Ultrafast Testing of Electronic/Optoelectronic Devices

by

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Curriculum Vitae

Chia-Chi Wang was born in Taiwan, Republic of China, in 1965. He received his B.S. in physics and M.S. in electrical engineering at National Taiwan University in 1987 and 1989, respectively. He then joined the Department of Electrical Engineering at University of Rochester in 1991.

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Abstract

With recent advances in high-speed electronics and optoelectronics, it has become increasingly important to have a tool that can test these devices, so that they can be characterized and thus optimized. Features of the testing tool, such as temporal resolution, voltage sensitivity, spatial resolution, and operating temperature are essential for various applications. In this thesis, a powerful electro-optic (EO) sampling system with features capable of testing of these devices is demonstrated. Furthermore, a scheme based on impulse and response measurement with EO sampling is established for the ultrafast testing of circuits made on different semiconductors. With this EO sampling system, ultrafast optoelectronic and superconducting devices were tested.

Two types of ultrafast photodetectors were characterized and their operating principles were studied as well. The first one involves a novel operation of photoconductive switches and the second is based on nanometer-scaled metal-semiconductor-metal (MSM) photodiodes. The response of these detectors was measured to have subpicosecond pulse widths and terahertz bandwidths.

These photodetectors were then used to generate ultrashort electrical pulses as the impulse signal for the broad characterization of high-speed electronic devices. These ultrafast optoelectronic switches are compatible in processing and operation with circuits made on different semiconductor substrates for monolithic integration. A cryogenic MSM diode was also developed for interfacing superconducting electronics.

As a demonstration, the technique of impulse and response measurement was applied to characterize superconducting Josephson junctions. Impulses with different amplitudes were used to switch Josephson junctions and different numbers of magnetic single-flux-quantum pulses were generated. Measured results are compared with computer simulations and have qualitative agreement. This is the first time that a single quantum pulse has been directly observed.
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Chapter One: Introduction

1.1 Motivation

Ultrafast electronics and optoelectronics are interesting for their applications in high-speed computing and communications. To enhance the speed of these devices, enormous efforts have been made to develop advanced processing techniques in recent years. Modern epitaxial techniques have led to the ultrafast performance of electronic and optoelectronic devices made of new materials and/or heterostructures. For example, a low-temperature-grown GaAs [1] metal-semiconductor-metal (MSM) photodetector has been reported to have a bandwidth of 0.5 THz [2] and SiGe-based bipolar transistors have now bandwidths over 100 GHz [3]. With heterostructures, a p-i-n photodiode with a bandwidth exceeding 100 GHz has been demonstrated [4], and high-electron-mobility transistors have had operational frequencies over 400 GHz [5]. Another advanced technique is the nanometer scaled lithography. Fabricated with electron beam lithography, an MSM photodetector made on bulk semi-insulating GaAs has been measured to have a 3-dB bandwidth of 300 GHz [1], and a field-effect-transistor with sub-hundred-nanometer channel length has been presented to have a cut-off frequency over 100 GHz [3]. Separately, Josephson-junction-based high-speed superconducting circuits with sub-micrometer junction sizes and high-critical-current density fabricated with all-refractory technology [6] had a clock speed higher than 300 GHz [7, 8].

In these circuits, electrical signals with duration in the picosecond regime are generated, transported, and processed. It is important to establish a tool that can perform the ultrafast testing of these devices, so that they can be characterized and thus optimized. However, because of the picosecond time-scale and the hundreds-of-gigahertz bandwidth, it is not easy to achieve this task even with modern sampling oscilloscopes or microwave network analyzers.

The objective of this thesis is to establish a reliable ultrafast testing system to study these ultrafast devices on a real-time basis. With this system, the fundamental mechanisms and characteristics of the high-speed operation of these devices may be
studied, and the circuit parameters may also be measured for the comparison with computer simulations. The experimental requirements to achieve this objective and our experimental accomplishments will be described in this thesis.

1.2 Experimental requirements

For ultrafast testing, the measurement tool itself should have a subpicosecond temporal resolution. Furthermore, the measurement should be compatible with circuit layout and operated on arbitrary positions on the device under test to achieve a chip-scale nodal analysis. Consequently, a micrometer spatial resolution is desired to test integrated circuits. For testing high-speed superconducting circuits, this tool should be able to operate in cryogenic environments and have a submillivolt sensitivity. In addition, on-chip measurements are required, otherwise connections between the device under test and the testing network may distort the signal. Obviously, the testing should be non-invasive.

Photoconductive sampling [9] and electro-optic (EO) sampling [10, 11] are possible solutions. A photoconductive sampling technique based on ion damaged silicon-on-sapphire has been reported to have a 0.6 ps resolution, limited by the carrier lifetime [9]. However, the sampling can only be performed where the photoconductive switches are placed. As a result, nodal analysis is not available. Besides, photoconductive sampling is invasive because part of the signal is gated and directed to another transmission line. On the other hand, an EO sampling system [10, 11] is more suitable for ultrafast testing. In this thesis, an EO sampling system satisfying the criteria mentioned above is developed to test ultrafast circuits.

In using an EO sampling system to test ultrafast circuits, a typical method is the impulse and response measurement. A known impulse signal is used to activate the device under test and the circuit parameters may be determined by measuring the response signals. Time domain information, for example the propagating speed of a transmission line, may be derived by measuring the propagation delay between the impulse and the response signals at known positions [11]. Frequency-domain characterization can then be performed by taking the Fourier transform of the time-
domain signals. For example, the linear dispersion and attenuation characteristics of transmission lines with different geometries have been measured with this method for up to one terahertz [12-15]. In those studies, propagating subpicosecond electrical pulses were measured at different points on transmission lines. The characteristics of these transmission lines were then derived by comparing the Fourier components of those signals that had different propagating distances. Because of the finite measuring time window of an EO sampling system, usually only the truncated Fourier transform can be performed. As a result, a large dc component may be introduced by the non-periodic offset signal and block the interesting high-frequency signals. This problem may be solved by applying an artificial "gating function" to eliminate the offsets [15]. If the gating function is chosen properly, only the low-frequency information is lost and the high frequency signals are maintained.

For digital circuits, many important timing parameters, for example gate delays, may be directly determined by measuring the relative time delay between the impulse and the response signals from a logic gate. Moreover, the non-invasive monitoring of the operation of a digital circuit may be performed using an electro-optic sampling system [16]. For nonlinear circuits, this method is also powerful for studying circuit parameters, aided by computer simulations. Actually, in this thesis, it is applied to study the response of nonlinear superconducting Josephson junctions to a saw-tooth like waveform [17, 18], which will be described in detail later.

As an impulse signal, the amplitude should be easily adjustable to characterize circuits with different parameters. Furthermore, a broad-band electrical pulse rather than an electrical step transient is desired, because the spectrum of the latter is dominated by its low frequency components. For testing high-speed electronic circuits, the duration of these electrical pulses should be in the picosecond regime to give enough high-frequency information. Consequently, the pulse generation network has to be monolithic with the device under test, or any connections between the network and the device may strongly attenuate the high frequency components [13]. The measuring scheme of an EO sampling system also requires the generation of these electrical pulses to be synchronized to laser pulses. In other words, there has to be an optoelectronic switch in the pulse generation network. In order to test devices made on different semiconductor substrates, this pulse generation method
should be applicable to different materials and compatible with the circuit processing for monolithic integration. As a result, reliable, material independent, integrable, optoelectronic pulse generation methods are required in testing ultrafast electronics with an electro-optic sampling system.

1.3 Experimental accomplishments—thesis outline

In this study, a versatile ultrafast testing system based on electro-optic (EO) sampling has been developed. Optoelectronic pulse generation methods compatible with circuits made on different semiconductors are demonstrated. The impulse and response measurement with a cryogenic EO sampling system is applied to study the characteristics of superconducting Josephson junctions. The outline of these experimental accomplishments is as follows.

In chapter 2, a state-of-the-art EO sampling system based on an all-solid-state Ti:sapphire tunable mode-locked laser is described, along with its operating principle. The nature of an EO sampler resulting in non-invasive and on-chip testing is explained. The prominent features of our EO sampling system, including temporal resolution, voltage sensitivity, and ability of sampling on microstrip lines are demonstrated with experimental results. The development and experimental achievement of a cryogenic EO sampling system are presented. Efforts to extend the ability of our EO sampling system are shown. Different switching schemes and their advantages as well as sampling techniques to achieve nodal analysis are described. The performance of different EO crystals and their applications are also discussed.

