Picosecond Response of Ultraviolet Photodiodes on GaN

Experimental results on the fabrication, packaging, and testing of very fast metal-semiconductor-metal photodiodes (MSM-PD's) made on gallium nitride (GaN) have been previously reported.[1] The devices—with feature sizes ranging from 0.3 μm to 5 μm—were packaged in a circuit that was designed to easily couple the electrical transients out of the device, thus making them suitable for practical applications. A temporal response of 55±5-ps full width at half maximum (FWHM) was measured in all devices, independent of feature size. External bias was changed from 1 V to 10 V, and the device area was decreased by a factor of 4 to reduce the total capacitance, neither of which had a significant effect on the measured speed. Only high illumination levels produced a change in the device response. This change was attributed to space-charge screening effect. These results led to the conclusion that the device response was dominated by the packaging and measurement system. Theoretical calculations[2–5] have predicted, however, that the steady-state peak electron velocity in GaN is around 3×10^7 cm/s, which is higher than that in GaAs. This implies that the inherent speed in GaN detectors should be substantially faster than in GaAs devices. Joshi *et al.*,[6] in particular, using Monte Carlo simulations, studied the dynamic response of GaN MSM-PD and predicted a FWHM of 3.5 ps for a device with 0.25-μm feature size under low-bias and low-level illumination.

To explore the inherent device response, a double-pulse measurement was performed[1] by splitting the optical beam into two parts with an adjustable delay and then recombining them to excite the device under test. Separable pulses from a typical device were observed at delays of less than 26 ps, confirming a much-faster inherent response.

In this article results measured with electro-optic (EO) sampling are reported.[7,8] This technique is connector-free and has a bandwidth of more than 1 THz, corresponding to a temporal resolution of 360 fs, providing a much-faster measurement system. To minimize the capacitance effect inherent to the MSM structure, small devices with active area of 25 × 25 μm^2 were selected. The sampling point, defined by the laser spot, was close to the active device area. A sufficient time window existed (about 15 ps) before the transient reflections from the circuit terminals set in, ensuring that the measurement of the intrinsic response could be separated from the packaging circuit.

The devices were made on GaN wafers (2-μm thickness) grown on c-plane sapphire and purchased from a commercial source. The residual impurities produced an electron concentration below 1×10^{16} cm^{-3}. Fabrication was carried out at the Cornell Nanofabrication Facilities (CNF) using electron-beam lithography. Metallization used to form Schottky contacts was either Ni/Au or Ti/Pt. Details of the device fabrication can be found in Ref. 1.

The device was excited by beams from a femtosecond, frequency-doubled, Ti:sapphire, mode-locked laser tuned at λ = 720 nm, with a 76-MHz repetition rate and an average power of 1 mW. The fundamental beam was used to probe the photogenerated electrical signal via a movable $LiTaO_3$ electro-optic crystal positioned close to the active area (Fig. 97.28), which served as a detector of the electrical transient. The excitation beam was focused down to the active area without passing through the electro-optic (EO) crystal. To maximize the EO coupling, the sampling beam was precisely focused on the edge of the metal pad, where the strongest electric field is located. The distance between the ends of the metal pads (1.3 mm in Fig. 97.28) defines the onset of the first reflection of the electric pulse and was seen in the evanescent portion of the transient. The dc bias needed to generate the dark electric field between the fingers was applied via wire bonds.

It should be noted that even though the optical wavelength of 360 nm was only 5 nm above the energy gap of the GaN film, the penetration depth was around 370 nm, as determined by transmission measurement at this wavelength. This is significantly shorter than the 2-μm thickness of GaN film and the 1-μm distance of the finger spacing. Therefore, the deep-carrier effect as observed in a silicon MSM diode[9] is negligible here.

