 mm away from the lens. The blue and green flat lines represent 10% and 90% of the maximum intensity respectively. The insert shows the relationship between the distance to the lens and the cross-sectional beam size.

The size of the beam is measured by occluding the beam using a razor blade mounted on a 2-dimensional precision translation stage, and the power is recorded when scanning the razor blade. The distance between positions of the blade, where 10% of the total power
and 90% of the total power were measured and regarded as the beam sizes. The cross-
sectional beam size for positions that are 0 mm (blade touching the microscope lens) to
10 mm away from the lens were measured, as shown in Figure 5.3. The beam showed
good Gaussian profile at all these positions, as determined by taking the derivative of the
curve. We define the region within 10% (shown as the blue flat line in Figure 5.3) to 90%
(shown as the green flat line in Figure 5.3) of the maximum power as the beam size. The
insert shows the relationship between the distance to the lens and the cross-sectional
beam size and the increasing part (1~10 mm away from the microscopic lens) showed a
good linear fit, as shown in Figure 5.3.

To access the performance of the devices, we mainly looked at the temporal behavior by
comparing their decay time. The rise times are mostly determined by the 20ns pulse
duration of the incident CrystaLaser. As the decay process in our test is very slow, the
normal characterization of the decay time by calculating the time from 90% to 10% of the
peak voltage is not accurate. Instead, we calculated the decay time of the response curve
by doing an exponential fitting on the decay part, based on the equation:

\[
\frac{V}{V_0} = a \cdot e^{-\frac{t}{\tau_{fast}}} + b \cdot e^{-\frac{t}{\tau_{slow}}} + c
\]  

(5.1)

We consider the fast part(\(\tau_{fast}\)) of the decay time as the time for the sweep out process of
the photo generated carriers. A large number of carriers are trapped in the deep level trap
centers after the optical illumination. The slow part \(\tau_{slow}\) mainly describes the very slow
releasing process of the trapped carriers. Figure 5.4 showed a typical example of the
biexponential fitting of the decay curve. Also, we access the responsivity by comparing
the peak voltage of the response curve. We estimate the dark current in pulsed laser
illuminated situations, by calculating the average voltage before the rising of the response
curve, which will otherwise be called the dark voltage. This is actually not accurate and will be discussed later.

![Image of decay curve experimental data versus bi-exponential fitting](image)

*Figure 5.4 Typical example of decay curve experimental data versus bi-exponential fitting*

### 5.2 Investigation on the Al% fluctuation influence on device performance

Based on the sample testing system and the 3-D movement stage, we did a beam scan along different positions of the device. Although we don’t know the exact Al% along the scanning path, we can get a qualitative knowledge of the influence significance.

The beam was scanned along the direction of the finger shaped transmission lines with a step size of 3 μm. The sample was placed at the focal point of the beam, so we consider the beam size to be around 1 μm based on the previous measurements. The beam size was about 1/3 the finger spacing of the device. If necessary, slight adjustments in z
direction were made to maintain focus, as determined by the signal amplitude. For the 14 positions in the scan, the temporal response curve is shown in Figure 5.5, and the curve of the peak voltage versus the scanning position was shown as the insert.

![Graph showing response curves and peak voltage vs position](image)

**Figure 5.5** Response curves of 14 scanned positions on the AlGaN photodetector. The insert figure is the peak power versus the scanned position.

The response curves from different illumination positions showed a 31% variation in the peak voltage. We can tell from the insert figure that the change in responsivity is random with the change of the position, so it is unlikely that the change is caused by the geometrical influence. Since the incident laser intensity was kept constant, this large difference in responsivity was due to the inhomogeneity of the underlying material. This big variation is comparable to the simulation results in Chapter 3 that materials progressing from AlN to GaN can cause 25% variation of responsivity. But this can only be a rough approximation as the laser wavelength in each simulation is not identical.
As for the decay time of different incident positions, the fast part varied from 13.7 ns to 10.5 ns, showing a 23.4% variance. And the slow part varied from 4.3 μs to 2.35 μs, showing a variance of 45.4%. The slow part and the fast part of the decay time versus the scan distance are shown in Figure 5.6. We can see that the decay time also showed random relationship with the scan distance, which is similar with the situation of response voltage. The slow and fast part of the decay time didn’t show an obvious correlation with respect to each scan point. Overall, the measuring points with smaller slow part of the decay time tend to also have smaller fast part. This randomness is relevant to the random distribution of the Al compositional nonuniformity.

Additional studies were carried out by comparing the performance of the devices which were from different locations of the wafer. All the devices were from the same wafer and were fabricated under exactly the same procedure, thus we consider all the difference in performance that we measured are result from the Al% fluctuation. These measurements
were taken with the beam size of 40 × 40 μm², almost covering the active area. Therefore, the measurements give the responsivity integrated over a larger active area. For each measurement, response curve was adjusted to maximize the peak voltage. The results are shown in Figure.5.7 (a). The responsivity showed a variation of 8.17%, which is much smaller compared to the former scan. The Root Mean Square (RMS) spread of the tests with bigger measurement area (0.26) and smaller area (0.23) are otherwise close. Considering the integration effects from illuminating a much bigger area, the result is reasonable.

Also, the responsivity by illuminating a 40 μm² area is relatively smaller than that by focusing on a 1 μm area. Both measurements are using the same laser set up, presumably shooting the same number of photons into the active area. However, for a bigger illumination area, part of the beam is blocked by the metal fingers, which made the responsivity lower. To be specific, the photo-induced part of the response voltage (peak voltage reduced by background leakage) is 0.058 V~0.12 V for the measurements with a 1 μm beam size, and is 0.047 V~0.07 V for the measurements with a 40 μm beam size, which is parallel with fact that roughly 50% of the illumination area is blocked by the metal contact.

Overall, the three devices also showed a longer decay time than the ones illuminated with smaller beam size. The slow part of the decay time varied from 5.5 μs to 3.96 μs (28% variance), while the fast part varied from 14.8 ns to 12.3 ns (17 % variance). To explain this, the photo-generated carriers are much more concentrated for the smaller beam size measurement, more traps are saturated in the illuminated area, thus the decay time is relatively shorter.
Finally, we compared the I-V curves for three devices, in Fig.5.7(b). The results indicate that the devices from different parts of the wafer showed similar I-V property but showed slightly different dark current. For example, the dark current variance is as high as 30.6% when the bias voltage is 40 V.

![Figure 5.7 Response curves of 3 devices from different position of a same wafer (b) I-V curve for the 3 devices](image)

To explain the responsivity variance caused by the Al% fluctuation, the theoretical model developed for modelling the photoconductive process by W. R. Donaldson et al. [5] can be used. For an inter-digited MSM structured photodiode, the load current can be described as:

\[ I_L = \frac{1}{2Z + \frac{1}{Aneu}} V_{bias} \]  

(5.2)

Where l is the electrode gap spacing, A is the cross-sectional area of the contact, n is the density of the photogenerated carriers, e is the electronic charge, and \( \mu \) is the sum of carrier mobility. \( V_{bias} \) is the bias voltage.

When we scanned the focused beam in the finger spacing area of our photodetector, all the above parameters stayed the same, except for the photogenerated carriers’ density \( n \) and the carrier mobility \( \mu \). What is more, these two parameters both decrease with the
increase of Al%, according to reference [6] and [7] respectively. As the Al% varied along the scanning path, the product of absorption coefficient and carrier mobility varied with the Al%, so that the photogenerated carriers varied with the scanned position, causing different photocurrent. This model can also be used to explain the trend revealed by the following measurement.

To conclude this chapter, device response tests were done by scanning a laser beam on different positions within the same device and then different devices from the same wafer. The scan showed a 31% variation in responsivity and an obvious difference in decay time over a 40-μm swaths of the devices. The devices from different parts of a single wafer also showed a large variation in responsivity (8%) and dark current (31%). Consequently, the percentage of Al fluctuation can significantly influence the photodetector’s responsivity, dark current, and decay time. This experimental result is somehow parallel with the theoretical simulations results in Chapter 3 that the detector would show a 25% decrease in the sensitivity as the material progresses from GaN to AlN. These findings can be used for future materials and device design and may be of great value for research on potential applications such as ultrafast and small-size spectrometers based on gradient Al-composition AlGaN photodetectors.

Reference


Chapter 6. Systematic test on device performance and investigation on the persistent photoconductivity effect

From the experimental results in Chapter 5, we could see that, except for the non-uniform behavior caused by the Al% nonuniformity, the devices all showed significant problems of extremely long decay time (up to milliseconds) after the optical stimulus has been removed. Moreover, the dark current is much higher than other reports. [1][2]. This phenomenon, which has been widely reported for GaN/AlGaN based devices [5–9], is often referred to as persistent photoconductivity (PPC). It has been a bottleneck for applications that require consistent operations and fast response. The possible causes of the PPC effect in GaN and AlGaN/GaN heterostructures have been debated in the literature and include metastable defects [3,7], gallium vacancy [8], and deep-level defects [8,9] within the epitaxial layers. However, these reports primarily describe photodetector decay behavior when turning on/off a continuous-wave (cw) incident laser. However, for a photodiode illuminated by an ultrafast pulsed laser, the number of injected photons, on a time scale comparable to the PPC decay, is much less than for cw lasers. Yet, the PPC effect in AlGaN photodetectors induced by ultrafast pulsed lasers has not been reported or systematically studied.

It is obvious that the suppression of PPC is very desirable for our application of ultrafast UV photon detection. Therefore, in this chapter, a study on the response behavior and I-V properties of our UV photodetectors with different structures, metals contacts and operating parameters is systematically carried out. Methods to reduce the extremely long decay time were explored and the mechanism of the long decay time is also analyzed.
6.1 Device structures and metal contact choice

During the fabrication process described in Chapter 4, devices with 3 different structures were fabricated in one single wafer during a full run of the fabrication process. The finger width and spacing were set to be the same size on two of the structures: 3 μm (denoted as Au33/Al33), 5 μm (Au55/Al55) respectively. Another group with 2 μm finger width and 5 μm finger spacing (Au25/Al25) was fabricated for comparison. All these designs had an active area of 50 by 50 μm² and were connected with a compensation pad with a calculated curvature (described in Chapter 2) tapered from the transmission line down to the active area for the aim to avoid the reflection noise introduced by the impedance mismatch. Gold was chosen as one of the metallizations for its high work function and chemical stability. Aluminum contact was chosen for comparison since Al is part of the AlGaN ternary system while showing high work function of around 4.3 eV. Also, there is not a lot research on Al as a contact for AlGaN photodetectors, so it provided an opportunity for studying a novel material system.

All the devices were integrated into the same circuit as described in Chapter 5, and the testing system shown in Chapter 5.1 was employed for most of the device testing in this chapter. The response signals were processed and fitted with bi-exponential function in the same way as stated before.

6.2 Electrical property testing of the different devices

The I-V curves of devices with different finger sizes and metal contacts were measured by Keithley 2450 Source Meter by simply adding a step voltage sweep on the device,
with all the measurements taken in the dark. The voltage was increased from 0 V to 40 V, with a 0.1 V step. The measured I-V curve was shown in Figure 6.1.

It is surprising to see that the gold contact showed higher dark current than aluminum contact, because gold has a higher work function. However, the Schottky barrier height is not always decided by the work function, and usually depends highly on the chemical bonding of the metal/semiconductor interface and the semiconductor–vacuum surface, which is related to the Fermi level pinning effects [19]. As in our case, the aluminum contact might have a higher Schottky barrier height than gold due to these chemical effects, and a lower dark current due to the higher Schottkey barrier.

The I-V curves of gold contact devices could be fit with a second order polynomial function, which would indicate a Mott-Gurney law type dependence. W. Shockley and R.C Prim developed a model [4] to describe the space-charge limited emission in semiconductors as an analog to the Child’s law, and they defined the relationship of the current and voltage as:

$$I = \frac{9k\varepsilon_0\mu AV^2}{8W^3}$$  \hspace{1cm} (6.1)

Where $k$=Dielectric constant, $\varepsilon_0$= the permittivity of the free space ($8.85\times10^{-12}$ F/m), $\mu$ = mobility (roughly $280 \frac{cm^2}{V\cdot s}$ for GaN at room temperature), $V$ = applied voltage, $W$= the distance between two fingers and $A$=the contact area. The I-V curve of the gold contact devices can roughly fit the Equation 6.1. For example, we calculated the I-V relationship of Au 55 using Equation 6.1. As there is no data for the parameters of AlGaN but fairly a complete database for GaN, we use some parameters of GaN for the calculation of Al$_{0.17}$GaN. When choosing the $k$ value, we used the value of 5.35 for GaN at high frequency and electric filed vertical to the $c$-axis of the lattice (different literature
give a value range of 5.3~10.4 [21][22]). The distance between two fingers is taken as 5 μm. For the contact area, as our device has with a planar structure rather than sandwich structures of slabs used in Mott-Gurney’s model, we calculated the equivalent contact area with the method developed by W. Donaldson [23]. We simplify the device structure into two parallel transmission lines with 5 μm width and 5 μm separation. As the separation and width are significantly larger than the thin film thickness (~0.3 μm), we made an approximation that A is the sectional area of the thin film under the transmission lines which is about 55.5 μm². The calculated result is I=6.63×10⁻⁷ V², which is close to the fitted I-V relation for Au55 device: I= 7.94×10⁻⁶ V². Given that there are some approximations for the calculation with Eq.1 like the contact area, and the values of mobility and dielectric constant may not be the actual value for the materials we are using, our data showed a good fit to the Mott-Gurney law.