Chapter 3 and 4 are dedicated to describing optoelectronic techniques for generating ultrashort electrical pulses. In this study, two powerful methods have been developed. The first case is edge illumination of photoconductive switches [19, 20], and the second is using ultrafast metal-semiconductor-metal (MSM) photodiodes [21, 22]. These studies are not only useful for our further experiments, they are also interesting for the application as ultrafast photodetectors.
In chapter 3, a material independent model based on the effect of displacement current [23] is used to explain the generation of subpicosecond electrical pulses by edge-illuminating a photoconductive switch. This method is powerful because only a normal photoconductive switch with a simple structure is required, making it compatible with circuits made on different semiconductors. Experimental results to support the displacement-current model are demonstrated on GaAs, InP, as well as on Si. Electrical pulses generated by this method are shown to have a pulse width of 540 fs on both GaAs and InP. The generation of an 800-fs pulse on silicon—the fastest pulses to date on bulk silicon—is also presented.

Our work on nanometer-scaled MSM diodes is described in chapter 4. In the past, most attention on MSM diodes was focused on diodes made on compound semiconductors. However, our focus is especially on silicon for testing silicon-based circuits. A historical review and the material-independent mechanism for high-speed operation are given. The bottle-neck for high-speed performance of silicon MSM diodes is discussed and methods to eliminate this limitation are presented. Silicon as well as silicon-on-sapphire MSM diodes are demonstrated to be capable of generating picosecond electrical pulses. For testing electronics operating at low temperature, cryogenic MSM diodes are developed and presented to have a pulse width of 10 ps, operating at 2 K. The performance of silicon MSM diodes with high repetition rate—a significant advantage—is addressed as well.

After developing a powerful testing tool and reliable pulse generation methods, we applied these techniques to observe single-flux-quantum (SFQ) pulses produced by superconducting Josephson junctions. In addition to the first observation of SFQ pulses, impulse and response measurement of ultrafast electronic devices is also demonstrated. These results are described in chapter 5. First, SFQ-based high-speed superconducting circuits are introduced as the motivation for observing SFQ pulses. The requirements for optoelectronically generating and detecting SFQ pulses are discussed. The proposed approach is then presented along with computer simulations. Finally, measured results are shown with the comparison of computer simulations.
Chapter 6 is a conclusion of this thesis. The principal accomplishments of this study may be summarized as follows.

- A state-of-the-art electro-optic sampling system was developed for ultrafast testing of electronic/optoelectronic devices. It has a temporal resolution of 540 fs, a voltage sensitivity of ~100 µV, a spatial resolution <5 µm, and is capable of non-invasive, on-chip testing. Its cryogenic version was also developed to measure circuits operating at low temperature.

- Reliable, optoelectronic pulse generation techniques were developed. Both edge illumination on a photoconductive switch and ultrafast metal-semiconductor-metal photodiodes may generate picosecond electrical pulses. With these techniques, pulse amplitudes are adjustable and the pulse generation is compatible with electronics made on different semiconductor substrates to achieve in situ testing of ultrafast electronics. These optoelectronic devices are also useful as ultrafast photodetectors.

- Applying the impulse and response measurement to Josephson junctions, the junction response to a saw-tooth-like waveform was measured with our cryogenic electro-optic sampling system and compared with computer simulations.

- For the first time, a single-flux-quantum pulse has been directly observed.
References


Chapter Two  The electro-optic sampling system

The ultrafast testing of electronic/optoelectronic devices in this research was performed using an electro-optic (EO) sampling system. This chapter is used to describe the basic set-up, operation, and features of our EO sampling system. An EO sampler can be considered as an optic-based scope that resolves subpicosecond voltage signals. Femtosecond laser pulses are directed to an EO crystal placed on top of an electronic circuit. The fringing electric field of the circuit modifies the refractive index of the crystal (the Pockels effect) and causes a change of laser polarization which can be converted to the change of intensity. This intensity modification is proportional to the intensity of electric field such that the signal amplitude is measured. In the mean time, temporal information is recorded by the cross-correlation of the laser pulse and the signal. Because the temporal resolution is achieved optically, there are no fast electronics required. On the other hand, due to the small modulation of the crystal index of refraction, a sensitive detection and noise-reduction scheme is necessary, which will be addressed in this chapter.

In this study, a Ti:sapphire self-mode-locked femtosecond laser is the essential apparatus, which will be described in the first section, together with an overview of our electro-optic sampling system. The second section is used to briefly review the operation, the transfer function and the sensitivity of an EO modulator: the transducer of our sampler. In section three, the prominent features of our EO sampling system, including the voltage sensitivity, the temporal resolution, and the spatial resolution, will be presented with experimental results. In order to study ultrafast superconducting electronics, we have developed a cryogenic EO sampling system which will be addressed in section four. Finally, extensions of our EO sampler to carry versatile testing will be discussed.
2.1 The Ti:sapphire laser and a system survey

The ultrafast-testing ability of an electro-optic (EO) sampling system is based on a femtosecond laser with a set of optics and electronics. Recent research on pulsed laser systems has yielded several usable lasers, for example, colliding pulse mode-locked dye lasers [1], active mode-locked diode lasers [2], optical fiber soliton lasers [3], titanium doped sapphire (Ti:sapphire) self-mode-locked lasers [4], etc. Among them, the superior Ti:sapphire laser is used as the light source of our EO sampling system. The all-solid-state and passive mode-locking nature makes a Ti:sapphire laser stable, durable, free from degradation, and less noisy. Furthermore, it is tunable in a wide range of wavelengths with a high output power, which makes it friendly to be used in different experiments.

For a mode-locked laser, there are typically a gain medium to support several lasing modes and an apparatus to provide the mode locking. Because these two functions are carried out by the same crystal in a Ti:sapphire laser, it is called a "self-mode-locked" laser. There is a well accepted model to explain the mechanism of the mode-locking: the Kerr lensing effect. The Ti:sapphire crystal, the gain medium of this laser, is a nonlinear material with second order EO effect (the Kerr effect). Due to the Kerr effect, when the inner cavity laser beam passes the crystal in which it is amplified, there is a light-induced increase of refractive index in the crystal. The light-induced higher index at the center of the crystal focuses the laser beam, known as the Kerr lensing effect. This focused beam has higher intensity that increases the refractive index of the crystal further and suffers a lower absorption due to the Kramers-Krönig relation. As a result, those modes with higher intensity are preferred. Combined with a pinhole, only the most center part of the beam with a pulsing mode (which has the highest intensity) can be amplified by the gain medium and exists in the cavity. Thus, self-mode-locking occurs. The pulse width of a Ti:sapphire laser is typically between ten and two hundred femtoseconds. Because the pulsing mechanism of a Ti:sapphire laser is passive, it is free from the noise caused by triggering or actively mode-locking the laser cavity. Actually, the dominant noise of our Ti:sapphire laser is from its pumping source, an argon ion laser, which has a power fluctuation less than two percent.
Another significant advantage of a Ti:sapphire laser is that the gain medium provides a wide range of lasing spectrum, typically between 700 and 1000 nm. The lasing wavelength is then selected by a birefringent crystal and is fully tunable. The output power in this wavelength range is high; almost two orders higher than that of the colliding pulse mode-locked dye lasers. For our Ti:sapphire laser, the peak power of each pulse is ~0.5 MW, providing an efficient frequency doubling. Thus, light source between violet and green becomes available. These photons cover a wide range of energy and make it possible to study photoresponse and the fundamental operating mechanism of optoelectronic devices made of different materials.

Our EO sampling system is based on a commercial Ti:sapphire laser (Coherent Mira 900) pumped by an argon ion laser (Coherent Innova 420) with all visible line power of ~12 W. The Ti:sapphire laser provides a pulse train with a pulse width of ~60 fs and a repetition rate of 76 MHz. The pulse train is split by a 30/70 beam splitter into two beams: a switching beam and a sampling beam, as in Fig. 2.1. The switching beam, containing most of the power, is focused on a BaB$_2$O$_4$ (BBO) crystal, and some of the photons are frequency-doubled to blue light. The beam is then modulated by an acousto-optic modulator to reduce noise (the detail will be described in section 2.3) and is directed to activate an optoelectronic switch. Either fundamental (red) or frequency doubled (blue) light is used for the switching beam, determined by a spectral filter. Each laser pulse excites an optoelectronic switch to generate an electrical transient which subsequently propagates along a transmission line (to the right in Fig. 2.1 or equivalently along the y-direction in Fig. 2.2).