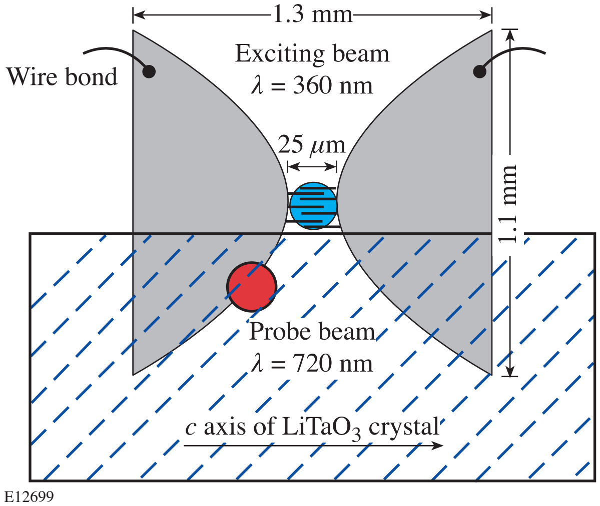

Figure 97.28
A schematic view of the sample configuration for measuring the electrical response of the MSM GaN photodiodes.

Figure 97.29 shows the fastest temporal response of the photodiode with 1-μm finger width and spacing and 25 × 25-μm^2 active area, under 12-V bias. The pulse shape in Fig. 97.29 is strongly asymmetrical: the 1.4-ps rise time is limited by the optical pulse width and by the RC time constant in the MSM structure and pads. The slower trailing transient, determined by the carrier transit across the finger gap, can be fitted with a bi-exponential function with time constants of 2.1 ps and 22 ps. They are attributed to the electron and the hole components, respectively. It should be pointed out that while the faster electron part is closely fitted with an exponential, the slower hole component is masked with reflections from the ends of the metal pads.

The electron velocity from the ratio of the half-distance between the electrodes (0.5 μm) to the measured FWHM (3.5 ps) is estimated to be 1.43±0.1 × 10^7 cm/s. This result compares favorably with the value of 1.5 × 10^7 cm/s measured[10,11] under an electric field of 120 kV/cm in a femtosecond optical time-of-flight experiment that monitors the change in the electro-absorption associated with the transport of photogenerated carriers in a GaN *p-i-n* diode.

The dependence of pulse duration and electron velocity on the electric field was extracted by changing the bias voltage from 5 V to 14 V. The inset in Fig. 97.30 shows the measured FWHM as a function of average electric field, which is calcu-

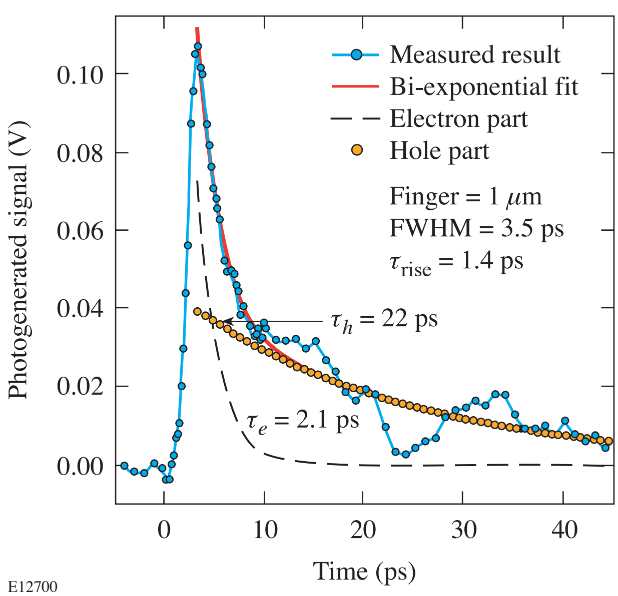

Figure 97.29
Electrical pulses generated by illumination of 360-nm photons and the bi-exponential fitting. The finger spacing and width of the diode are both 1 μm.