Dark current for the aluminum contact devices, however, showed more complex relationship with the bias voltage. The I-V curve did not show a power law dependence. The mechanism needs further investigation.

The dark current of different device structures were compared for both gold and aluminum contact devices. The devices with 3 μm finger spacing showed higher dark current than the 5 μm ones (due to bigger finger spacing W), and the 2 μm finger width devices showed lower dark current than the 5 μm ones (due to bigger contact area A). What’s more interesting, for both contacts, the devices with 3 μm finger spacing showed about 5/3 times higher dark current than the 5 μm ones at bias voltage over 15 V. These I-V behavior comparisons can be well explained with with Pouillet’s law:

\[
R(\Omega) = \frac{\rho \cdot d}{A} = \frac{\rho \cdot d}{l \cdot w}
\]  

(6.2)
where $\rho$ is the resistivity, $d$ is the finger spacing, $A$ the contact area, $w$ the finger width and $l$ the total finger length. We also found that, for both contact types, the I-V curve at voltage above 15V is close to a linear relationship. Given that Pouillet’s law normally calculates the resistivity of an Ohmic contact, it is doubtful that the contacts were Schottky-like and were instead Ohmic. This will be further discussed in the following section.

The comparison of the dark current between device structures is consistent with the prediction of the simulations by APSYS in Chapter 3, although the simulation utilized a highly simplified model. Moreover, the simulation results showed similar I-V curve shape to the Al contact devices. This indicated that the APSYS program is using a different injection mechanism than the Child’s law, which is similar to the injection mechanism of Schottky contact devices. The Al contact devices are more likely establishing a Schottky barrier.

Figure 6.1 The I-V curve for device with 3 $\mu$m finger width and 3$\mu$m finger spacing, 5 $\mu$m finger width and 5 $\mu$m finger spacing, 2 $\mu$m finger width and 5 $\mu$m finger spacing. The left is for gold contact and the right is for aluminum contact.
Finally, the structure geometry error in the fabrication process, as well as the Al% composition fluctuation talked in Chapter 4, may contribute to an influencing factor on the dark current comparison, making the experimental results different from theoretical prediction. Actually, the results in 5.1 showed a 30.6% difference in dark current for devices with same structure but fabricated on different positions of the wafer.

There are two common ways to integrate the tiny piece of device onto the circuit board: by wire bonding or silver paste or epoxy. We measured the I-V curve for devices dealt with both method and the results are shown in Fig.6.2. For both cases, the wire bonded devices showed obviously lower dark current (25.8 %~31.2 %) than the device with the silver paste. This is quite reasonable as silver paste exposed larger interface area between the paste and the AlGaN material, and the metal silver has a much lower work function than Au/Al. Both these reasons would lead to a higher dark current.
Figure 6.2. I-V curve comparison for devices glued by silver paste and wired bonded. The upper one is for aluminum contact and the lower for gold contact.

For both aluminum and gold contacts, the dark current was huge compared to other reports [1] [6] and was also much larger than theoretical predication made by APSYS and Equation 6.1. Several major reasons are causing the high dark current. One of the major contributors to the dark current is the compensation pad designed to eliminate the impedance mismatch between the active area and the transmission line. We made an estimation by theoretical calculation on the resistance of the device both for the active area and the compensation pad area, and results showed that the compensation pad can contribute 173.4 times higher dark current than the compensation pad. Insulation layers under the compensation pad will be added in our next generation devices design. Another
reason for the high dark current is the poor materials quality. Previous materials characterization of the wafers used in this study indicated that the AlGaN thin films had a high dislocation density of around \(1.38 \times 10^8 \text{cm}^{-2}\), an aluminum compositional that varied (spatially) from 7% to 21% and widely distributed macroscopic defects like cracks, grain boundaries and mosaic features. [24] The high density of different kinds of defects can cause a large dark current by providing intermediate (sub-bandgap) states from which free carriers can be excited. The defective materials may also affect the metal semiconductor interface, degrading the Schottky barrier quality.[7][25] Also, the silver paste used to couple the device into the measurement circuit elevated the dark current level. The silver paste covers a larger area than the metallization that is defined by lithography (roughly 1 mm\(^2\)). The relatively low work function of silver (~4.26 eV) might cause a high leakage current at the silver/semiconductor interface. Our experiment showed that devices employing silver paste had a larger dark current (26 %~31 % higher) than the devices connected by wire bonding directly between the device metallization and the transmission line). Briefly, the large contact area of the compensation pad, the highly defective AlGaN thin film as well as the metal/semiconductor interface, and the application of the silver paste are the main reasons of high dark current. [25].

For both aluminum and gold contact, the dark current is huge compared to other reports [1][6]. Briefly, the large contact area of the compensation pad, the highly defective AlGaN thin film as well as the poor quality of the metal/semiconductor interface (defective interface lattice structures, poor cleanness), are the main reasons [2][25]. More discussions will be made at the end of this chapter.
6.3 Device optical response test

6.3.1 Temporal response measurement for devices with different structures and metal contacts

Devices with different finger sizes and contact materials were tested for temporal response by attaching them to the 3-D movement stage described previously. The output signal was coupled out with fast cable to a 1.5 GHz oscilloscope. The size of the beam was adjusted to around 40 μm by moving the Z direction stage, and signal was adjusted to the maximum by adjusting the XY direction translation stage.

We saw that Au contact devices have higher responsivity and higher dark current than Al contact. This is consistent with the previous dark current test. Because of the complicated dark current behavior we talked about in the previous part, we subtracted the dark voltage from the response signal and regarded the remaining as photo-induced voltage, which is plotted in Fig 6.3.

Considering different devices geometry, the APSYS simulations predict that bigger finger width/spacing would result in longer response time but lower responsivity. The experiments on our device showed similar results. Au25 and Al25 both showed the highest responsivity among the three different geometries. This is quite predictable because of the relatively high ratio of active area in these devices. Device with 3 μm finger width/spacing showed higher responsivity than those of 5 μm finger width/spacing, and slightly faster decay (7.58% for Au contact devices and 5.32% for Al contact devices) of the response signal. The simulation predicts that the 3 μm devices would show 1.74
times higher response current than the 5 μm device. While in our experiments, this number is 2.33 and 3.25 for the Au contact and Al contact devices respectively. Also, the response time difference is not significant compared to the simulation results. This is partly because that the incident laser and testing package is not fast enough to resolve the actual response time. Also, the decay time is mainly determined by the PPC effects, not the device geometry.

![Figure 6.3. Response curves of different device structures with gold and aluminum contact (the dark current been subtracted)](image)

Other factors, like the geometrical inaccuracy, as well as the different interface conditions (cleanness, interface states etc.) of devices caused by the fabrication process, can also cause difference in device response. It is also worth mentioning that the AlGaN wafers we used for fabrication have high Al composition fluctuation (7%~21%). Three devices with the same finger structure but taken from different parts of a same wafer showed a fluctuation of responsivity (8%) and decay time (28% for the slow part and 17% for the fast part) based on the research in Chapter 5.2. These variations are comparable with the device performance difference we measured in this part. The device performance...
difference caused by the Al% inhomogeneity would obscure the relationship between device structure and device performance.

6.3.2 Temporal response measurement for device under different bias voltage

We examined the influence of the bias voltage on the device response by using a BK Precision DC Power Supply 1635. We changed the voltage on the device from 5 V to 30 V, and recorded the response curve under different bias voltages. All the measurements were taken in the same measurement set up, with the same incident laser. The normalized response curves under different bias voltages are shown in Fig.6.4. The peak photo-induced voltage, and the ground level voltage of each curve versus the bias voltage are plotted in Fig.6.5. Both increase with the increasing bias voltage with a near-linear relationship. We can therefore say that the responsivity and the dark current both increase with the bias voltage in a linear relationship.

It is worthwhile to mention that dark current here is not the same with the dark current we got from the I-V curve measurement, which was measured under total darkness. The dark current here is much higher than that and showed a linear relationship with the bias voltage rather than a parabolic relationship. One reason is that the dark current measured here was readout in an HF circuit instead of DC circuit with two simple probes. Also, the ground state voltage did not decay back to dark current level. As the decay time is extremely long, the next pulse rose even before the voltage decay back to ground level.

We can easily tell from the normalized curves that the decay time decreases with the increasing bias voltage. By fitting the curves with the equation (5.1), we can get the fast and slow part of the decay curves, which are also shown in Figure 6.5, with the right axis showing the time scale. The fast part of the decay time decreased from 304.6 ns to 128.9
ns with the bias voltage from 5 V to 30 V, while the slow part of the decay time decreased from 18.15 μs to 11.63 μs. The reduction in decay time is significant, especially for the fast part. This is quite reasonable, as the increasing bias voltage will increase the drift velocity of the carriers, resulting in a faster sweep out of the carriers to the contacts. And it can also accelerate the releasing of the trapped carriers, decreasing the slow part of the decay time.

![Graph showing the normalized response curves under different bias voltages.](image)

**Figure 6.4. The normalized response curves under different bias voltages**

![Graph showing the fast part and slow part of the decay, the peak response, the ground level voltage, and their relationship with the bias voltage.](image)

**Figure 6.5. (a) The fast part and slow part of the decay; (b) the peak response, the ground level voltage, and their relationship with the bias voltage, linear fits included.**
6.3.3 Temporal response at different incident laser power

We also examined the influence of the incident power on the device response. The incident power of the laser was adjusted by putting a UV ND filter in the beam path. OD=0.3, OD=1 and OD=2 filters were used. The generated response curves were shown in Figure 6.6, and the inserted figure showed the normalized curves.

The response voltage decreases as the incident power decreases, but not proportionately. For example, with a 10% of the incident power (OD=1), the photo induced voltage only dropped from 0.039 V to 0.011 V. This is evidence that not all the generated carriers were swept out to the contact directly, a large portion of the carriers were trapped in deep level traps and were released gradually, leading to a long tail in the decay curve. The ground state voltage increased with the incident power, this provides evidence that the signal did not decay to the ground level before the rise of the next pulse. With more photons incident on the device, there would be more remaining carriers before the rise of the next pulse, leaving a higher ground level voltage.

With the inserted normalized response curves, we can easily see that the decay time decreased significantly with a higher incident power. By the bi-exponential fitting, we found that by reducing the incident power to the 10% of the original power, the fast part of the decay time increased from 84.96 ns to 135.36 ns, while the slow part of the decay time increased from 5.015 ms to 8.61 ms. This might be explained by the saturation of the deep level traps. At lower illumination levels, the majority of the traps were occupied. With the increase of the injected carrier density, more carriers that are free from being trapped drift to the electrodes, which is reflected as a faster decay time. Another
explanation might be the screening effect of the space charge region with a high level of carrier injection. Under high density of carriers screening the field, parts of the carriers got recombined by the mutual attraction of the holes and electrons, instead of drifting to the electrodes. These processes also would reflect a faster decay in the response curve. The following experiment on devices applied with the pulsed bias voltage can also be related to this space charge screening effects. [1] [10]

![Figure 6.6. The response curves of the photodetector under different incident power of laser adjusted by the UV ND filters. The insert showed the normalized curves.](image)

### 6.3.4 Temporal response for devices under different temperatures.

It is reported in several articles that the long decay time can be reduced by elevated temperatures which accelerate the carrier liberation rate [11], [12]. In M. Hou’s work[11], where they increased the temperature of the device from room temperature to about 300° C by a specially designed in-situ heating system, and successfully reduced the decay time from 39 hours to 24 seconds.
However, their research was done with CW laser and are mostly talking about the devices decay behavior by turning on/off the CW incident laser. But for a photodiode illuminated by ultrafast pulsed laser, significantly less photons were injected than with the CW lasers, as the illumination time was much shorter. Also, the injection process is faster than the turning on/off process of a CW laser. PPC effects in AlGaN photodetectors induced by ultrafast pulsed laser, to our knowledge, have not been reported in the literatures. Therefore, it is worthwhile that we further investigate the influence of temperature on our device response with an ultrashort pulsed laser.

We heat the photodetector by fixing a 10 Watt 150 Ω electrical resistor on the back of the circuit board and control the heating process by an YSI proportional temperature controller. The resistor was put into a 110 V AC circuit in series with a 25-W 500 Ω resistor and the temperature controller. The sensor of the temperature controller was attached next to the device active area with a copper clip and thermal paste. The temperature tolerance is set to be 0.2 °C.