The sampling beam travels through a computer-controlled delay line and then a LiTaO$_3$ crystal tip, an electro-optic transducer, sitting on the transmission line. The sampling beam is 45° linearly polarized according to the optical axis of the LiTaO$_3$ crystal, and is guided in a total-internal-reflection mode to the crystal [cf. section 2.5] and reflected to the analyzer and detectors, as in Fig. 2.1.
The electric field on the transmission line changes the refractive-index of the EO crystal (see Fig. 2.2), known as the Pockels effect. As a result, the polarization of the sampling beam is modified. The analyzer differentially converts the change of polarization to intensity modulation, which is detected by the detectors. This intensity modification is proportional to the strength of electric field, thus the amplitude of the electric field on the transmission line is measured. The compensator adds an extra $\pi/2$ phase retardation between the vertical and horizontal components of the sampling beam to insure the linearity and the maximum sensitivity [cf. section 2.2]. Changing the optical path (the relative time delay) of two beams maps out the electrical transient in the time domain, which is recorded by a computer.

Because only the fringing field on the transmission line is measured, this EO sampling technique is noninvasive. However, a calibration process is required to convert the measured EO signal to "real" voltage transient on the transmission line. Because the EO signal is proportional to the strength of the electric field, this process
can easily be achieved by applying a known signal to the transmission line and measuring the EO response. The electro-optic modulation of the laser intensity will be described in detail in the following section.

![Diagram of opticoelectronic switch](image)

**Fig. 2.2** The switching beam activates an optoelectronic switch and generates an electrical transient propagating on the transmission line. The electrical signal changes the refractive index of the LiTaO₃ crystal and modifies the polarization of the sampling beam.

### 2.2 The electro-optic modulator

An electro-optic (EO) crystal is used in our sampling system as the transducer to convert the electrical signal to light-intensity modulation, with which ultrafast electrical signals can be measured using a femtosecond laser. In other words, the crystal acts as an EO light intensity modulator. This conversion is based on the linear EO effect, or the Pockels effect, which will be briefly reviewed in this section.

For a crystal with Pockels effect, the optical indices of refraction on different crystal axes are modified differently by the external electric field. For example, in the
presence of an external electric field along the z-axis (the optical axis), the refractive indices in y- and z-direction of a LiTaO$_3$ crystal are expressed by [5]

\[ n_y = n_o - \frac{1}{2}n_o^3 r_{13}E \quad \text{2.1 (a)} \]

\[ n_z = n_e - \frac{1}{2}n_e^3 r_{33}E, \quad \text{2.1 (b)} \]

where \( r_{13} \) and \( r_{33} \) are the electro-optic coefficients, \( n_o \) and \( n_e \) are the ordinary and exordinary indices of refraction, and \( E \) is the external electric field. When a laser beam propagates along the x-direction with a 45° linear polarization according to the optical axis (see Fig. 2.2), the two polarizing components on the y- and z-axis experience different optical path due to the different indices of refraction. As a result, there is an optical-phase retardation between the y- and z-polarizing components. This phase retardation (\( \Gamma \)) is given by [6]

\[ \Gamma = \Gamma_0 + \Delta \Gamma = \frac{4\pi}{\lambda} (n_e - n_o) d - \int_0^d \frac{2\pi}{\lambda} (n_e^3 r_{33} - n_o^3 r_{13})E r(x) \, dx, \quad \text{2.2} \]

where \( \lambda \) is the wavelength of the laser, \( d \) is the thickness of the LiTaO$_3$ crystal, and \( r(x) \) represents the electric-field variation along the x-direction. The first term (\( \Gamma_0 \)) in Eq. 2.2 gives a static retardation caused by the crystal anisotropy, while the second term (\( \Delta \Gamma \)) expresses the electric-field-induced retardation contributed by the Pockels effect.

When an analyzer with its direction orthogonal to the polarizer before the EO crystal (see Fig. 2.1), the transmission coefficient of light through such a combination is given by \( T = \sin^2 \left( \frac{\Gamma}{2} \right) \) [5], which describes the ratio of transmitted to incident light intensity and is plotted in Fig. 2.3. Usually, an optical compensator is inserted between the EO modulator and the analyzer. The compensator gives an optical bias, such that the overall phase retardation from the crystal anisotropy and the compensator is \( \pi/2 \). In this case, the transmission function becomes

\[ T = \sin^2 \left( \frac{\pi}{4} + \frac{1}{2} \Delta \Gamma \right) = \frac{1}{2} + \frac{1}{2} \sin \Delta \Gamma \sim \frac{1}{2} + \frac{1}{2} \Delta \Gamma \text{ (for small } \Delta \Gamma), \quad \text{2.3} \]
which has the most sensitive and linear response of the transmission ($T$) to the field-induced retardation ($\Delta \Gamma$), as in Fig. 2.3.

![Graph showing the transmission function of the electro-optic (EO) light intensity modulator.](image)

**Fig. 2.3** The transmission function of the electro-optic (EO) light intensity modulator. Biased at $\Gamma = \pi/2$ with a 50% intensity transmission, the EO modulator has its most linear and sensitive response.

Most optoelectronic devices operate at several volts, which can only introduce a phase retardation $\Delta \Gamma$ of $\sim 10^{-3}$ rad with a LiTaO$_3$ crystal, depending on the wavelength, the thickness of the crystal, and the geometry of the modulating electrodes. This small phase retardation can only modulate the intensity of transmitted light by $\sim 0.05\%$. As a result, a sensitive light-intensity-detection scheme is required to resolve the strength of the external electric field. It is achieved using a lock-in amplifier in our EO sampling system. Furthermore, differential detection is used to reduce the common mode noise with the utilization of a polarizing beam splitter as the analyzer. While the field-induced retardation increases the transmitted light intensity, the intensity of the deflected light is decreased. Taking the differential signal of the detectors (see Fig. 2.1), the common-
mode signal is rejected and the full modulated signal is measured with a large dynamic range.

2.3 Prominent features of our electro-optic sampling system

In this study, an electro-optic (EO) sampling system was used to perform the versatile testing of ultrafast electronics. The prominent features of our EO sampler are demonstrated in this section with several experimental results.

The temporal resolution of an EO sampling system depends on several factors, the duration of the sampling laser pulses, the optical spot size, the response time of the EO crystal, the thickness of the crystal and the geometry of the transmission line where the electrical signals are measured. The pulse width of our Ti:sapphire laser is \( \sim 60 \) fs which sufficiently supports sub-hundred-femtosecond testing, while a similar set-up using a LiTaO\(_3\) crystal as the transducer has been reported to successfully measure a 200-fs electrical pulse [7]. Another limitation factor of the temporal resolution is the finite spot size of the sampling beam. When an electrical signal propagates on a transmission line, there is a finite propagation time for that signal to cross the sampling spot. This propagation time, depending on the geometry of transmission lines, is estimated to be \(<100\) fs for a 5-\(\mu\)m sampling spot. As a result, there is an averaging effect to smear the temporal resolution. The dominant limitation of the temporal resolution of our EO sampling system is the thickness of the EO crystal, which determines the transit time of the sampling beam in the crystal. For a LiTaO\(_3\) crystal with thickness of 15 \(\mu\)m, this transit time is \(\sim 220\) fs, which may be improved using a thinner crystal. On the other hand, this limitation may be relieved if the electrical signal is measured on a microstrip line because of better confinement of the electric field (see the \(r(x)\) factor in Eq. 2.2).

Figure 2.4 shows an RC-limited electrical pulse generated on a GaAs transmission-line gap, where \(R\) is the impedance of the transmission line and \(C\) is the capacitance of the gap. It shows that the pulse has a width of 540 fs and a rise time of 325 fs [8], indicating the upper limit of the temporal resolution of this system.
Fig. 2.4 An RC limited electrical pulse was measured to have a pulse width of 540 fs and a rise time of 325 fs.