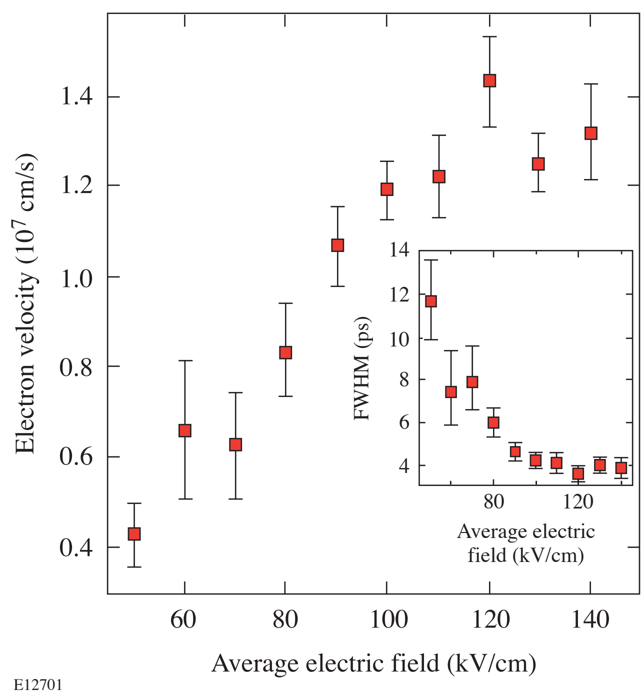

Figure 97.30
The experimentally determined electron velocity and measured FWHM (inset) as a function of average electric field.

lated by dividing the bias voltage by 1-μm finger spacing. In the low-field region, the experimentally determined electron velocity, shown in Fig. 97.30, increases with bias. Above 100 kV/cm, the electron velocity begins to flatten, reaching a plateau at 120 kV/cm. If the average of the plateau region is used, rather than the peak, then the estimated electron velocity becomes $1.3\pm0.1 \times 10^7$ cm/s. The fact that the peak velocity measured in our experiment is lower than the calculated steady-state peak electron velocity for GaN[2] may be attributed to the high defect density in the device and/or the capacitance effect of MSM structure that are not accounted for by theory.

The high-field results of Fig. 97.30 can be compared with Monte Carlo simulations.[6] For a device with 0.25-μm finger spacing, the corresponding FWHM is expected to be around 1 ps, based on our measured electron speed. This is substantially faster than the simulated results of 3.5 ps.[6] To check further, a device with 0.5-μm finger spacing was tested. A typical transient, shown in Fig. 97.31, shows two features distinct from the 1-μm device: a slower rise time of 3.2 ps and a broader FWHM of 6.2 ps. This result is at first surprising; however, it is consistent with an increased capacitance that dominated the measured response from the smaller device. In the MSM structure, the device capacitance increases with smaller finger spacing. For our samples, the capacitances are calculated[12] to be 0.0126 pF and 0.0263 pF for the 1-μm and 0.5-μm devices, respectively. With a measured package-circuit impedance of 63 Ω,[1] the corresponding RC time constant would increase with increased capacitance and gives a 10%–90% rise time of 3.7 ps for the 0.5-μm device, essentially accounting for the slower response observed in Fig. 97.31. Further comparison with theory will then require devices fabricated with much smaller detection areas.

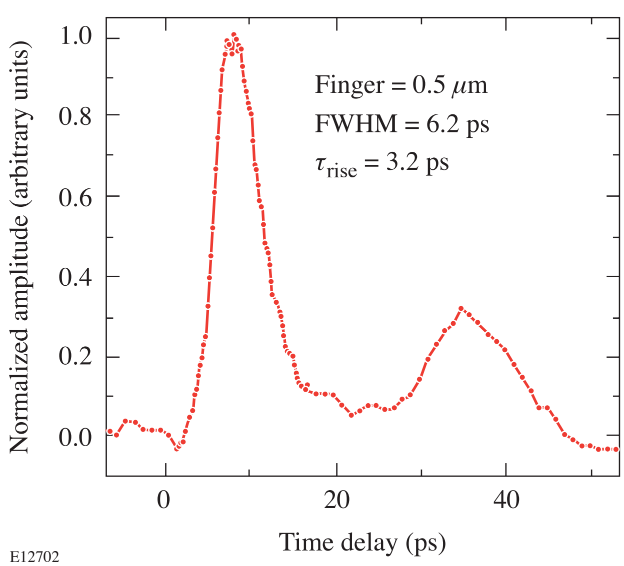

Figure 97.31
Impulse response measured from a device with 0.5-μm finger width and spacing. Both rise time and FWHM are longer than those from a device with 1-μm finger width and spacing as discussed in text.

In summary, EO sampling has been used to test the intrinsic response of GaN MSM photodiodes. The best performance measured from devices with 1-μm feature size showed a fast 10%–90% rise time of 1.4 ps and FWHM of 3.5 ps. This result represents the fastest ultraviolet GaN photodiode reported to date. The peak velocity of electrons in GaN was determined to be 1.43×10^7 cm/s, which compares favorably with independent photoexcitation experiments.

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