Considering the poor thermal conductivity of the PCB board and the epoxy under the device, we fixed the temperature for half an hour for each of the measurement, trying to obtain a homogenous temperature between the temperature sensor and the device, and thermal tape was used to reduce the thermal dissipation into the air. The maximum temperature that could be achieved in this setup was about 70°C, limited by thermal dissipation to the ambient air and the output power of our temperature controller. The need to maintain optical access and laboratory safety regulations precluded a higher level of thermal isolation.
Response curves under different temperatures (from room temperature to 70 °C) were recorded, as shown in Fig. 6.7. We didn’t go with higher temperature because of the heating capability of the setup, and to protect the PCB and the fragile glue/wire bonding. The photo-induced voltage, ground level voltage and the response time were calculated as in the voltage related tests, which were shown in Fig. 6.8 and 6.9 respectively.

The photo-induced current and the ground state voltage both increased with the temperature in a near linear relationship. This is simply because that there are more carriers generated with an increasing temperature. As we know, AlGaN has a high bandgap of 3.77 eV, and the temperature as high as 70 °C is not enough to ionize more carriers ($k_BT$=0.029 eV, which is smaller than ionization energy for any of the common impurities of AlGaN[26][27]). However, increasing the temperature can increase the intrinsic carrier density ($n_i = (N_c N_v)^{1/2} \exp(-E_g/(2k_BT))$) and carrier mobility, thus lowering the resistivity of the device. The increase in the photo-induced current is because of the higher mobility and less trapped carriers.

The response time, contrary to the reference works [11][12][13], showed more complex trend. The fast part of the decay time decreased with the increasing temperature (from 42 ns to 30.1 ns), while the slow part increased (2.2 ms to 3.4 ms). To explain this phenomenon, the increased temperature is increasing the drifting velocity of the carriers, making the sweep-out process faster, which is parallel with the decreasing fast part of the decay time. However, for the carriers which are captured in the deep level traps of the materials, increasing the temperature is increasing the collision between the carriers and the traps, making the trapped carriers spending longer time before being released, which is parallel with the increasing slow part of the decay time.
The response time has a quadrature relationship with the actual device response time as

\[ \tau_{\text{meas}} = \sqrt{\tau_{\text{pulse}}^2 + \tau_{\text{osc}}^2 + \tau_{\text{det}}^2}, \]  

(6.3)

where \( \tau_{\text{pulse}} \) and \( \tau_{\text{osc}} \) are the fall time of the incident laser pulse and the oscilloscope resolution, respectively. The actually detector decay time \( (\tau_{\text{det}}) \) is calculated to be 40.8 ns to 28.4 ns with the temperature change. We can obtain an approximation of the actual mobility of the materials we are using by

\[ \tau_{\text{det}} = \tau_{\text{sweep out}} = \frac{d}{\mu E} = \frac{d}{\mu \frac{V_{\text{bias}}}{d}}, \]  

(6.4)

where \( \mu \) is the mobility, \( E \) is the electric field, \( d \) is the finger spacing between electrodes, and \( V \) is the bias voltage. The calculated mobility is \( \sim 0.28 \) to \( 0.38 \) cm\(^2\)/(V•s) with the temperature changing from room temperature to 350 K. Since other reports claimed the mobility of electrons in GaN can change roughly from 280 to 340 cm\(^2\)/(V•s) when the temperature rises from 300 K to 350 K [13], we could surmise that the AlGaN material we use is of poor quality with high defect concentrations causing bad scattering and blocking problems during the sweep out process of the carriers. Increasing the temperature has proven to elevate the carrier mobility, making the sweep-out process faster. On the other hand, with the increase of the temperature, the number of collisions between the free carriers and the traps also increase, thereby increasing the capture rate of the free carriers. This would result in a longer release process of the trapped carriers, which reflects the increase of the slow part of the decay time.
Increasing the temperature from the room temperature to 70°C, the decay time remained the same magnitude, and the changes were within 35%. Compared to Ref. 13, they reduced the decay time from 39 h to 24 s by increasing the temperature to ~270°C. The change of decay time we saw in our research is much less. A larger decay time change might be found if our device is heated to a much higher temperature, using techniques like in-situ heating on the device chip similar to what was described in Ref. 13.

Figure 6.7. The response curve of the device under different temperature from room temperature to 70°C
Figure 6.8. The peak voltage and the ground state voltage versus the temperature, with a linear fit.

Figure 6.9. The fast part and the slow part of the decay time by bi-exponential fitting.
6.4 Investigation on the nature of the metal-semiconductor contact

The above experiments showed that, all of our devices with different structures and metal contacts suffered from significant larger dark current and longs decay time, as compared to the other reports on MSM photodetector fabricated on GaN/AlGaN materials [14][15]. There are possibilities that, while both Au and Al have a relatively high work function and is expected to establish Schottky contact on AlGaN thin films, the metal-semiconductor contact actually showed behavior of Ohmic contact, the fabrication process of which still nonetheless remains something of an art. Ohmic contact MSM detectors normally show higher dark current and much longer decay time than Schottky contact devices [25].

It is reported that Al/Au on highly defected or compositional fluctuated AlGaN thin films may form ohmic contact based on the fabrication method.[16] Correspondingly, our previous investigation showed that the wafers we used had high Al composition fluctuation (7 %~21 %), large density of dislocations (4.1×10⁶cm⁻²) and high density of macroscopic defects (~ 4 × 10⁹ cm⁻²). Therefore, it is necessary to investigate the nature of the metal-semiconductor contact we fabricated.

We applied a square pulsed voltage on the device and studied the on/off behavior of the photodetectors. A Stanford Research System Digital Delay Generator was used to produce a series of four square pulsed voltage (4 V) on the device, the pulse duration was set to be 0.6 μs and the pulse separation was set to be 1 us. The CrystaLaser is triggered by the digital delay generator, so that the laser pulse was set to incident 0.3 μs after the front edge of the first square pulse, and there is a bias voltage of 4 V at the moment when
light-induced carriers were generated. The optical-capacitor and the 1 kΩ bias resistor were taken out to reduce the current caused by the charging and re-charging of the capacitance. The response signal with and without the laser incidence were both recorded by the oscilloscope and were shown in Fig.6.10. The pure photo-induced current is calculating the difference between the two curves. We further subtract the part when the square voltage is on and put these parts together, as shown in Fig.6.10 (insert).

![Response curves with a square pulsed bias voltage applied on the photodetector and a laser pulse incident during the first square voltage. The curves with/without the laser incidence and the photo induced current are shown. The insert shows the combination of the photo induced current when the square voltage was on.](image)

*Figure 6.10. Response curves with a square pulsed bias voltage applied on the photodetector and a laser pulse incident during the first square voltage. The curves with/without the laser incidence and the photo induced current are shown. The insert shows the combination of the photo induced current when the square voltage was on.*
The subtracted pulse was nearly continuous if we ignore the spikes caused by the charging/recharging of the circuit capacitance. These results showed that the carriers generated by the incident laser have nearly no recombination or drift process when there is no bias voltage. This indicates that there is no built-in voltage or depletion region on the device, otherwise the carriers would be partly depleted by the build-in voltage of the Schottky barrier. The carriers were kept in the deep level traps when there is no bias voltage, they didn’t drift to the electrodes and are too far from each other to recombine. The releasing process resumes when the bias voltage is back on. Therefore, the contacts are more likely showing ohmic behavior, causing high dark current.

However, if there were Schottky contacts, the traps may also prevent the carriers from being swept out by the Schottky built-voltage. To provide more evidence, another test is done by setting the incidence of the laser pulse slightly before (~0.1 μs) the rising edge of the first square pulse. A setup, similar to the previous was used. The response signal with and without the laser incidence are shown in Figure 6.11. Photo induced current is also subtracted from these two curves and we can find that there is nearly no current in the entire measurement period. The photo generated carriers didn’t generate any current even when the bias voltage resumed. This is probably because that all the photo-generated carriers recombined before the bias voltage is on. There was no bias voltage when the carriers were generated. The carriers recombined driven by coulomb attraction in a very short time (less than 0.1 μs). No carriers were swept to the electrodes by the Schottky barrier after they are generated, further proving the ohmic behavior of the contact. To get a deeper understanding, further investigation would be taken by changing the time of the laser incidence and compare the behavior of the photo induced current.
Figure 6.11. Response curves with a square pulsed bias voltage applied on the photodetector and a laser pulse incident before the first square voltage. The curves with/without the laser incidence and the photo induced current are shown.

6.5 Discussion of the device performances and the PPC effect

One of the most important problems we saw from the previous testing was that all these devices with different structures and metal contacts showed very high dark current. This is indicated in both the I-V measurement and the temporal response tests. Typical response curve of Au 55 devices showed 0.31 V peak voltage in the response curve under 30 V bias voltage, within which about 0.18 V is dark current.

To give an intuitive model for explaining the high dark current, I simplified the device as a simple slab of AlGaN material with metal contact on both side. The resistivity of the materials is given by
\[
\rho = \frac{1}{q(\mu_n \cdot n + \mu_p \cdot p)} \tag{6.5}
\]

Considering the irregular shape of the big compensation pad, I divided the pad into individual segments, as shown in Figure 6.12, and calculated the dark current of each segment. Using the data got from Equation 2.10, the current caused by the compensation pad can be calculated by

\[
I = \sum V_{bias} \frac{1}{\rho_X} q(\mu_n \cdot n + \mu_p \cdot p) \cdot V_{bias} \sum \frac{dy(x-dx)}{2 \cdot dx} \tag{6.6}
\]

Based on the equations above, the dark current can be estimated as \(1.39 \times 10^{-7}\) A at 30 V bias, if we only consider the active area with the finger structures. This is very low and is comparable to some of the similar research reporting low dark current AlGaN photodetectors [20]. However, if we count in the current introduced by the compensation pad, the result we got from Equation 6.6 is about \(2.41 \times 10^{-5}\) A. Obviously, the dark current introduced by the compensation is much higher than the active area. It is
therefore desirable to add an insulating layer between the compensation pad and the semiconductor material. The actual dark current we got is even higher than this calculated value, which is mainly due to the high density of the defects in the AlGaN thin film and the interface. These traps provide intermediate states, which is easier for the generation of carriers. Other factors like the silver paste and fabrication method will also contribute to the dark current.

Moreover, the diode is giving a relatively weak signal although we are using a high bias voltage with sufficient laser incidence. Based on calculation, the incident laser gives roughly $1.26 \times 10^{11}$ photons/pulse. This is a huge number of injected photons. If we assume every photon can generate an e-h pair, these photons can cause a high carrier density of $3.36 \times 10^{20}$/cm$^3$ (considered AlGaN thin film absorption) and excite an electron from 1.8% of the atoms. This would generate a response voltage even higher than 1 V if all the carriers got swept out immediately. However, most of the carrier got scattered or trapped in the defects in the materials, making the sweep-out process much slower, and causing a much lower peak signal. This is reflected in the broadened response curve shape and the extremely long tail. In fact, the total amount of generated carriers can be estimated by integrating the photo-induced current with pulse repetition period, which turn out to be $2.35 \times 10^{10}$ electrons and indicated a reasonable 18.65% quantum efficiency of the detector. In a word, the deep level traps significantly lowered the response signal, combining with the very high dark current, making the response signal hard to resolve. A relatively high laser power is needed for device testing, which would cause damage and heating problem to the device.
Another problem is the extremely long decay time. The response curve would not decay to ground level even when the repetition rate of the incident laser was set to be around 0.1 kHz, indicating a decay time even longer than 10 ms. The rise time, however, is very fast. Precise measurement of the rise time with a faster 10 ps ORIGAMI laser and a 6 GHz oscilloscope was done, and we got a rise time of around 500 ps. A shorter rise time might be achieved if we can get rid of the measurement package’s influence.

There are different factors that can influence the decay time. From the previous experiments with different bias voltage, laser intensity and temperature, we determined a number the factors influencing the decay time. By increasing the bias voltage from 5V to 30V, both the fast and slow part of the decay time are reduced by 57.6% and 35.9% respectively. By reducing the intensity of the incident laser using different filter from OD0.3 to OD2, the fast and slow part of the decay time are increased by 41.8% and 37.3% respectively. By increasing the temperature from room temperature to 70 °C, the fast part of the decay time reduced 28.3%, while the slow part increased 35.3%. All the above factors can infect the decay time effectively, but in different mechanisms.

In order to explain the mechanism of the PPC effect, different theories had been put forward. A. Carbone’s work [17] believed that the long decay time is caused by the high density of the defects and grain boundaries in the materials, which act as massive traps that captured the free carriers. The positive charged traps due to the captured holes act as a barrier for the photo-excited holes, thus significantly slowing down the recombination process, elongating the decay time of the device. [17] [18]
However, more explanations were made in a microscopic way like localized point defects (nitrogen vacancy, gallium vacancy, gallium antisite etc.) that act as deep level traps. There is plenty of related research, which is briefly reviewed in Chapter 1.