Because we are interested in testing ultrafast superconducting electronics which have a signal level of \(-1\) mV, sensitive detection and noise reduction are crucial. To increase voltage sensitivity, a scheme of megahertz mixing and phase sensitive detection is used [9]. Typically, the switching beam is acousto-optically modulated at 1 MHz to reduce the 1/f noise of the Ti:sapphire laser. The detected signals are then mixed down to 2.55 kilohertz with radio-frequency mixers. With this frequency-mixing technique and impedance matching coils, the lock-in amplifier is operating at its less noisy state. The electrical grounding of the whole phase sensitive detecting system is carefully arranged to avoid the electrical noise from the grounding loop. Of course, longer data acquisition time allows more data averaging and increases the signal to noise ratio. Sometimes, Fourier filtering is applied digitally to reduce high frequency noise. Figure 2.5 shows a submillivolt signal with a noise level \(<100\) µV measured by our EO sampler and filtered at 500 GHz.
Fig. 2.5 A submillivolt electrical signal was generated by an optoelectronic switch with the illumination of a faint laser pulse.

The voltage sensitivity of external EO sampling on microstrip lines was also examined to ensure the ability of testing electronic circuits that are mounted on microstrip lines. As mentioned earlier, the electric field is more confined in microstrip lines than coplanar transmission lines. This characteristic benefits the field-effect EO sampling in reducing the dielectric-loading of the EO crystal. However, on the other hand, only a small fraction of the fringing field is adjacent to the EO crystal, which reduces the sensitivity. Then, the key issue to optimize the sensitivity of the external EO sampling on microstrip lines is the pick up as much fringing electrical field as possible. It is achieved by keeping the smallest separation between the crystal and the microstrip lines. Typically, the crystal is carefully placed so that this separation is down to several hundred nanometers, determined by viewing the interference pattern between the crystal and the device substrate. In our EO sampling system, efforts have been made to have reliable testing ability on microstrip lines even for signals with millivolt amplitudes [10], as in Fig. 2.6.
Fig. 2.6 A millivolt electrical waveform measured on a microstrip line.

It has been demonstrated that our EO sampling system is capable of measuring ultrafast signals on either coplanar or microstrip transmission lines. Because these measurements are done externally with a LiTaO$_3$ crystal, they are compatible with different circuit layouts and ideal for on-chip testing.

Our electro-optic sampling system has been surveyed. The temporal resolution of this system is estimated to be $\sim$250 fs, while the excellent sensitivity with sub-hundred-microvolt voltage resolution supports the measurement of millivolt signals on both coplanar and microstrip lines. A cryogenic version and extensions of this system capable of fulfilling different tasks of testing will be introduced in the following sections.
2.4 A cryogenic electro-optic sampling system

Modern superconducting electronics are interesting for their operation with high-speed and low power dissipation [11]. Furthermore, superconducting striplines with low attenuation and dispersion are important for the transportation of high-frequency signals [12]. In order to test these circuits, a cryogenic version of electro-optic (EO) sampling system was developed.

A liquid-helium based cryostat operating from room temperature to ~2 K is used in this system, as illustrated in Fig. 2.7. Basically, flowing helium gas, obtained by vaporizing liquid helium, is used to cool the sample tube. The flowing rate of liquid helium is adjustable with a needle valve. The temperature in the sample tube is then controlled by an evaporator (a heater) with temperature monitor. With the evaporator off, liquid helium stars to accumulate in the sample tube and allows the sample to be immersed, cooling the sample to 4.2 K. Moreover, liquid helium may be pumped to bubbleless superfluid that cools the sample down to 2 K and gives an optical access to the sample. These types of cooling, especially the superfluid, provide sufficient cooling that keeps the sample at a constant temperature while intense laser beams are focused onto the sample.

The EO sampling is achieved with reflective sampling [13]—a LiTaO₃ crystal with near-infrared high-reflective (HR) coating is attached to cover the circuit. The frequency-doubled (blue) light, the switching beam, penetrates the HR coating to activate the optoelectronic switch. The fundamental light, serving as the sampling beam, passes through the crystal and is reflected by the HR coating to the analyzer. Both beams are focused by a single microscope objective (details will be described in the next section) and delivered through an optical window to the device under test, which is immersed in superfluid helium.

The sample holder is supported by an micropositioner sitting on top of the sample tube, as in Fig. 2.7, and the whole cryostat is mounted on a heavy-duty translation stage. This set-up gives the sample a three dimensional movement with micrometer accuracy, thus, the switching and sampling beams may reach an arbitrary position on the sample.
Fig. 2.7 A schematic diagram of the cryostat.
To illustrate the cryogenic testing ability of our electro-optic sampler, Fig. 2.8 shows the measured response of a 1-μm metal-semiconductor-metal photodiode operating at 2 K [14].

![Graph showing amplitude vs. time for a photodiode response](image)

**Fig. 2.8** A 1-μm metal-semiconductor-metal photodiode operating at 2 K had a pulse width of 10 ps with the illumination of blue light.

In this cryostat, there are liquid helium and liquid nitrogen reservoirs, surrounded by an insulating high-vacuum space. The liquid helium reservoir has a capacity of four litters and continuously supports the sample tube to be filled with superfluid helium for ~4 hr. Within this period, enough data are acquired to increase the signal to noise ratio. With this cryogenic electro-optic sampling system, the magnetic single-flux-quantum pulses were for the first time observed, which will be described in Ch. 5.
2.5 Extensions of our electro-optic sampling system

Several extensions of our electro-optic (EO) sampling system have been made to accomplish different requirements of testing. These extensions will be discussed in this section to give a whole picture of the testing ability of our EO sampler.

There are two types of switching schemes in our system to characterize different electronic/optoelectronic circuits. The switching beam may be guided by an optical fiber (as in Fig. 2.2), or focused by a microscope objective passing through the EO sampling tip (as in Fig. 2.9) to excite the optoelectronic switch. With a fiber, the sampling tip can be placed at different places to measure the propagating signals without changing the excitation point. This switching method may be used to characterize, for example, the propagation attenuation and dispersion of transmission lines [15, 16]. On the other hand, the propagation distortion of signals on transmission lines limits the measuring of ultrafast signals. For example, the rise time of a step waveform was measured to be broadened from ~1 ps to ~2 ps after a propagation distance of 1 mm [16]. With the configuration of Fig. 2.9, the propagation distance of the electrical transient before it is measured [7] is minimized [7].

The EO sampling tip was designed to attach a piece of LiTaO₃ crystal on a fused-silica base, as in Fig. 2.9. The size of the crystal is typically 200×200 µm with thickness of ~15 µm. This small sampling tip has a negligible dielectric loading to the transmission line. The facets of the fused-silica base are 60° to horizon and guide the sampling beam, which is focused by a microscope objective, in a total-internal-reflection mode. The same objective is used to focus the switching beam directly down to the optoelectronic device, positioned closely (<5 µm) to the sampling spot. As a result, the intrinsic response of optoelectronic devices may be measured with minimal propagation distortion [17].
A band pass filter is installed in front of this microscope objective to reflect both sampling and switching beams and allow visible light passing through. This set-up gives us the ability of viewing the positions of both beams and moving them arbitrarily on the device under test, thus, nodal analysis becomes possible. Focused by a 10× objective, the spot size of both beams is ~5 μm, which is the spatial resolution of our sampling system. An objective with higher power may be used to improve this.
resolution. The same arrangement of microscope objective and viewing filter is also used for our cryogenic sampling system.

In many cases, an electrical circuit (e.g. a digital gate) has to be triggered and reset. Here, a two-excitation-beam set-up is introduced to achieve this requirement. As shown in Fig. 2.10, an arrangement similar to a Michelson interferometer can be used to optically split the switching laser pulse to two pulses with adjustable optical delays and then recombine them to generate two electrical pulses. This set-up allows us to use an EO sampler to test logic cells and to determine their characteristic parameters.

![Diagram of a two-excitation-beam setup](image)

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**Fig. 2.10** The switching beam is split by a beam splitter. Moving the position of mirror A, a tunable time delay is applied to these two excitation laser pulses.

So far, a LiTaO₃ crystal has been used in our EO sampler for its high electro-optic coefficient and better mechanical properties. However, the high dielectric constant of LiTaO₃ gives a large dispersion to the ultrafast signals propagating on the transmission line, in particular, coplanar lines. Furthermore, the optical set-up only allows us to probe the transverse electric field with LiTaO₃ (see Fig. 2.2). On the other
hand, the study of longitudinal electric field is interesting in, for example, mapping the near field of millimeter wave radiation [18]. Several crystals with relatively low dielectric constant are able to accomplish the longitudinal probing. Table 2.1 lists the properties of these crystals along with LiTaO$_3$ as a comparison [5].