In our situation, we have observed high density of dislocations, and also found crack-like features in the SEM image of the thin film sectional wall. Furthermore, the huge lattice mismatch between AlGaN and the sapphire substrate, as well as the large Al% fluctuation across the wafer, might indicate a large density of point defects. The widely distributed hexagonal structures that can be seen from the surface of the thin film can possibly related to the existence of grain boundaries. Therefore, it is hard to decide which theory above is more suitable for our devices. Systematic comparison of performance with devices fabricated on better quality wafers needs to be done to better locate the actual cause of the PPC effects. After all, it is necessary to say that the mechanisms above are not mutually exclusive, and they can happen at the same time.

References:


Chapter 7 Revision of device design and second-generation device fabrication

7.1 Revision of the device design

The devices fabricated in the previous chapters didn’t show ideal properties that we expected. Two of the biggest problems were the high dark current and the extremely long decay time. According to the analysis in the previous chapters, these problems are mainly due to the poor materials qualities and insufficient consideration in device design. The large Al composition fluctuation, high defects density and poor surface flatness caused the devices to have a non-uniform photo response behavior, as well as showing an obvious PPC effect.

There are two principal causes for the dark current: one is the large defect density and composition fluctuation of the AlGaN thin film, which causes the metal-semiconductor contacts to show ohmic behavior (as proved by the experiments in Chapter 6.4); the other is the large contact area between the metal compensation pad and the AlGaN thin film. Some devices, glued with silver paste, had an even larger contact area with the AlGaN thin film, which contributed to a larger dark current, which is discussed in the previous chapter. Furthermore, the devices were very fragile, vulnerable to scratches and oxidation, as the thin layer of metal structure is exposed directly in the air.

To improve the device performance based on the conclusions we drew in the previous chapters, we made several changes for the device design and the materials as follows:
a) A buffer layer of roughly 10 nm AlN is added between the AlGaN thin film and the substrate, in order to compensate the lattice mismatch of the two materials. New AlGaN with better Al uniformity and surface flatness were bought from Kyma Technologies, Inc.

b) Platinum, which has higher work functions, is used for the metal contacts, to form a better quality Schottky barriers. Gold contacts were also fabricated for comparison. A thin layer of Titanium is used to help improve the adhesion of both Au and Pt on the AlGaN thin film, and to reduce the surface oxidation.

c) A thin insulating layer of SiO₂ is inserted between the compensation pad and the AlGaN layer to effectively block the dark current in the majority areas. The active area with finger structures is still directly fabricated on the AlGaN thin film to collect the response signal.

d) Based on simulations, a thin layer of SiO₂ (44.34 nm) was deposited on top of the device, which acted as both a protection layer and anti-reflection layer. The antireflection layer can effectively increase the transmission of the 266 nm UV laser from 95.7% to 99.5% according to the simulation results by

e) Three wafers with different doping type and dopant density were purchased, and the details of the doping profiles are shown in Table. 7.1. The influence of the doping profile on the detector performance will be investigated by comparing the same structured devices fabricated on these wafers.

### 7.2 New wafer quality test
Prior to the device fabrication, the materials properties of the wafer were tested, to make sure that the new materials were good enough for the expected improvement, and to help the results analysis later.

- **Al composition uniformity**

The Al composition uniformity was confirmed by EDX measurement. The energy of the e-beam was set to be 5kV. Interactive volume simulations were done to investigate the penetration depth of the e-beam on the AlGaN thin film. The simulation results showed that the 5kV e-beam can reach a depth of roughly 300 nm in AlN and 170 nm in GaN, as shown in Figure 7.1. As the thickness of our AlGaN thin film is around 300 nm, it is safe to say that we are actually measuring the X-ray generated from the AlGaN thin film, not the substrate.

![Interactive volume simulations about the e-beam’s interactive region in the incident materials, the left is the result for AlN and the right for GaN.](image)

We randomly collected the electromagnetic emission spectra from six different areas with size varying from 5 um*4 um to 78 um*59 um. The X-ray collection area was defined by zooming in/out and moving the SEM imaging. The composition of Al was then calculated.
by comparing the count number of each elements’ characteristic peak. The six areas showed very similar Al% and showed an overall Al% uniformity within 1.2%.

- **Wafer surface roughness**

![3D mapping of the surface flatness](image)

*Figure 7.2 The 3D mapping of the surface flatness*

The surface doesn’t have periodic features like hexagonal shape islands as seen from the SEM, and showed uniform contribution of Al element from EDX mapping measurement. Ambios Surface profiler was used to access the surface roughness of the wafer. A rectangular area of 1 mm by 750 μm was randomly picked for measurement. The data consisted of 15 parallel linear runs each with a 50 μm separation. The 3D mapping of the surface roughness was shown in Fig 7.1, and the surface roughness has a variation of about 15 nm. Also, it is worthy mention that 10 nm is nearly at the edge of the tool accuracy limitation, and the small peaks are mostly inherent noise by the tool. The surface roughness of the new wafers are fairly good compared to the former wafers. The
former wafers showed widely existence of features with height of over 30 nm and size of over 10 μm. These are related to the hexagonal features on the wafer surface, which are likely causing the Al compositional non-uniformity.

- **Wafer surface flatness**

  The overall wafer surface flatness is also a factor that needs to be considered in case of the accuracy of fabrication. The surface flatness is a key factor that influence the fabrication accuracy during the lithography process. A Poor flatness may put the wafer be out of the focus of the lithography equipment, leading to inaccuracy in the pattern writing, and even cause the abruption of the lithography process. Surface flatness was measured by monochromatic light interference by a 632 nm red light and the fringes showed 24 light bands (as shown in Fig 7.2), which indicated a 7.584 μm peak to valley difference. By finger pressure test, the fringes went towards the edge of the wafer, indicating a convex shape of the wafer. For the following fabrication process, a Microtech Laserwriter LW405 with a 405 nm violent laser beam was employed for lithography, and the surface flatness of our wafers are within the depth of focus of the tool (roughly 10 μm).

*Figure 7.3 Monochromatic light interference map by a 632 nm red light source*
Spectrometry of the wafers

The transmission spectrum was measured by a Lambda 1050 spectrometer. The transmission and the absorption curves we got are shown in Figure 7.4. It is obvious that both the N-type and P-type doping changes the absorption edge of the materials. Both doping types lower the absorption edge to a deeper UV region. The absorption edge of the intrinsic wafer is around 341 nm, while 329 nm and 315 nm for N-doping and P-doping wafers respectively. The doping profile of both N and P type wafers seemed to expand the bandgap of AlGaN, lowering the absorption edge. The dopant could be used for the bandgap engineering of the materials. At the wavelength of 266 nm where we carried out most of our device characterization, less than 2% of the light is transmitted, and most of the light got absorbed by the AlGaN thin film. There is about 1.2% more transmittance of p-doping wafers than the others. There would be very minor difference in device responsivity caused by the difference in transmittance. The wafers spectrum were also measured at multi-positions. Unlike the first-gen wafers, there is no shift in the absorption edge within the same wafer, indicating a uniformity in the optical properties.

Figure 7.4 Transmission(left) and absorption(right) spectrums of the n-doped wafer, p-doped wafer and intrinsic wafer.
7.3 New fabrication procedure

The 2-inch wafers were cut into four pieces symmetrically by American Dicing Inc. prior to the fabrication. Each piece was fabricated with different device designs, as shown in Table.6.2. This helps making better use of the materials and enables comparison of more possible structures and materials of the device.

Due to the improvement in the devices design, new fabrication recipes were developed using different tools from the first-generation devices. The new fabrication process was carried out at URnano facilities using a lift-off process with UV lithography. The detailed recipe is listed as follows:

1. Pattern Drawing and Covert

Draw the device structure with Auto CAD and covert the file format for the software Clewin (WieWeb software, 2018) to read and process. Two layers of structures were drawn: one with only a compensation pad and the other with a compensation pad as well as the finger structures. Two cross-shape marks were drawn on both .cif files to provide precise alignment marks.

2. Wafer cleaning

Immerse the sample into diluted HCl solvent overnight to remove dirt and oxide. Rinse the sample with Isopropyl alcohol(IPA), acetone and deionized (DI) water in sequence to effectively remove the surface organic pollutions. Use nitrogen air gun to dry the sample, and bake the sample under 120 °C for 10 min for dehydration and cool down in the air.

3. Spin primer
Spin a thin layer of primer HMDS to improve the photoresist wetting and adhesion. Use a spin speed of 4000 rpm and spinning time of 60 seconds.

4. Spin photoresist

Use MICROPOSIT S-1813 as the positive photoresist and chose a spin speed of 5000 rpm for a proposed thickness of 1.3 μm. The spinning time was set for 60 second. After coating, the resist was baked at 115 °C for 60 seconds to remove residual solvent.

5. Write pattern of the first layer

Use Microtech Laserwriter LW405 with a minimum resolution of 0.7 μm for writing the patterns on the wafer. The patterns were generated by accurately moving the target wafer underneath a focused UV laser beam with a wavelength of 405 nm wavelength. The first layer was written with only the compensation pad shape on the sample with an exposure power of 320 W/cm². The rectangular corner of the wafer was used as a reference point and the adjacent side line as a reference direction for a good alignment. This helped make sure that the patterns were well written in the designated area within the wafer piece. Ring focus method was chosen to maintain the wafer focused as it was moving.

6. Sample develop

Immerse the sample into the MF-319 solvent using tweezers and gently shake it for better development results. Develop for 60 second and then stop the developing process immediately by rinsing it with water.

7. Wafer cleaning after develop

Rinse the sample thoroughly for 2 minutes to clean all the residual developer and dry the wafer with nitrogen air gun.

8. First layer pattern deposition
Use PVD-75 Lesker Hybrid Sputter-Evaporation Tool to deposit a layer of 30 nm SiO$_2$ as an insulating layer on the sample. Then deposit another layer of 20 nm Ti for easier alignment of the second layer, as the 30 nm layer of silica is too thin and transparent to be seen from the camera of the laser writer.

9. Wafer cleaning

Immerse the sample into diluted HCl solvent overnight to remove dirt and oxide. Rinse the sample with Isopropyl alcohol (IPA), acetone and deionized (DI) water in sequence to effectively remove the surface organic pollutions. Use nitrogen air gun to dry the sample and bake the sample under 120 °C for 10 min for dehydration and cool down in the air.

10. Spin primer HMDS to improve the photoresist wetting and adhesion. Use a spin speed of 4000 rpm and spinning time of 60 seconds.

11. Spin photoresist

Use MICROPOSIT S-1813 as the positive photoresist and chose a spin speed of 5000 rpm for a proposed thickness of 1.3 um. The spinning time was set for 60 second. After coating, the resist was baked at 115 °C for 60 seconds to remove residual solvent.

12. Write pattern of the first layer

Use Microtech Laserwriter LW405 with a minimum resolution of 0.7 µm for writing the patterns on the wafer. The patterns were generated by accurately moving the target wafer underneath a focused UV laser beam with a wavelength of 405 nm wavelength. The first layer was written with only the compensation pad shape on the sample with an exposure dose of 320 W/cm$^2$. The rectangular corner of the wafer was used as a reference point and the adjacent side line as a reference direction for a good alignment. This helped make
sure that the patterns were well written in the designated area within the wafer piece.

Ring focus method was chosen to maintain the wafer focused as it was moving.

13. **Sample develop**

Immerse the sample into the MF-319 solvent with tweezer and gently shake it for better development results. Develop for 60 seconds and then stop the developing process immediately by rinsing it with water.

14. **Wafer cleaning after develop**

Rinse the sample thoroughly for 2 minutes to clean all the residual developer and dry the wafer with nitrogen air gun.

15. **First layer pattern deposition**

Use PVD-75 Lesker Hybrid Sputter-Evaporation Tool to deposit a layer of 30 nm SiO2 as an insulating layer on the sample. Then deposit another layer of 20 nm Ti for easier alignment of the second layer, as the 30 nm layer of silica is too thin and transparent to be seen from the camera of the laser writer.

16. **First layer lift-off**

Soak the sample into acetone and place it into an ultrasonic machine for 2 minutes to lift off the redundant part covered by photoresist. Rinse the sample with DI water and dry it with nitrogen air gun.

17. **Photoresist coating for second layer fabrication**

Repeat the process of primer/photoresist spin, bake process for another 1.3 um coating of S-1813. This is for the deposition of the second layer metallization.

18. **Write pattern for the second layer**
Accurately locate the two cross-shape marks with the microscopic camera of the laser writer. Use these two marks for two points alignment of the second layer. Write the pattern of second layer with an exposure dose of 320 W/cm².

19. Deposit the pattern for the second layer

Repeat the process of 6-8, and for the second layer, layers of 10 nm Ti and 120 nm gold was deposited on the sample. For comparison, 10nmTi/120 nm Pt were deposited on another group of samples.

20. Lift-off process for the second layer

Repeat the lift off process and set the ultrasonic machine for 5 minutes for a better cleaning of the delicate finger structures.

21. Deposition for the anti-reflection layer

Use the Atomic Layer Deposition tool to deposit a layer of 44.34 nm SiO2. This layer is used as both a protection layer and an anti-reflection layer.

22. Wafer dicing

Send the wafer to commercial vendors for dicing. There are many devices fabricated on each wafer for practical purpose and it is necessary to dice them out to integrate into fast package.

The schematic view of the whole process is shown in Fig. 7.4
Figure 7.5 Schematic illustration of the fabrication process
<table>
<thead>
<tr>
<th>wafer</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al%</td>
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<td>8.90%</td>
<td>10%</td>
</tr>
<tr>
<td>AlGaN Thin film thickness</td>
<td>316.7</td>
<td>331</td>
<td>330</td>
</tr>
<tr>
<td>Doping type</td>
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<td>P</td>
<td>intrinsic</td>
</tr>
<tr>
<td>Doping element</td>
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<td>Mg</td>
<td>N.A.</td>
</tr>
<tr>
<td>Doping element density</td>
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<td>1.20E+19</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

*Table 7.1 Wafer properties from KYMA. Inc*

<table>
<thead>
<tr>
<th>Insulating</th>
<th>Antireflection layer</th>
<th>Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>2</td>
<td>Y</td>
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</tr>
<tr>
<td>3</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>4</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

*Table 7.2 Different device design for four pieces of wafer cut from KYMA wafers*

As mentioned before, three wafers were bought from KYMA and the profiles of the wafers are shown in Table 7.1. They are all cut into four pieces and each piece was fabricated with different structures, as shown in Table 7.2.

The devices were then integrated into fast measuring circuit and systematically tested. The comparisons of temporal response behavior and I-V properties are elaborated in the next chapter.
Chapter 8 Second generation photodetector characterization

Based on the optimized fabrication recipe described in Chapter 6, the devices fabricated on the new high-quality AlGaN wafers with different designs were diced into individual chips and coupled into the same fast circuit as described in Chapter 5 and Figure 5.1. For simplicity, the devices in the following part are denoted in a similar way as in the chapter 5. For example, N-Pt55 refers to the device with n-type doping profile, a metallization of platinum and finger width/spacing both of 5 μm.

8.1 Device testing equipment description

The device testing system was improved for the second-generation devices. The test system was designed to resolve faster temporal signals with the capability to control the pulse energy.

An ORIGAMI femtosecond laser from the company of NKT Photonics was employed as the laser source for the new testing system. The laser has a wavelength of 1053 nm, pulse duration of 200 fs and is synchronized with a 76 MHz clock signal. Seeded with the ORIGAMI laser, a diode-pumped regenerative amplifier (DPRA) is used to produce narrow-band, 10 ps pulses by the Nd:YLF gain narrowing effect. The repetition rate is reduced to 5 Hz, which is synchronized with the OMEGA Hardware Timing System (HTS) 38 MHz clock. The collimated DPRA output is then converted into second (526 nm) and fourth harmonics (263 nm) by using nonlinear, BBO crystals that are angularly
tuned for maximum conversion efficiency. The 263 nm forth harmonic beam with 10 ps duration and 5Hz repetition rate is used in our testing configuration.

The design of the new testing system is shown in Figure 8.1. The output energy of the FHG beam can reach to 0.15 mJ, which is too high for the operation of our photodetector. Therefore, we used absorption filters as Fresnel reflection mirrors, to get only 4% surface reflection of the original energy after each mirror. The filters absorb the rest of the laser energy and avoid the secondary reflection from the back surface, which may cause secondary peaks or pulse broadening in the response signal of our detector. In order to precisely control the energy reaching the detector, a half wave plate is put into the beam path to change the beam polarization. A UV-coated polarizer made with alpha-BBO crystal is put after the wave plate, and the transmitted fully polarized extraordinary ray is used for testing. Another piece of transmitting fused silica filter is put into the beam path and a roughly 4% reflected portion goes into the reference diode/energy meter. Finally, a UV coated focus lens is used to focus the beam spot down to a size that is close to the active area of our detector. The size of the beam waist is measured by occluding the beam using a razor blade mounted on a 2-dimensional precision translation stage, similar to the method described in Chapter 5.1, and is measured to be 123 μm. By adjusting the half waveplate, the energy per pulse that reaches the detector after all the optical elements ranges from 12 nJ to 140 nJ.

Due to the instability of the cavity in the laser system, the energy of the laser source showed a relatively high fluctuation of up to 30% even when the waveplate setting was unchanged. This would cause a huge inaccuracy when deciding the influence of the energy that reaches the detector. In order to precisely access the quantum efficiency and
responsivity of the photodetector, a single shot mechanism was used, as shown in Figure 8.1. An electrical shutter, which is triggered by a Stanford Research System Digital Delay Generator, is put into the beam path to select a single pulse. The delay generator (DG) is triggered by the same HTS clock that triggers the laser source. The DG generates three square pulse signals with independently adjustable timings. The three generated signals trigger the measuring oscilloscope, the reference oscilloscope (which takes signal from the reference diode) and the electrical shutter respectively. The time intervals of the three signals are precisely adjusted so that all the instruments can be triggered at the same time. Therefore, once the laser source generates a pulse, the electrical shutter is triggered selecting a single pulse from the 5-Hz train, which would arrive at the MSM detector and the reference diode/energy meter, and trigger the oscilloscopes at the same instance.

Figure 8.1 The testing system for the MSM photodetectors and the single shot mechanism
Single shot pulse energy calibration

Before testing the devices, we replaced the MSM detector with an energy meter and use a reference diode to calibrate the energy reaching at the MSM detector. In single shot mode, we record the reading in the energy meter and the pulse shape at the reference oscilloscope after each laser pulse incidence. By tuning the waveplate, we could record the response pulse of the reference diode under different pulse energy. We then integrated the response curve with time and the integral should be proportional to the number of the carriers that are generated by the laser, thus proportional to the laser pulse energy. Thirty groups of data were taken and there is a good linear fit between the integral and the reading of the energy meter, as shown in Figure 8.2.a. The root mean square error (RMSE) of the linear fit is calculated to be 6.7 nJ. For a comparison of the reference accuracy, a reference energy meter is used for calibrating the laser energy at the position of the reference diode. Similarly, we took 30 single shots and recorded the reading of the two energy meters each time, which showed an even better linear fit (shown in Figure 8.2.b). The RMSE of the latter fit is 3.1 nJ, which is much smaller than the former fit. Therefore, we chose the energy meter as the reference to decide the pulse energy. We referred to the used reading of the reference energy meter upon each single shot of our following measurement and find the corresponding pulse energy from Figure 8.2.b, as we triggered the MSM detector and the reference energy meter at the same time. The RMSE of 3.1 nJ was used as the size of the error bar with regard to the energy per pulse.
Figure 8.2 (a) Linear fit between the integral of the reference diode response curve and the energy per pulse; (b) Linear fit between the reference energy meter and the energy per pulse
8.2 Response signal processing algorithm

For the testing of the MSM detector, we used both a 45 GHz, single-shot LeCroy oscilloscope, and a 12.5 GHz Tektronics oscilloscope. For each acquired oscilloscope trace, a portion of the trace approximately 100ps wide around the peak was fitted with a Gaussian function:

\[ V = V_0 \cdot e^{-\left(\frac{t-b}{\tau}\right)^2} \]  (8.1)

A typical example of the temporal response curves is shown in Figure 8.3, as well as the Gaussian fit. We regard the fitted value \( V_0 \) as the peak value of the response curve, and the value of \( \tau \) is related to the FWHM of the Gaussian curve:

\[ \tau_{\text{measure}} = \tau_{\text{FWHM}} = 2\sqrt{\ln 10} \cdot \tau \]  (8.2)

In fact, the FWHM that we measured is not exactly the response time of our MSM detector, but the quadrature sum of the laser pulse width, the intrinsic response of the detector, the response of the measurement system and the broadening effect of the measurement cable, which can be expressed in the following equation:

\[ \tau_{\text{measure}} = \sqrt{\tau_{\text{intrinsic}}^2 + \tau_{\text{oscilloscope}}^2 + \tau_{\text{cable}}^2 + \tau_{\text{laser}}^2 + \tau_{\text{circuit}}^2} \]  (8.3)

According to the manual, \( \tau_{\text{oscilloscope}} \) is 7.8 ps for the LeCroy oscilloscope (28 ps for the Tektronics oscilloscope) and \( \tau_{\text{laser}} \) is 10 ps as stated earlier. From the SPICE simulation in the Chapter 2, the fast measurement circuit we are using is producing a FWHM of 16.9 ps pulse when illuminated by a 10 ps pulse. Therefore, the pulse broadening that the circuit could cause is calculated to be 13.6 ps, which is regarded as the \( \tau_{\text{circuit}} \).
The measurement cable is another factor that can cause obvious pulse broadening. To
decide the broadening effect of the cable, we put a same cable in series with our
measurement cable and acquired the response curves. By taking several response curves
under same bias voltage and incident pulse energy, and averaging the fitted FWHM value,
we can get a different $\tau_{\text{measure}}'$, and there is

$$
\tau_{\text{measure}}' = \sqrt{\tau_{\text{intrinsic}}^2 + \tau_{\text{oscilloscope}}^2 + 2 \cdot \tau_{\text{cable}}^2 + \tau_{\text{laser}}^2 + \tau_{\text{circuit}}^2}
$$

(8.4)

We can therefore that $\tau_{\text{cable}} = 22.5$ ps from Equation 8.3-8.4. For all the testing results in
this chapter, the peak response voltage and intrinsic response time are calculated by
Equation 8.1-8.3.

We have to mention here that, even with a 45 GHz, ultrahigh-speed, sampling
oscilloscope, the response time is still bandwidth limited. To more accurately measure the
intrinsic response time, an electro-optical sampling could be employed. The EO sampling
system can work like an optic-based sampling scope that takes advantage of the ultrashort
temporal resolution of a femtosecond pulsed laser to probe the electric waveform
generated in the photodiode through a nonlinear crystal. This method can also get rid of
the limitation of the packaging fixture by directly measuring the waveforms in the
materials. However, the fast circuit and the measurement system in this work is more
practical for single-shot characterization of the response properties of the devices. What
is more, in practical applications of the photodetectors, the single-shot applications and
an oscilloscope must be used for a simple and accurate resolution of the response signal.
Therefore, all of the characterizations are using this method in our work.

It is also worth mentioning that, to make sure that the conclusions drawn in this chapter
are repeatable, most of the experiments were repeated on several devices that are
fabricated with the same geometric structure and materials profile. For each different device type, there are more than ten duplications fabricated during each process flow to facilitate replicating experiments are needed.

![Figure 8.3](image.png)

**Figure 8.3** Response curve of device with platinum contact fabricated on n-type doping wafer. The device has a finger spacing and finger width of both 5 μm, and a 10 nm thick SiO₂ insulating layer. The signal is taken under a bias voltage of 15 V and a pulse energy of 52 nJ. The Gaussian fit of the main peak is also plotted while the other data points denoted by red crosses are excluded.

### 8.3 Detector response under different incident energy

After the calibration of the reference energy meter, we investigated the device response under different incident energy. An MSM photodetector fabricated on n-type doping wafer with platinum contact was used for this test. The finger width and spacing were both 5 μm and the device was fabricated without insulating layer. We changed the energy by rotating the half waveplate, triggered the reference energy meter and MSM detector at the same time, and acquired 14 different response curves. All these tests were taken at a bias voltage of 15 V and the Tektronix oscilloscope with a bandwidth of 12.5 GHz was
used. The fitted value of the peak response voltage versus the pulse energy was shown in Figure 8.4(a). As stated earlier in the pulse energy calibration part, the RSME of linear fit between the energy of reference meter and the photodetector was shown as the horizontal error bar in here, and the vertical error bar is the error of $V_0$ at each Gaussian fit. Among the 14 data points that were taken, the pulse energy varied from 56 nJ to 155 nJ, and the corresponding peak voltage rose from 0.2 V to 0.56 V.

There is a very good linear fit between the energy per pulse and the peak voltage, and no saturation was observed within these measurements. This is quite reasonable as the photo-generated carriers increase linearly with the pulse energy, which causes a linear increase in the peak voltage. This is also an indication that the quantum efficiency of the MSM detector stayed almost the same with the increase of the pulse energy.