<table>
<thead>
<tr>
<th>Substance</th>
<th>CdTe</th>
<th>GaAs</th>
<th>ZnTe</th>
<th>β-SiC [19]</th>
<th>LiTaO$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal Symmetry</td>
<td>43m</td>
<td>43m</td>
<td>43m</td>
<td>43m</td>
<td>3m</td>
</tr>
<tr>
<td>Wavelength (nm)</td>
<td>1000</td>
<td>900</td>
<td>633</td>
<td>633</td>
<td>633</td>
</tr>
<tr>
<td>EO Coeff. (10$^{-12}$ m/V)</td>
<td>$r_{41}$=4.5</td>
<td>$r_{41}$=1.1</td>
<td>$r_{41}$=4.04</td>
<td>$r_{41}$=2.7</td>
<td>$r_{13}$=7.5 $r_{33}$=33</td>
</tr>
<tr>
<td>Index of Refraction</td>
<td>2.84</td>
<td>3.60</td>
<td>2.99</td>
<td>2.64</td>
<td>n$_o$=2.176 n$_e$=2.180</td>
</tr>
<tr>
<td>Figure of Merit (10$^{-12}$ m/V)</td>
<td>103</td>
<td>51</td>
<td>108</td>
<td>49</td>
<td>133</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>9.4</td>
<td>13.2</td>
<td>10.1</td>
<td>10</td>
<td>41</td>
</tr>
</tbody>
</table>

Table 2.1 Crystals with 43m symmetry are suitable for longitudinal electro-optic probing.

In these crystals, CdTe and GaAs have lower band gaps and are not transparent for red light, the typical operating wavelength of our Ti:sapphire laser. With higher index of refraction and electro-optic coefficient, ZnTe has a high figure of merit. Moreover, its dielectric constant is much lower than LiTaO$_3$ and allows more fringing electric field penetrating into the crystal. As a result, it should be a better crystal than LiTaO$_3$ for an EO sampling system. Another material, β-SiC has more stable chemical property and is also a possible candidate for longitudinal EO probing.
Summary

We have surveyed our electro-optic sampling system. It is based on an all-solid-state, tunable, femtosecond Ti:sapphire laser. With frequency doubling, this system has switching photons covering from blue to near infrared region, which is important for studying circuits made on different semiconductor materials. The transducer of this sampling system, an electro-optic light intensity modulator, has been introduced with its operating mechanism and performance. A noise reduction scheme and sensitive electronics for measuring the small electro-optic signals are also discussed. Demonstrated with experimental results, the prominent features of this state-of-the-art electro-optic sampling system have been described and are concluded as follows.

- The temporal resolution is \(\sim 250\) fs.
- The voltage sensitivity is \(\sim 100\) µV on both coplanar and microstrip lines.
- The spatial resolution is \(\sim 5\) µm and able for nodal analysis.
- The cryogenic version, with operating temperature continuously down to 2 K, has been developed.
- With adequate sampling tip and switching method, signals with different propagating distances, including zero, may be measured.
- The measuring process is noninvasive.
- A two-excitation-beam set-up may be used to generate electrical signals with adjustable time delay for studying timing parameters for digital circuits.
- With different electro-optic crystals, both transverse and longitudinal electric fields may be probed.

With this versatile electro-optic sampling system, several ultrafast optoelectronic devices, as well as superconducting electronics, have been tested with their operating mechanisms being studied. These results will be described in the following chapters.
References


Chapter Three
Optoelectronic Generation of Ultrashort Pulses—
Study of Edge Illumination on Photoconductive Switches

As mentioned in Ch. 1, the typical method for using an EO sampling system to test ultrafast electronics is the impulse and response measurement. The requirements of these impulse signals and the generation methods were also discussed. These electrical pulses should be adjustable in amplitude and have widths in the picosecond regime. The optoelectronic switches used for generating these pulses have to be compatible in processing and lay-out with circuits. We have explored different approaches for reliably generating these pulses, and the following two chapters are dedicated to these works.

In these two chapters, two optoelectronic methods which monolithically generate picosecond pulses are demonstrated. One is using metal-semiconductor-metal (MSM) photodiodes; another is edge-illuminating a regular photoconductive switch. These methods are independent of materials and the optoelectronic switches have simple planar structures, resulting in convenient interfacing with the device under test made on different semiconductors. Beyond being necessary for our further experiments, these studies are also interesting in high-speed optical fiber communications, networking, and optical interconnections between integrated circuits.
3.1 Introduction to edge illumination of photoconductive switches

As mentioned, an optoelectronic switch is a key element for using an electro-optic sampling system to test ultrafast electronics. A photoconductive switch (the "Auston switch") consisting of metal electrodes on a piece of semiconductor is perhaps the commonest optoelectronic switch. When a biased photoconductive switch is illuminated uniformly by a laser pulse, the photogenerated carriers close the switch effectively to produce an electrical transient. These transients are characterized by having a subpicosecond rise time limited by the RC-time constant of the switch. However, their fall time is much longer and limited by the carrier lifetime, which is on the order of nanosecond to microsecond for undoped, semi-insulating substrates. The high-frequency contents of such step-like transients are masked by their low-frequency contents and are not useful for broadband characterization of ultrafast electronic circuits. In order to use these photoconductive switches to test broadband electronics, monolithic pulse-forming network is required to shape the step-like waveform to a pulse. Several pulse forming networks have been demonstrated, for example, high-pass filters [1, 2], nonlinear transmission lines [3, 4], and a network with two optical excitations [5]. These methods can not be conveniently interfaced with the device under test, due to their high complexity or problems of dc biasing the device. Obviously, a simply structured optoelectronic switch with the ability of generating short pulses is desired.

In the past, most of the techniques to generate ultrafast electrical pulses relied on specialized photoconductive switches. These switches were made on special substrates with defects which reduce carrier lifetimes significantly. Photoconductive switches made on, for example, amorphous silicon, low-temperature-grown GaAs and ion-damaged silicon-on-sapphire, were shown to have picosecond photoresponse [6-8]. Unfortunately, these techniques limit the use of ultrafast electrical pulses for testing high speed electronics which are typically made on high quality semiconductor substrates. For example, in order to couple the ultrafast electrical pulses generated with these special switches to the device under test, a wirebond may be required and the high frequency components of the pulses are strongly attenuated [9]. As a result, it is important to have an optoelectronic switch that monolithically generates subpicosecond
electrical pulses in semiconductor circuits. This switch has to have a simple geometry and an operating mechanism independent of materials, so that it has a convenient interface to electronics made on different semiconductor substrates.

The generation of subpicosecond electrical pulses using photoconductive switches with long carrier lifetimes has been achieved on undamaged silicon-on-sapphire [10] and semi-insulating GaAs substrates [11] with unknown mechanisms. In those studies, instead of illuminating the whole gap of the photoconductive switch, the excitation laser pulse was focused to illuminate only one edge of the electrodes (as in Fig. 3.1(a)) which were separated by tens of micrometers typically. One possible explanation for this “edge illumination” method to generate ultrafast pulses is the field screening effect which will be described in detail later. This model was first proposed by Sano and Shibata with theoretical calculations based on full-wave analysis [12], and was then further confirmed by Xing Zhou with Monte Carlo simulations and two-dimensional numerical simulations [13-15]. It was verified in this thesis experimentally [16-18].

The field screening model begins with the premise that carriers generated by edge illumination, instead of closing the photoconductive switch totally, screen the electric field between the metal electrodes of the switch, thus, the electric field profile quickly redistributes. The field in the illuminated area is depleted as the photogenerated carriers increase the conductance of this region, whereas in the un-illuminated area the field is increased to maintain the total voltage bias, as shown in Fig. 3.1(a). Maxwell’s equations assert that a change in the electric field produces a radiating displacement current. This radiation couples to the transmission line and induces a subpicosecond electrical pulse propagating on the line as in Fig. 3.1(b). The propagating pulse has a width ultimately determined by the speed with which the electric field redistributes itself between the transmission line electrodes. Following this, the electric field relaxes to its original profile with a much slower process that dissipates photogenerated carriers through drift, diffusion, and recombination. This slow relaxation process causes a localized change of electric field which does not propagate. If measured close to the excitation point this localized field change is seen as a shoulder following the initial pulse, as shown in Fig. 3.1(b).
Fig. 3.1 The field screening model predicts that edge illumination distorts the electric field around the illuminated area and induces a displacement current pulse. (a) A schematic view of the excitation configuration. Top: a photoconductive switch with edge illumination on only one electrode. Bottom: the spatial electric field distribution before and after excitation. (b) The propagating and localized electric field as a function of time.