We also plotted the intrinsic response time versus the pulse energy, as shown in Figure 8.4(b). The horizontal error bars were the same with (a) and the vertical error bars were calculated from the error of $\tau$ at each Gaussian fit, as determined by the Matlab fitting function. The response time stayed roughly the same with the increase of the pulse energy. With the pulse energy rising from 56 nJ to 155 nJ, the response time varied within 42 ps-44 ps, which is smaller than the error bars. This experiment of the response under different pulse energies was repeated on different devices. The same trend was found for all the tested devices. As all the data points were taken under the same bias voltage, this is an indication that the response time is mostly determined by the carrier mobility and the electrical field in the finger spacing. The density of the free carriers does not have an obvious influence on the drift velocity of the free carriers. Therefore, it is necessary to examine the behavior of the photodetectors under different bias voltages.
Further investigated the response behavior of the detectors under different bias voltages. We changed the bias voltage from -30 V to 30 V with a BK Precision DC Power Supply 1635, and the detector stayed unchanged during the test. Due to the fact that the incident laser pulse energy was unstable, we acquired the response signal for four times at each bias voltage and compared the average results. More data points were taken within the range of -10 V to 10 V, as more information might be unveiled in the lower biased region.

The peak voltages under different bias voltages are plotted in Figure 8.5(a), and the fitted function is: Peak Voltage=0.12\cdot\text{Bias Voltage} + 0.0018(V). We can clearly see that the peak voltage increases with the bias voltage approximately linearly. The line is symmetric between negative and positive bias voltages. This is an indication that the
MSM detector has a very good symmetricity, with two same-height Shottky barriers sitting back to back.

Figure 8.5. (a) The peak voltage of the photodetector response under different bias voltage from -30 V to 30V, a linear fit was made based on the data under lower biased
voltage, the red crossed points are the excluded high voltage biased points; (b) The residual distribution of the points to the fitted linear function; (c) The response time versus the different bias voltage

Initially a linear fit was done using all the data points, the fitted line didn’t go through the (0,0) point, and there is an obvious deviation under lower biased voltage. We therefore selected the points under lower bias voltage (−5 V to 5 V) for the linear fit instead, as shown in Figure 8.5(a), and the fitted function went much closer to the zero point. The residual of the data points to the linear fit is shown in Figure 8.5(b). We see that there is slight saturation when the device is biased above 5 volts, and the saturation under positive bias voltage is comparably more obvious. This might be an indication of the asymmetry of the Schottky contacts, but we would further investigate the physics of the contacts such as illumination only a small area of the device and compare the response. Device test using higher bias voltage can also be carried out to examine if there is further saturation.

The response times under different bias voltages with the error bars are also plotted, as shown in Figure 8.5(c). The standard deviations between the four different measurements were also counted in the error bar.

However, there are other error sources. The response time is the FWHM of the curve by Gaussian fit (as shown in Figure 8.3), and only part of the data points were selected in the Gaussian fit. Therefore, the number of the data points selected could cause an error in the fitted FWHM. We did numerous fitting by selecting different amount of data points and compared the resulted FWHM, thus getting the error caused by the amount of data points
selected. For each Gaussian fit result given by Matlab, there is an error bar within 95% confidence bounds, which is also counted in the error bar. All the three error sources constitute the overall error bar with a quadratic relationship, as shown in Figure 8.5(b)

The response time seemed having a more complex relationship with the bias voltage. Firstly, the response time under negative bias and positive bias are not strictly symmetric, the response time under negative bias is comparably longer, but could still be the same given the large error bar. Secondly, under both bias directions, the response time decreases from 0 V to about 15 V, and then tends to increase.

In order to make sure that the trend we saw on this device is not accidental, we repeated the experiment on different devices with the same design and saw the same phenomenon. It is easy to understand that, from 0 V to 15 V, when increasing the bias voltage, the carriers’ velocity increase with the increasing electric field, resulting in a faster sweep out of the carriers, thus a faster response. The carrier velocity may get saturated after around 15 V. Another possibility could be that, under high bias voltage, there is ionization of the trap sites within the AlGaN thin film, slowing down the drifting of the drifting carriers. However, the reason that the response time increases after 15 V may need further investigation. Experiments using higher bias voltage could be carried out on the detectors to check if this trend persists. However, as limited by our equipment and the laboratory regulation, the highest bias voltage we can achieve is 30 V. At last, it is worth mentioning that, given the large error bars, the mechanism shown here maybe biased, and the actual response time change may be veiled by the error bar.
The photodetector spectral responsivity test

The spectral responsivity is a very important parameter for the UV photodetectors, especially for applications where blindness to certain wavelength is desirable. Our intrinsic devices are fabricated on the AlGaN thin film with an Al percentage of around 11% and are supposed to have blindness to the lasers with wavelengths longer than 340 nm. Theoretically, the absorption edge for the n-doping and p-doping devices is expected to be 328 nm and 315 nm respectively, based on the wafer absorption spectrum test in Chapter 7.2.

Due to the limitation of our available equipment, it is impossible to set up a spectral responsivity test. However, our previous investigation on the AlGaN thin film absorption spectrometry in Chapter 7.2 showed very good agreement with the theoretical predications. The intrinsic, n-doping and p-doping wafers showed steep absorption edge at 341 nm, 329 nm and 315 nm respectively. Therefore, a drop of responsivity is expected to happen around these wavelengths due to the significant drop in the absorbed numbers of photons. And the average value of absorbance beyond the absorption edge was 0.08, which was very low.

We further tested the devices response under the incidence of a 351 nm laser. The laser source was achieved by doing a third harmonic generation (THG) of the ORIGAMI laser source described earlier in this chapter. All the devices with intrinsic, n-doping and p-doping profiles showed no response upon the laser illumination. This demonstrated the detector’s excellent blindness above the absorption edge.
8.5 Comparison of devices properties with different metal contacts and doping profiles

As stated in Chapter 7, and described in Table 7.2, devices with different contact materials, different geometry designs were fabricated on wafers with three different doping profiles respectively. It is worthwhile to compare their I-V properties as well as the response behaviors under laser incidence, for a guidance of the materials choice and the geometric structure optimization for the future research.

Similar to the first-generation devices, the I-V curves of platinum and gold contact devices fabricated on three different doping profiles were tested by Keithley 2450 Source Meter with a linear sweep. The voltage range was set to be -30V through 30V with a step of 0.1 V. All the measurements were taken in the dark, and a time delay of 1 second was added between each voltage step to get rid of the circuit capacitance charging/recharging influence. The I-V curves are shown in Figure 8.6: (a) shows the I-V curves of devices fabricated on n-doping wafers, and (b)(c) are for p-doping and intrinsic wafers respectively.

There is an obvious difference of I-V properties between different doping devices: the p-doping devices showed a very high dark current, up to 0.06 A under a voltage of 30 V (for device Au55). Compared to the first-generation devices which showed PPC effects, these devices even showed a higher dark current. The n-doping devices showed a relatively lower dark current, of around 5.3 μA under voltage of 30 V (for device Au 55) and were much lower than the first-generation devices. However, the devices fabricated on the intrinsic wafers showed an extremely low dark current as around 4.8 nA at 30 V.
bias (for device Au 55). The I-V curves of the intrinsic devices became relatively noisier, which is mainly because that, as the dark current becomes too low, the inherent noise of the measurement tool became relatively significant compared to the device dark current.

Figure 8.6 (a) The I-V curves for the devices Au55 and Pt55 fabricated on the n-doping wafer; (b) The I-V curves for the devices Au55 and Pt55 fabricated on the p-doping wafer; (c) The I-V curves for the devices Au55 and Pt55 fabricated on the intrinsic wafer
We can also see that, for the N-doping devices, the dark current increases obviously after 15 V, which is consistent with the fact the response curves broadened under bias voltages above 15V. As the background current is much smaller compared to the response signal (less than 2%), it is unlikely the response curve broadening is caused by the dark current.

It is necessary to mention that the doping level for the N-type (Si doping) and P-type (Mg doping) wafers are $4.4 \times 10^{18}$ cm$^{-3}$ and $1.2 \times 10^{19}$ cm$^{-3}$ respectively. As the doping level are much higher than the intrinsic carrier density, which is around $2 \times 10^{10}$ cm$^{-3}$[1], their carrier concentration can be approximated as the same as the doping density. As the conductivity of the materials can be expressed as:

$$\sigma = e(n\mu_e + p\mu_h)$$  \hspace{1cm} (8.5)

Where n and p are the concentrations of electrons and holes, $\mu_e$ and $\mu_h$ are the mobility of electrons and holes respectively. The mobility of electron and holes of our materials’ doping level are roughly 200 cm$^2$V$^{-1}$s$^{-1}$ and 20 cm$^2$V$^{-1}$s$^{-1}$ respectively [2]. As the carrier concentration of the intrinsic wafers are more than $10^8$ times smaller than the N-doping and P-type wafers, the conductivity of the N-doping and P-type materials are $1.83 \times 10^7$ and $1.03 \times 10^7$ times higher than the intrinsic AlGaN thin film. This explains the reason why the intrinsic wafer showed significantly lower dark current than the doped wafers.

The difference of the Schottky barrier height established on the N-doping and P-doping wafers is causing the big difference of the dark current on those devices. Actually, for the bias voltage above 15V, curve fitting of the I-V curves showed that the N-type devices fit to parabolic function well, indicating a Child’s law type of mechanism, which
is already elaborated in Chapter 6.2. And the P-doping devices showed good linear fit, which indicates that the dark current is dominated by the bulk resistive flow. The I-V characteristics of a MSM diode is typically given by the following equation [8,9]:

\[ I = \frac{2I_1I_2 \sinh(aV)}{I_1e^{-aV} + I_2e^{aV}}, \quad \alpha = \frac{q}{2kT} \]  

(8.6)

Where \( I_1 \) and \( I_2 \) is related to the barrier height of the Schottky barrier sitting back to back on two sides. The I-V curves of all the different devices were fitted with the above equation, but we didn’t get a good fit for any of the data set we acquired. This might indicate a more complex carrier injection mechanism, where a mixture of ohmic contact and Schottky contact is even possible. The Schottky barrier characterization can be more accurately measured by cooling the device with liquid nitrogen.

One obvious conclusion, which can be drawn from the I-V curves comparison, is that the type of the metallization can influence the Schottky barrier height. As seen from Figure 8.6, no matter what the doping profile was, devices with gold contact showed lower dark current than the devices with platinum devices. Similarly, previous research has found that Aluminum contact devices showed lower dark current than the gold devices. Moreover, the doping types seem to play a more vital role in influencing the barrier height and the interface chemistry. To be specific, N-doping devices showed roughly \( 1.13 \times 10^4 \) times lower dark current than the P-doping devices, while showing roughly \( 1.1 \times 10^3 \) times higher dark current than the intrinsic devices (at 30V).

Given such big differences in the I-V properties within different devices, it is well worth investigating the differences in the optical response between these devices. There might be some connection between the device dark current and response time/responsivity.
The six devices described above were tested with the same set up as described previously in this chapter. All these devices have both a finger spacing and finger width of 5 μm. They were forward biased at 15 V and the incident pulse energy was set to be the same (the waveplate stayed unchanged). All the devices were fixed on the 3-D movement stage, and the position of the device was adjusted in the x and y direction so that the response signal reached the maximum. They were fixed at the same z direction, in order to maintain a same beam spot size on the devices. The acquired signals were processed with the method described previously and different devices showed very different behaviors. For all the devices, the data acquisition was repeated for four times, and the average values were calculated after the fitting in order to cancel out the fluctuation of the pulse energy. The intrinsic response time and the peak voltage of the six devices are listed in Table 7.1

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<th>FWHM(ps)</th>
<th>PeakVoltage(V)</th>
</tr>
</thead>
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<td>1.34</td>
</tr>
<tr>
<td>Au55-N</td>
<td>46.3</td>
<td>1.35</td>
</tr>
<tr>
<td>Pt55-I-2layer</td>
<td>29.1</td>
<td>0.78</td>
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<tr>
<td>Au55-I-2layer</td>
<td>40.5</td>
<td>0.88</td>
</tr>
<tr>
<td>Pt55-P</td>
<td>~0.04 ms</td>
<td>1.76 (0.69)</td>
</tr>
<tr>
<td>Au55-P</td>
<td>~0.21 ms</td>
<td>2.1(0.75)</td>
</tr>
</tbody>
</table>

*Table 8.1 The response time and peak voltage of devices fabricated on different doping profile wafers with different metal contacts, the voltage in the bracket is the photoinduced voltage by subtracting the dark current from the peak voltage*
The response time showed significant differences between different doped devices: the devices on intrinsic wafers showed the fastest response time, which was consistent with the fact that the intrinsic devices had lowest dark current. More interestingly, the p-type devices showed obvious PPC effects (a typical example response curve for the p-doping Au55 device is shown in Figure.8.7), which is very similar with what we saw on the first-generation devices. Moreover, the PPC effect is consistent with the fact that the devices showed extremely high dark current. Either the PPC effects and the high dark current are both caused by the same kind of materials defects, or one of them is the cause of the other. Further materials properties investigation is followed in the latter sections.