In addition to explaining the propagating pulse and the localized shoulder, this field screening model also predicts the shoulder can be positive or negative, depending on the measuring point [12, 15]. If the transient is measured on the same side as the
excitation (left in Fig. 3.1(a)), a positive shoulder should be observed due to the electric field increasing from its excited state, near zero, to its original profile. Testing on the opposite side (right in Fig. 3.1(a)), a negative shoulder should be detected.

It is very difficult to model the whole phenomenon, because, as stated by Sano and Shibata [12], "it is necessary to solve Poisson's equation in conjunction with Maxwell's curl equation and current continuity equations." Three dimensional geometry and femtosecond photocarrier injection are involved. As a result, Sano and Shibata's model was simplified to consider only ohmic metal-semiconductor contacts and drift-diffusion approximation for carrier transport. However, with their calculation, it is clear that the generation of ultrashort pulses is due to the displacement current induced by the screening of electric field. This field screening model has been confirmed with complementary studies by X. Zhou et. al. In Zhou's study, one dimensional Monte Carlo simulations were used to solve the transport problem from first principle [13] and numerical simulation based on the drift-diffusion formalism was used to investigate the physical mechanism of pulse generation of edge illumination [14]. According to these theoretical studies, the generation of ultrashort electrical pulses by edge illumination is an r-space instead of k-space phenomenon and should be independent of materials. It implies that a photoconductive switch with such a simple structure and fabrication may be used as an optoelectronic pulse generator to test ultrafast electronics made of different semiconductors.

We have conducted an extensive study of this technique of pulse generation on different substrates to examine this field screening model. Furthermore, we'd like to explore the possibility of a reliable and convenient source of pulse generation with, particularly, a simple geometry and fabrication.

3.2 Edge illumination on GaAs

To study the edge illumination effect of photoconductive switches, we have fabricated coplanar transmission lines on different semiconductor substrates, including GaAs, InP, and Si. The gap between the lines was used as a photoconductive switch (a shunt switch to the transmission line), as in Fig 3.2. While the switch was excited
by a laser pulse, the generated electrical transient coupled to the transmission line and was measured with our electro-optic sampling system. The experimental set-up is as follows. A lithium tantalate finger probe was placed on top of the switch and laser pulses illuminated only one edge of the switch through the crystal directly (see section 2.5). The sampling beam was guided in a total-internal-reflection mode by the facets of the finger probe and might be placed at different points (point A, B, and C in Fig. 3.2) to measure the sign of the localized shoulder electro-optically. The switching and sampling positions were monitored with a microscope objective and separated by \(-100\ \mu m\).

![Diagram](image)

**Fig. 3.2** A lithium tantalate finger probe was placed on top of a coplanar transmission line to electro-optically detect electrical transients. The metal-semiconductor interface was illuminated by an ultrafast laser pulse, and the electrical response was measured at points A, B, and C.
Fig. 3.3  (a) The polarity of the measured shoulder depends on the position of the sampling beam.  
(b) The shoulder-free pulse in detail shows a 540-fs pulse.
Our first study was on GaAs [16, 17]. Our samples consisted of coplanar transmission lines made by depositing Au on semi-insulating substrates with a lift-off photolithography technique. The gap between the two electrodes, acting as a photoconductive switch, was typically dc-biased at 27 V.

Electrical transients measured at different points are shown in Fig. 3.3(a). The transient measured at point A has a positive shoulder; on the other hand, a negative shoulder was measured at point C (see Fig. 3.2 for sampling points). These results strongly support the field screening model predicting that the localized shoulder could be either positive or negative depending on the sampling positions. Finally, more interestingly, by sampling near the center (point B in Fig. 3.2, or more precisely in the gap at the edge of the excitation pulse), the increasing (left in Fig. 3.1 (a)) and the decreasing (right in Fig. 3.1 (b)) local fields were averaged to zero. In other words, the effect of the local field was balanced and only the propagating pulse was observed. This “shoulder-free” transient has a 540-fs full-width at half-maximum (FWHM) [see Fig. 3.3(b)] which is limited by the RC time constant of the switch. It is symmetrical and essentially dispersion-free, since it was measured by the setup shown in Fig. 2.9 to have a minimal propagating distance.

In order to measure the propagating pulse only, the switching beam was guided by an optical fiber and the LiTaO3 crystal tip was placed ~200 μm away from the switching point. A typical transient is shown in Fig. 3.4. The pulse has a FWHM of ~1 ps and a rise time longer than the fall time, indicating the dispersion in the pulse after propagating the distance between switching and sampling spots. The oscillation observed after the main pulse is a combination of the pulse dispersive ringing and the unguided radiation emitted at the excitation site and subsequently reflected by the backside of the substrate.
Fig. 3.4 Electrical pulse generated by edge illumination at a distance of ~200 μm from the sampling site. The dispersion of the pulse indicates its propagation on the transmission line.

It was suggested [11] that the positive shoulder observed in Fig. 3.3(a) is due to carriers excited to the upper L valley in GaAs. According to this concept, the slower L-valley electrons would contribute to a secondary, positive shoulder in the generated transient as they scatter back to the I' valley. In order to study this theory, we used photons with energies above or below the initial energy required to excite the L-valley electrons. As seen in Fig. 3.5, the resultant electrical transients are essentially the same. Moreover, as seen in Fig. 3.3(a), the shoulder can be positive, negative, or even reduced to near zero by simply changing the sampling position. It appears that the filed screening model is better supported by our experimental results.
Fig. 3.5 Picosecond pulses generated by edge-illuminating a photoconductive switch at three different optical wavelengths.

According to the field screening model, an electrical pulse should be generated as long as there is a perturbation of the initial electric field in a photoconductive switch. In other words, an induced displacement current pulse should be seen with not only the edge of an electrode but also the center part of a photoconductive switch being illuminated by a focused laser beam. The amplitude of this pulse then reflects the strength of the initial electric field at the illuminated area. We have examined this suggestion by measuring the electrical transients generated at different excitation positions in a 50-μm gap. Indeed, electrical pulses were induced consistently. The peak amplitudes of these pulses were mapped across the gap. It can be seen in Fig. 3.6 that an electrical pulse with a peak amplitude of ~1.3 V was generated when the anode of a photoconductive switch was illuminated by a laser beam with a spot size of ~5 μm. The amplitude is about an order smaller with center illumination and slightly increases with cathode illumination. These amplitudes show that the initial field distribution in
our GaAs photoconductive switches is nonuniform across the gap, in good qualitative agreement with numerical simulations [14].

![Graph](image_url)

**Fig 3.6** The amplitude of the generated pulse as a function of the excitation position across [along the x-direction in Fig. 3.1 (a)] a 50-μm gap of a photoconductive switch. The solid line is a guide of the eye.

The very different amplitudes with cathode and anode illumination indicate that the metal-semiconductor contacts are not simply ohmic. For example, most of the dc-bias is dropped across the depletion region of a back-to-back Schottky diode. As a result, a larger displacement current pulse is induced with edge illumination on the depletion region [10]. Furthermore, trapping states may also modify the initial field distribution [13]. In practical, it is very difficult to model and control this field distribution which is a function of metal-semiconductor contacts, trapping and surface states [13-15, 19-21].

It seems that our experimental results support the field screen model and suggest a simple and reliable way to generate subpicosecond electrical pulses with a
regular photoconductive switch. However, the geometry of a photoconductive switch shown in Fig. 3.2 (a parallel gap) is not ideal for ultrafast testing of circuits with the impulse and response measurement techniques. A switch consisting of a "series gap" in a transmission line (as shown in Fig. 3.7) is more preferred, because the bias of the switch does not affect the bias of the device under test with this scheme.

![Diagram](image)

**Fig. 3.7** Due to the high resistance of the series gap, the bias of the photoconductive switch does not affect other devices connected to the transmission line.