Compared to the very fast rise time for these devices (75 ps for the p-doping Pt55 device and 90 ps for the Au55 device), the time it takes for the response signal to decay to the ground state is extremely long. This would prevent the device from being employed in the high frequency applications. For example, the device Au55 can’t be used for frequency higher than 5 kHz, as the signal won’t decay to background level before the next pulse arrives.

When comparing the devices with two different metallization, although the gold contact devices showed lower dark current, they have longer response time than the platinum contact devices. As a reference, for the first-generation devices, the aluminum contact devices showed lower dark current, but longer response time than the gold contact devices. There seems to be a trend that a lower dark current is related to a longer response time, and higher work function of metals doesn’t result in a lower dark current.

When considering the peak response voltage, the p-doing devices have the highest peak voltage, while the intrinsic devices showed lowest responsivity. One of the reasons could
be that the dark current is contributing to the peak voltage. In spite of the high peak voltage of the P-doping devices, the photo-induced voltage (subtract the dark current out from the total current) is the lowest compared to the other two types. Similar with the device response discussed in Chapter 6.5, a significant part of the carriers is trapped in the defects of the materials rather than directly drifting to the electrodes, leaving a long tail in the decay curve and a comparably lower photo-induced voltage. There are differences of absorbance at 266 nm between different doping materials, as demonstrated in Figure 7.4. The absorption rate of the n-doped wafer is the highest and the intrinsic wafer is the lowest, which is in consistent with the responsivity comparison.

Figure 8.7 Response curve of Gold contact device fabricated on p-doping AlGaN wafer, the insert is a zoom in around the peak region
Influence of the SiO$_2$ insulating layer

It is worth mentioning that the intrinsic devices are fabricated with the SiO$_2$ insulating layer. The extremely low dark current can either be caused by an extremely high Schottky barrier height on the intrinsic AlGaN thin film, or by cutting off the leakage current underneath the big compensation pad with the help of the SiO$_2$ insulating layer. It is therefore worth checking the influence of the insulating layer on the device response. Two Pt 55 devices fabricated on the same n-doping wafer were chosen for comparison: one is fabricated with the SiO$_2$ insulating layer, the other is not. Their I-V curves are shown in Figure 8.8(a), and it is obvious that the insulating layer is reducing the dark current (by about 25%). However, the dark current of both devices are still much higher than the PT 55 devices fabricated on the intrinsic wafer. We can therefore conclude that the doping profile is the factor that influences the dark current more significantly, while the insulating layer can only reduce the dark current by up to 25%.

The response curves are also compared between the two devices, and the device with insulating layer showed slightly shorter response time (~7.6%). As the beam size in the measurement is about 130 µm and is larger than the device active area, there are carriers generated outside the active area, symbolic example of which is shown in Figure 8.8. Because of the complexity of the electric field in this region, the carriers may drift either to the metal fingers or the compensation pad, both of which will cause longer response time. The insulating layer is cutting out the carriers that may otherwise drift longer distance with slower velocity and arrive at the compensation pad, thus resulting in a slightly shorter response time. This can be further confirmed by more accurately mapping
out the electric field distribution outside the active area, which could be realized by numerical simulations by software like COMSOL.

The responsivity, however, showed more significant difference and the device with insulating layer showed about 10 times lower peak voltage. The microscopic investigation on the device surface morphology indicated that the devices with insulating layers had residuals of the photoresist in the finger spacing regions, which might absorb a significant amount of the UV laser. The residuals were produced by the very high temperature during the deposition of platinum, which were very adhesive to the AlGaN thin film. However, no excessive cleaning action could be taken on the residuals because of the relatively poor adhesion of the platinum on the SiO₂ layer. The cleaning process would cause the peeling of the compensation pad. This is also a good indication that the responsivity is highly dependent on the cleanliness of the device active area, which should be paid extra caution during the fabrication process.

Figure 8.8 The drifting mechanism of the carriers generated outside the active area. The circle represents the incident beam, the green part represents the metal contacts.
Difference between the device mounting methods

In the previous chapter, we have checked different methods to mount the device into the measurement circuit. The I-V curves of the first-generation devices mounted by both wire bonding and silver paste have been tested, and wire bonded devices showed lower dark current than the silver glued devices.

As new materials and different metallization have been used for the second-generation devices, it is worth checking the difference that the mounting methods can cause. Specially, it is of adequate importance to check the temporal response difference between these two kinds. We tested two Pt55 devices fabricated on the n-type wafers, one of which was wire bonded with three Aluminum wires (thickness of 0.0254 mm) on each side of the compensation pad, the other one was silver pasted. Both their I-V curves and temporal response are compared, as shown in Figure 8.9.
Figure 8.9 (a) The I-V curves comparison of devices with wire bonding and silver paste; (b) The temporal response curves comparison of devices with wire bonding and silver paste.
We can confirm from the I-V curve comparison that the wire bonded devices showed lower dark current than the silver pasted devices, which is even lower than the devices with insulating layers. This indicates that the leakage current between the silver paste and the AlGaN thin film is higher than that between the compensation pad and AlGaN thin film.

Regarding the temporal response of both devices, the wire bonding devices showed a slightly longer response time. This could be explained by the fact that the thin aluminum wires showed much higher inductance than the silver paste. The higher inductance is causing the broadening of the response curve.

In order to validate this, we did a SPICE simulation in the similar setup as described in Chapter 3. We first calculated the inductance of the microstrips in our circuit, the equation we used for the calculation is:

\[
L_{ms} = 0.00508 \times L \cdot \ln \left( \frac{2L}{W+H} + 0.5 + 0.2235 \cdot \frac{W+H}{L} \right)
\]  

(8.6)

Where \(L_{ms}\) is the inductance of the microstrip in microhenries (\(\mu\)H), \(W\) is the width of the strip in inches, \(L\) is the length of the strip in inches, \(H\) is the distance between the strip and the ground plane. The inductances of the microstrip on both sides of the device are calculated to be 23.21 nH and 11.2 nH respectively, while the inductance of the silver paste and bonding wires are estimated at 0.7 nH and 4 nH respectively. The simulated response curves is shown in Figure 8.10, and an obvious broadening of the pulse FWHM of around 5 ps can be observed in Figure 8.10.
Lastly, the I-V properties and response behaviors comparisons between devices with different finger spacing/width were carried out and repeated on N-Au22 and N-Au55, and the test results are shown in Table 8.2. Similar trend which had already been shown earlier in Chapter 5 was found here: devices with narrower finger spacing/width shows obvious faster response time, but relatively higher dark current. The main reason of the difference in dark current is the different ohmic resistance of the two structures, which can be explained with the same theory in Chapter 5.3.

<table>
<thead>
<tr>
<th></th>
<th>t_{FWHM} (ps)</th>
<th>Peak(V)</th>
<th>Dark current at 30 V(μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AU22-N</td>
<td>41.3</td>
<td>1.37</td>
<td>11.6</td>
</tr>
<tr>
<td>AU55-N</td>
<td>48.3</td>
<td>1.35</td>
<td>5.12</td>
</tr>
</tbody>
</table>

Table 8.2 The comparison of devices properties between AU22-N and AU55-N
8.6 Materials defects research and discussions

In our previous chapters, we have figured out that the high dark current and the PPC effects are related to the materials defects. Previous materials property investigations on our first-generation devices have shown that the first-generation wafers are highly fluctuated in the Al composition. Also, XRD rocking curve measurements showed that the materials have a relatively high dislocation density \( (4.08 \times 10^8 / \text{cm}^2) \), and the cross-sectional SEM images of the AlGaN thin films showed widely distributed void-like features. We concluded that the extremely long decay time of the devices might be because of the deep level microscopic defects like vacancies or dislocations which trapped the carriers and keep them from being released. The reason might otherwise be the macroscopic defects (voids, cracks etc), which caused segregation of the carriers, and the resulted potential barrier kept the carriers from drifting to the electrodes.

Since the new devices fabricated on different wafers have shown very different performance in both dark current and the response time, and some devices also showed PPC effects, it would be worthwhile to check the defects in these second-generation wafers, and further investigate the reason for the PPC effects.

We investigated the XRD rocking curves of the wafers with three different doping profiles, and the rocking curves we got is shown in Figure 8.11. The higher left peaks come from the sapphire substrate, and the right lower peaks come from the AlGaN thin film. The shift of peaks positions is mainly because of the manually induced error by the equipment operator. There are variance of the two peaks positions difference, which is an indication of the strain difference between each sample.
The dislocation density of each wafer was calculated by the Equation 4.1 respectively and is listed in Table 8.3.

![XRD rocking curve](image)

**Figure 8.11** The XRD rocking curve for (a) N-doping wafer; (b) P-doping wafer; (c) intrinsic wafer

<table>
<thead>
<tr>
<th></th>
<th>Rocking curve broadening</th>
<th>Thread Dislocation Density</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intrinsic</strong></td>
<td>416.16</td>
<td>4.76</td>
</tr>
<tr>
<td><strong>P-doping</strong></td>
<td>327.6</td>
<td>2.95</td>
</tr>
<tr>
<td><strong>N-doping</strong></td>
<td>273.6</td>
<td>2.06</td>
</tr>
<tr>
<td><strong>First generation wafer</strong></td>
<td>384.7</td>
<td>4.08</td>
</tr>
</tbody>
</table>

**Table 8.3** Rocking curves broadening and thread dislocation density of different wafers

Apparently, we can see that, although the second-generation wafers showed better chemical uniformity and the most devices showed better performance, there is no significant improvement in the thread dislocation density. The Intrinsic wafers even have higher dislocation density (1.17 times higher). The P-doping and N-doping wafers are showing less dislocation density; however, the difference is not significant (only less than
two times lower). As mentioned earlier, the Al% composition for all the new wafers are very good, and the fluctuation is only around 1%. Therefore, the Al% uniformity would not cause difference in the dislocation densities. A highly fluctuated Al% might cause high density of point defects instead. Therefore, no significant difference in the point defects density should be expected within the second-generation wafers, as they all show very low Al% fluctuation.

Figure 8.12 The rocking curves of four different measurement locations on a single piece of intrinsic AlGaN wafer

Additionally, as the sampling size of the XRD rocking curve measurements is only a few micrometers on the wafer, it is possible that the dislocation density varies between different positions on the wafer. To guarantee the accuracy of the measurements, we measured the rocking curves of four different locations on the intrinsic wafer, and the rocking curve we got is shown in Figure 8.12. No obvious changes in the curve broadening were observed within these curves, and the calculated dislocation density
only varied from \(4.31 \times 10^8\)/cm\(^2\) to \(4.88 \times 10^8\)/cm\(^2\). Therefore, our previous comparison about the dislocation density is reasonably reliable.

After all, although an AlN buffer layer was introduced in the second-generation wafers and the Al% uniformity was obviously improved, the dislocation density was not significantly reduced, and it seemed not to be the factor that influences the Schottky contact quality and causes PPC effects. The point defects density, which is very likely to be similar among different wafers, is also not a likely cause of high dark current and PPC effects. More similarity in materials properties needs to be found between the first-generation devices and the P-doping devices, in order to locate the actual reason.

We made deeper investigation towards the materials defects by observing the cross-sectional view of the wafers. A piece from each wafer was coated with 5 Angstrom of platinum (to avoid surface charging and get a good image quality) and was put into the SEM system. We tilted our sample to 54° and used the Focused Ion Beam (FIB) feature to drill a hole on the surface of the wafer. As the hole is 2 microns in depth, we could clearly see the layers of AlGaN thin film, AlN buffer layer and the substrate in sequence from the top to the bottom.

The sectional view of each piece is shown in Figure 8.13
Figure 8.13. The cross-sectional SEM image of the AlGaN wafer with (a)n-type doping;(b) p-type doping;(c)non-doping. The sample is FIB treated and the layer from top to bottom are: AlGaN, AlGaN and substrate (sapphire) respectively.

There are obvious differences between the images of these sectional walls. Compared to the first-generation wafers, the N-doping wafers and intrinsic wafers showed much cleaner sectional walls, free of void-like defects. Although there are voids in the AlN buffer layer, the AlGaN layer is very clean. However, the p-doping wafers showed different features. There are large voids (~200 nm in size) existing in the sectional wall, and the average distance between the adjacent voids are about 1.56 μm, which indicates the approximate density of the voids to be $2.6 \times 10^{11}$ cm$^{-3}$. Compared to the active area of around 50 μm by 50 μm, there are supposed to be a fairly high amount (~ 1000) of the voids underneath the laser illumination area. This could influence on the devices performance. There is also a layer of special feature near the surface, which could be
easily seen from Figure 8.13. The SEM image with higher magnification couldn’t give further information on this layer, it is worthwhile to examine the chemical composition of the p-doping wafer sectional layers.

An EDX mapping on the section wall was taken and the distributions of different elements (Aluminum, Gallium Oxygen, Nitrogen and Carbon) are shown in Figure 8.14. The SEM image of the measurement region is also shown in Figure 8.13(a), for a geometric reference. The AlGaN layer, AlN layer and a small portion of sapphire substrate were all included for a whole comparison. The grey value of each pixel only represents the relative composition distribution of each element, and it is not comparable between the values of different elements. We can see from the mapping that there is a layer consistently existing in the mapping of most of the elements, which is parallel with the layer near the surface shown in the SEM image.

Figure 8.14(a) The SEM image for the measurement area of the EDX mapping; (b)~(f): The EDX mapping for the distribution of the element Aluminum, Gallium Oxygen, Nitrogen and Carbon respectively on the p-doping wafer
To better analyze the image quantitatively, we added the pixels up in the horizontal direction, and the added values versus the locations (the values from left to right in this figure are related to the locations from the bottom to the top in Figure 8.14(a)) are shown in Figure 8.15. We can see that from the substrate to the surface, the compositions of aluminum and oxygen both gradually decreases, as the materials changed from Al$_2$O$_3$ to AlN and Al$_{0.1}$GaN. It is worth mentioning that, since the change is gradual and there are no abrupt steps, there is possibly diffusion of the oxygen atoms from the substrate into to the AlGaN layer.

Interestingly, there is an obvious valley in the composition curve of both Ga and N, and the value of Al also showed a shallow valley, which is not significant compared to Ga and N. On the contrarily, there is an obvious peak at the C composition curve, at the same location as the Ga and N, and is related to the layer near the AlGaN surface in the SEM.
image. The increase of the carbon atoms is related to the obvious compositional decrease of the Ga and N atoms.

From the comparison of the EDX mapping and the add-up grey values, we can conclude that there is obvious carbon segregation within a region next to the surface of the AlGaN thin film. The segregation of carbon is related to the compositional drop of Ga and N, which may indicate that the carbon atoms at the substitutional site of Ga or N atom sites in the AlGaN lattice, and the number of the Carbon atoms is comparable to the Ga and N atoms.

The carbon atoms, apart from hydrogen, is the primary impurity in AlGaN grown by MOCVD, and its presence is unavoidable because it originates from radicals of the metalorganic sources [3]. To reduce its content to inconsequential levels, the V/III ratio is considered to be particularly important because at high values (above 500), one can achieve a significant reduction in carbon incorporation into the layers.[4,5] Some results show that the amount of carbon is very sensitive to an increase in the flow rate of the hydrogen carrier gas when the ammonia flow rate is low.[4,6] According to the theoretical predication by the first-principle method [3], carbon atoms substituting nitrogen sites behaves mainly as a deep acceptor, carbon substituting gallium acts as a donor without inducing states in the bandgap, and carbon atoms in the interstitials sites tend to show amphoteric behavior[4]. Also, in p-type GaN materials, carbon atoms substituting gallium atoms are more likely to happen. [7] As for our case, although the concentration of Ga and N both dropped in the layer, it is likely the carbon atoms are substituting more gallium sites or nitrogen sites. Therefore, the carbon atoms are likely introducing donors in the layer.
Although the cross-sectional SEM image of the n-doping wafers and intrinsic wafers are clean, and no obvious layers are found in the AlGaN thin film, we still did the EDX mapping of the sectional view, to make sure that there is no similar elemental segregation. The EDX mappings and the corresponding figures of the add-up grey value for the N-doping wafers were shown in Figure 8.16 and 8.17 respectively. The calculation methods were the same as for the Figure 8.15 and 8.14. We can confirm that there is no carbon segregation phenomenon on the AlGaN thin film, and the element distribution of Aluminum, Gallium Oxygen, Nitrogen and Carbon are comparably uniformly distributed. Therefore, the carbon segregation phenomenon and the voids defects are unique for the P-doping wafers from this manufacturer.

![SEM image and EDX mappings](image)

*Figure 8.16(a) The SEM image for the measurement area of the EDX mapping; (b)~(f): The EDX mapping for the distribution of the element Aluminum, Gallium Oxygen, Nitrogen and Carbon respectively on the intrinsic wafer.*
Figure 8.17 The summation gray values of the horizontal pixels on the EDX mapping image for different elements (intrinsic wafer).

To summarize the materials defects investigation, p-doping wafer differ from the other wafers in multiple ways. P-doping wafer have obvious voids features with a fairly high density and big size, which is very similar to the first-generation wafers. Also, p-doped wafers have an obvious layer of special features from the SEM imaging, and it is proved to be because of carbon segregation by the EDX mapping. The carbon atoms may substitute the atom sites of Ga and N and cause a drop of their compositional percentage. However, all three wafers are proved to have similar thread dislocation density (p-doping wafer have even smaller dislocation density than intrinsic and n-doping wafers). What’s more, they have similar chemical uniformity and lattice mismatch, which indicates that the point defects density should be similar.
Considering the fact that the p-doped devices showed extremely high dark current and PPC effects, which is very similar with the first-generation devices, it is more likely that the PPC effects is caused by the voids or other macroscopic defects in the materials, and also the carbon segregation effects. The microscopic materials defects, such as dislocations and point defects, are not the main reason causing the PPC in our devices. As for the mechanism of the PPC effects, it is more likely that the slow decay of the response curve is because of segregated carriers around the macroscopic defects. And the potential barriers caused by the segregation significantly slow down the drifting process. This could be a very useful guidance for the future materials choice and device designs on the ultrafast MSM photodetectors and offers a solid explanation of the PPC effects in the III-V materials based on practical devices performances.

Reference


Chapter 9  Conclusions and Proposal for future research

9.1 Conclusions

This thesis focused on the development of ultrafast UV photodetectors with picosecond response times and understanding the materials properties’ influence on the detector performance. Two generations of Metal-semiconductor-metal UV photodetectors based on AlGaN thin films were designed, simulated, fabricated and tested. The second-generation devices successfully eliminated of the persistent photoconductivity (PPC) problems, and both the response time and dark current have been improved by more than 6 orders of magnitude. The detector’s optical response showed excellent linearity to the bias voltage and the laser power. The detectors were insensitive to the laser wavelengths above the absorption edge. These promising results would be important to a wide variety of applications in ultrafast laser characterization and diagnostics, integrated photonics and high speed optical communications, especially when blindness to a specific wavelength is desirable.

For the first-generation devices, different structures and materials layout with different metal contact and packaging methods were designed and fabricated. The device performance including the I-V property and temporal response under different circumstances were both simulated by APSYS and tested experimentally. Various parameters including device layout, bias voltage, incident power, operating temperature, beam size and focusing location were varied to demonstrate their influence on the device performance. The fluctuation in the percentage of Aluminum (denoted as Al %) was investigated from the materials perspective and its influence on the device performance
was investigated both theoretically and experimentally. The metal-semiconductor contact nature was studied by applying a pulsed-voltage measurement, and the PPC phenomenon found in the device temporal response was investigated and methods to reduce it were tried out.

To achieve faster device response and lower dark current, second-generation devices were fabricated on better quality wafers with improved device designs. Within the different doping profiles and contact materials of the second-generation devices, the best devices showed a fast response time (< 20 ps) and dark currents below 10 pA. The devices also showed excellent response linearity with the bias voltage and the laser energy.

The PPC effects and high dark current were also observed on P-doping devices and the reason for this was investigated from the perspective of materials properties. The results showed that the macroscopic defects (cracks and voids in the AlGaN thin film), rather than the microscopic defects (point defects, dislocation), are likely the major reason causing the extremely slow decay of the response time. There are also carbon segregation layers found on in the P-doping materials, which is likely to be connected with the PPC effects and high dark current of the devices.

**9.2 Proposal for future research**

To follow up the research presented in this thesis, the most important point is to accurately measure the intrinsic response time of the photodetectors and to improve the overall high-speed performance of the UV photodiode.

As stated in Chapter 8, although the best devices showed response time under 20 ps after taking account into the pulse broadening effects caused by the measurement fixtures and
the laser pulse, the response time we got by single-shot oscilloscopes is still bandwidth limited by the oscilloscope. Therefore, either a higher bandwidth oscilloscope with a narrower pulse characterization laser could be employed. As a reference, Finisar claimed to use 70GHz scope for their ultrafast detector test [1] or Electro-optic(EO) sampling method could be used to discover the inherent temporal response of the device.

Our second-generation devices showed significant improvement in the materials quality, with regard to the compositional uniformity and the defects density. However, the second-generation wafers have about 10% of aluminum, which is much lower than the first-generation wafers (Al$_{0.2}$GaN). Therefore, the improvement in the materials quality may be partially related to the relatively lower Al content. It has been widely reported, that it is harder to achieve good material quality and high quality Schottky barriers with higher Al content AlGaN thin films [2][3]. Thus, it is worth checking the properties of devices fabricated on higher Al content wafers. This would also be beneficial for developing high performance solar-blind UV photodetectors, or other applications in deep UV region.

Also, as we have not investigated the spectral response of our photodiodes. It is suggested to test the device with various incident light wavelength in the future research. As mentioned in Chapter 8.4, it would be desirable to test the devices using bias voltages higher than 30 V. The saturation and the pulse broadening under high bias voltage deserves further investigation. The proposed future work is elaborated in the remainder of this chapter.

1. **Improvement of the device design and the testing system**
To improve the high frequency performance of MSM photodiode, the most efficient way is to reduce the size of the active area, because the capacitance decreases with the square of the active area size, thus reducing the RC time constant of the device.

However, there are several drawbacks about the reduction of the active area. The first concern is that the smaller area will limit the electric power that can be produced by the diode and may require a smaller focal point beam size of the testing laser. The smaller focal spot will increase the energy intensity of the laser beam, which may damage the device or cause the space charge screening effect. Also, the smaller beam size and active area increase the difficulty of handling the beam and making sure that the beam is centralized over the active area. If the beam is covering the part outside the active area, the generated free carriers would slowly diffuse, rather than being swept, to the electrodes, leaving a long tail following the main peak of the response curve.

Another improvement that could be made is reducing the finger width/spacing of the photodetector. A narrower finger spacing can result in a faster sweep out process of the photo-generated carriers, since the drifting distance of the carriers is shorter. However, the device will suffer from higher dark current, which is already demonstrated in the previous chapters. As limited by our optical lithography tool (laser writer and contact aligner), the finest feature of the fabrication is almost limited within micron region. The smallest finger width/spacing that our devices could achieve is 1 μm.

Therefore, for the future research, it is suggested to use e-beam lithography for the patterning. Previous research works by J. Li [4] have successfully achieved 300 nm finger width by e-beam lithography. It is, however, worth to mention that the e-beam
lithography would take far more time than the optical lithography and therefore not adequately suitable for wafer-scale mass production.

What’s more, for the testing system, it is suggested to use narrower pulse width UV lasers to characterize the device, and higher bandwidth oscilloscope is also suggested to be used. This would be helpful to resolve the intrinsic response time of the photodetector based on single shot real time sampling.

2. **Electro-optic (EO) sampling study on the inherent temporal response of the device without the limitation of the circuit and package fixture.**

Our previous experiments clearly showed that the intrinsic response time is obscured by the measurement system and the packaging fixture. Thus, it is worth investigating dynamic behavior of the free carriers generated by the incident laser and map out the temporal profile of the intrinsic response without the limitation of the packaging fixture. EO sampling method is an ideal candidate for this purpose. EO sampling system works like an optic-based sampling scope that takes advantage of the ultrashort temporal resolution of a femtosecond pulsed laser to probe the electric waveform generated in the photodiode through a nonlinear crystal. The fringing electrical field causes the refractive index change of the nonlinear crystal that is placed upon the photodiode, inducing a modification of the laser polarization, which can be converted to the intensity change of the sampling beam. By adjusting the delay between the electric waveform and sampling beam, we can then map out the temporal profile of the signal. With this system, it is possible to record the signal in sub-picosecond resolution.
The ultrafast optoelectronic group at LLE has well developed experience of EO sampling in characterizing the high frequency response of electrical transients [5][6] and various optoelectronic switches [8][7] for many years. Minor modification is needed for the already developed systems to test wide bandgap material of AlGaN. However, it is still worth mentioning that although the EO sampling method can unveil the intrinsic response speed of the photodetectors, it is not a practical way to measure the response signals from the photodetectors. Usually the device eventually need to be cooperated into a fast circuit and measured by the oscilloscope.

3. **Exploring AlxGaN photodetectors with higher aluminum percentage**

It is known that AlxGa1-xN would have higher bandgap and therefore a deeper UV cut-off wavelength when x increases. This would be especially useful for deep UV applications where the detectors would otherwise need to be blind to relatively higher wavelength. However, many of the epitaxial grown AlGaN thin films at higher aluminum percentage show poor materials quality such as high density of dislocations and macroscopic defects [9]. It is thus interesting to select proper materials with satisfactory defects density and explore the possibilities of fabricating MSM photodetectors on them. In the process, materials investigation techniques like SEM, XRD and EDX mapping described in Chapter 4 and Chapter 8 can be especially useful in deciding the density of different kind of defects, and predicting whether the materials is likely to give a fast response and low dark current.
References