We have measured the electrical pulses generated by edge-illuminating a 20-μm series gap (see Fig. 3.7) on a coplanar waveguide (CPW) with a 50-μm electrode spacing and width. As in Fig. 3.8, picosecond pulses were observed on both slots of the CPW. The high degree of symmetry in these two transients indicates that the propagated waveform contains only the preferred "CPW modes" which are less dispersive [22].
Fig. 3.8 Picosecond electrical pulses were generated by edge-illuminating a 20-μm series gap on a coplanar waveguide (CPW), as in Fig. 3.7. The positive and negative pulses are measured electro-optically on the top and bottom slots of the CPW.

The remaining question of using this pulse generation technique for ultrafast testing electronic circuits is whether the amplitude of these pulses is adjustable, as mentioned in section 1.2. Intuitively, either changing the bias voltage of the switch or the illumination intensity modifies the amplitude of the induced displacement-current pulse. The former changes the strength of the initial electric field and the latter changes the density of photocarriers screening the electric field.

The dependence of pulse amplitude on bias voltage was studied with both parallel and series gap geometries and produced similar results. Figure 3.9 shows a summary of this dependence, taken with the series-gap excitation scheme. For up to 18 V, the amplitude depends on approximately on the square of the bias voltage. At higher bias, the peak amplitude deviates from the square-law dependence and eventually appears to saturate. For example, when the bias voltage is increased from 9 to 45
volts, the pulse amplitude increases by a factor of four, in good agreement with Monte Carlo and two-dimensional numerical simulations [13, 14].

![Diagram](image)

**Fig. 3.9** The pulses amplitude as a function of the applied bias for the series-gap excitation.

This highly nonlinear relation indicates that the initial filed distribution at the excitation spot is highly nonlinear to the bias voltage, which was also revealed with theoretical calculations [13, 14]. This highly nonlinear nature of edge illumination is very different from the case of illuminating the whole gap uniformly, which is well known to have a gain proportional to the bias voltage.

The dependence of the pulse amplitude on the incident light intensity is also highly nonlinear, which can be seen in Fig. 3.10. These results were taken with series-gap excitation with a bias voltage of 27 V. While the incident light intensity varies three orders of magnitude, the resulting pulse amplitude changes by only about one order. It implies that the electric field between the electrodes is efficiently screened even with a
small amount of photocarriers. This result is also in good qualitative agreement with Xing Zhou's simulations [13, 14].

Fig. 3.10 The pulse amplitude as a function of the incident light intensity for the series-gap excitation.

These results show that electrical pulses can be generated with a wide range of incident light intensities. Within this range, the pulse shape remained approximately the same, except at very low light intensities, as in Fig. 3.11 where the extreme excitation light intensities of Fig. 3.10 are shown. When the induced waveform degraded with low incident light intensity, a shoulder appeared after the main pulse. This shoulder is speculated to be the drift current of the photogenerated carriers. It then seems that changing the dc bias is a better way to modify the pulse amplitude, especially for small amplitudes
Fig. 3.11 Electrical pulses can be generated with a wide range of excitation light intensity. However, at very low optical power, a drift-current shoulder is pronounced.

3.3 Edge illumination on InP and Si

The most important evidence with practical significance to support the filed screening model is the material independence. If this model is correct, it should be applicable to other materials, and would suggest a material-independent technique to generate ultrafast electrical pulses. In order to check this model furthermore, Ti/Au coplanar transmission lines were made and tested on InP and Si [18] which have totally different band structures from GaAs.

When the InP photoconductive switches were edge-illuminated with 720-nm (red) light, electrical transients were observed with different shoulder polarities at different sampling points. As shown in Fig. 3.12, same as GaAs photoconductive switches, the measured electrical transient had a positive shoulder when sampled on the same side as the excitation (point A in Fig. 3.2) and negative shoulder at point C. The
shoulder-free pulse, measured at point B, has a full-width at half-maximum (FWHM) of 540-fs limited by the RC time constant of the switch, same as GaAs samples.

Fig. 3.12 The metal-semiconductor interface of InP is illuminated with red light. The electrical transient response is electro-optically sampled between the coplanar electrodes at three points -100 μm away from the excitation: A) at the excitation electrode, B) near the center of the gap between the two electrodes C) at the un-excited electrode.

The filed screening model seems to be correct. However, in order to have a powerful pulse-generation method to test ultrafast electronics, edge illumination technique has to be examined on silicon, of which most of the electronic circuits are made. The same red light on Si photoconductive switches produced the pulses shown in Fig. 3.13. These pulses look very different from those produced in GaAs and InP. However, we can still see the process of a slowly recovering electric field pattern from the shoulders.
Because Si has a large penetration depth at 720 nm (~10 μm comparing to ~1 μm in GaAs), this effect was examined again with photons having a much smaller penetration depth in silicon. Blue light with 400-nm wavelength was used to have a penetration depth in silicon more than an order of magnitude less than for red light. As can be seen in Fig. 3.14, a remarkable improvement in pulse quality was achieved by using blue excitation. These pulses with 1.1 ps FWHM are similar in shape and duration to those of InP and GaAs excited with red light. Once again, the effect of the local electric field was observed: positive shoulder on the excitation side (point A), negative shoulder on the opposite side (point C), and no shoulder in the gap at the edge of the excitation pulse (point B).
Fig. 3.14 Exciting Si by edge illumination with blue light produces ultrafast pulses. The electrical response of Si at the three sampling points is similar to GaAs and InP.

Our results directly support the filed screening model for ultrashort pulse generation with edge illumination. The local field in the vicinity of the excitation is observed, but only the subpicosecond pulse propagates down the transmission line. We believe our success in generating a pulse on Si is due to our choice of excitation wavelength. The only other successful ultrafast pulse generation on Si, with light having a large penetration depth, was performed on a silicon-on-sapphire (SOS) substrate [10]. The Si layer used in the SOS substrate had a thickness much less than the penetration depth at the excitation wavelength, thus it was possible for Krökel, et al to generate a pulse. With a shallow absorption length, only the electric field profile near the surface is disturbed, causing a surface redistribution of the electric field. We speculate that by exciting Si with red light, the large absorption length generates deep carriers which cause a volume redistribution of the electric field. This weakens the displacement current from the surface field, and thus smears the pulse shape.
The band structure in Si is totally different from that of InP and GaAs. Thus, our results show that the mechanism behind edge illumination is not material dependent. Therefore, the applicability of this method to various semiconductors makes edge illumination a powerful technique for ultrafast pulse generation.

![Graph showing Amplitude vs Time](image)

**Fig. 3.15** An 800-fs electrical pulse was generated on Si by edge illumination with blue light.

In the fiber-guided experiments, excitation beam was located ~500 μm away from the sampling point to allow the measurement of only the propagating signal. The measured pulse had a width of ~2 ps, indicating again that only the displacement current pulse propagates and the shoulders are localized. Finally, edge illumination with blue light on silicon switches made of Cr/Au electrodes was also examined. A shoulder-free electrical pulse is shown in Fig. 3.15 to have a FWHM of 800 fs—the fastest pulse generated on bulk silicon to date.
Summary

Subpicosecond electrical pulses have been generated by edge-illuminating conventional photoconductive switches made on GaAs, InP, and most importantly Si. The pulses generated on GaAs and InP have a width of ~540 fs, limited by the RC time constant of the switches. The same method has been applied to silicon switches with blue light illumination to have a much shorter penetration depth and avoid deep carriers. In one case, our Si switches generated an 800-fs pulse—the fastest pulse generated on bulk silicon to date.

Our experimental results directly support the field screening model that only the displacement current caused by suppression of the electric field around the illuminated area is propagated. The shoulders are shown to be localized effect and have different polarities, depending on the sampling positions.

With the edge-illumination technique, a photoconductive switch with a long carrier lifetime may be used as an ultrafast photodetector with subpicosecond temporal resolution. However, the repetition rate of this kind of photodetector is limited by the carrier life time or the drift-diffusion time. The most useful feature of edge illumination is that it does not require any extra processing; i.e., it can be performed with the existing transmission lines on integrated circuits. By utilizing edge illumination, broadband frequency domain characterization of devices fabricated on GaAs and InP as well as Si can be as easily performed. When combined with an electro-optic sampling system, edge illumination is a simple and powerful tool for in situ characterization of circuits.
References


Chapter Four
Optoelectronic Generation of Ultrashort Pulses—
Testing of Metal-Semiconductor-Metal Photodiodes

Metal-semiconductor-metal (MSM) photodiodes are known as high-speed photodetectors with high responsivity. It was suggested that the mechanism for high-speed performance of MSM diodes is independent of materials. The simple planar structure of MSM diodes makes them compatible in processing with integrated circuits. As a result, MSM diodes are integrable with high-speed electronic circuits made on different semiconductor substrates and useful in characterizing these circuits with an electro-optic (EO) sampling system. In this study, MSM diodes made on GaAs, InP and Si were tested. Especially, our focus was on silicon-based MSM diodes, including bulk silicon and silicon-on-sapphire, to have reliable optoelectronic switches for interfacing silicon electronics. Not only useful for our further experiments, these silicon-based diodes are also interesting in applications as high-speed photodetectors.

In this chapter, the operating principle of MSM diodes is introduced and demonstrated to be applicable to different semiconductor substrates. Fabricated with electron-beam lithography, diodes with different sizes were measured with our EO sampling system and are shown to have high-speed response, as expected. The limitation of the high-speed performance of these diodes is discussed. A silicon diode compatible with superconducting electronics is also presented to have high speed at cryogenic temperatures.
4.1. Historical review and introduction of metal-semiconductor-metal photodiodes

Metal-semiconductor-metal (MSM) photodiodes have attracted a lot of interest for more than ten years [1-21] and are known as high-speed photodetectors with simple planar structure. An earlier approach to fabricate MSM diodes with picosecond responses was based on amorphous silicon (α-Si). In α-Si, the structural defects act as efficient trapping and recombination centers to provide the desired, short photoconductive response time [1-3]. However, the low carrier mobility and short carrier lifetime of α-Si caused a poor photocarrier collection efficiency and a small responsivity. Hence the ensuing research was focused on increasing the quantum efficiency, or responsivity [3-5]. The basic concept was that MSM diodes with electrode separations comparable to the carrier drift length would result in ultrashort transit time and greatly improve carrier collection efficiency. Both sandwich-type MSM diodes with ultrathin α-Si deposited between metal electrodes and planar, submicrometer-sized interdigitated MSM diodes were reported to have quantum efficiency higher than 30% [4-5]. Furthermore, interdigitated MSM diodes were made on silicon-on-sapphire (SOS) substrates, which allowed backside illumination to avoid blocking of light by the metallic fingers to increase responsivity [5]. Another advantage of using SOS substrates is that it decreases the depletion capacitance and allows for fast response time [5]. For ultraviolet applications, silicon MSM diodes were reported to have a quantum efficient of 10%—much higher than sandwich-type p-i-n diodes at similar wavelengths [6, 7].

Recently, the interest in MSM diodes with submicrometer finger spacing and width has been shifted from high quantum efficiency to high-speed performance [8-21]. Metal-semiconductor-metal photodiodes with submicrometer-sized finger separation have been made on crystalline semiconductors [8-20]. The intrinsic temporal response of these diodes was simulated to have a fast electron peak followed by a slower hole tail, due to the lower hole mobilities [13, 16]. As a result, MSM diodes made on compound-semiconductor substrates have attracted most of the attention for their high electron mobility [14-21]. However, in this thesis, MSM diodes made on silicon are more interesting for the use as an optoelectronic interface to silicon circuits which are the majority of the existing electronics.
The interdigitated structure and the band diagram of an MSM photodiode can be illustrated in Fig. 4.1 [16]. The high speed performance of an MSM diode relies on the submicrometer finger spacing and the Schottky contacts between the metal electrodes and the semiconductor substrate. The Schottky contact prevents carriers from being injected into the semiconductor. In other words, the semiconductor is fully depleted while a voltage bias is applied to the interdigitated metal electrodes. With the illumination of a laser pulse, there are photocarriers generated which will be swept out by the biasing electric field and collected by electrodes. Because the spacing between
the metal electrodes is only submicrometer, the transport of these carriers is ballistic and the operation speed of MSM diodes is limited by the transit time of photocarriers. This mechanism is independent of material and should be applicable to different semiconductors.

To illustrate the performance of MSM diodes, Monte Carlo simulation results by M. Y. Liu et al. are reproduced in Figs. 4.2 and 4.3 [13, 16]. The intrinsic response of MSM diodes typically has two components: a fast electron peak and a slower hole tail, as in Fig. 4.2. For compound semiconductors, these different contributions are even pronounced, due to the very different carrier mobilities. In practical, device parasitics also affect the temporal performance and result in a slower external response, as shown in the same figure.

![Graph showing intrinsic and external response of MSM diode](image)

**Fig. 4.2** Monte Carlo simulations show that an MSM diode has an intrinsic response consisting of an electron peak and a hole tail. Device parasitics result in the external response.

The intrinsic transit time in Fig. 4.2, defined as the full-width at half-maximum of the electron peak, is dependent of the electrode spacing, the electric field between
electrodes and the electron velocity of semiconductors. This transit time of silicon MSM diodes with different electrode spacing is shown in Fig. 4.3, which was calculated with an average electric field of 50 kV/cm and an electron saturation velocity of $1 \times 10^7$ cm/s [13, 16]. It can be seen that, indeed, silicon diodes have desired high-speed. For example, a diode with finger spacing of 500 nm, feasible with photolithography, has a response time of about 8 ps, corresponding to an operation speed of 60 GHz.

![Graph showing intrinsic response time vs finger spacing](image)

Fig. 4.3 Simulated intrinsic response time of silicon MSM diodes as a function of finger spacing.

To verify that the transit-time limited performance is applicable to different semiconductors, we have fabricated MSM diodes with submicrometer electrode pitches at the Cornell Nanofabrication Facility [22]. Our MSM diodes with different electrode spacing and width were made on GaAs, InP, as well as bulk silicon with electron-beam lithography and lift-off. The process is shown schematically in Fig. 4.4.
The polymethyl-methacrylate (PMMA) resist was spun on a semiconductor substrate to have a thickness of about 1800 Å and was baked at 170 °C for about 1 hour. The interdigitated patterns were then written by focused electron beam on the resist, as in step 2 in Fig. 4.4. The PMMA layer was then developed with 1:1 methyl isobutyl ketone-isopropal for about 1 minute. After the resist was developed, a Ti/Au metalization was deposited on the wafer with electron beam evaporation. The metal interdigitated electrodes were then lifted-off by acetone. Because the aspect ratio of the developed PMMA is about one, in the metal evaporation process, the substrate was
positioned about two feet away from the source to have almost vertical depositing and ensure the ratio of finger spacing and width.

Fig. 4.5 A scanning electron micrograph of an MSM diode with finger spacing and width of 200 nm. The diode area is $10 \times 10 \ \mu m^2$. The top and bottom metals are part of a coplanar strip line.

After the submicrometer electrodes were made, a following photolithography and lift-off were performed to fabricate coplanar strip lines (CPS’s) for biasing and termination. The diodes were positioned as a shunt to the CPS’s. The metallization was Ti/Au with thickness of 15/35 and 15/200 nm for the diode fingers and CPS’s, respectively. The impedance of the strip line was calculated to be $\sim 80 \ \Omega$, depending on the substrates. Figure 4.5 shows the scanning electron micrograph of a silicon diode with finger spacing and width of 200 nm and an active area of $10 \times 10 \ \mu m^2$. The top and bottom metals are part of the CPS used to bias the diode.
4.2 Testing of GaAs and InP metal-semiconductor-metal photodiodes

In order to complete the demonstration of a material-independent scheme for picosecond pulse generation, we have tested the ultrafast response of metal-semiconductor-metal (MSM) diodes made on GaAs, InP, and Si. In this section, our work on GaAs and InP diodes is reported.

The response of these diodes to femtosecond laser pulses was measured with our electro-optic sampling system. The usual bias used in these measurements provided an average electric field of about 100 kV/cm between metal fingers. A typical response of MSM diodes made on bulk GaAs is shown in Fig. 4.6. This 10×10-μm² diode has a finger spacing and width of 100 nm and is expected to have an intrinsic transit time of about 0.4 ps [15]. However, our measured result shows an external response time of 1.5 ps, much longer than expectation. A more careful examination on the device parasitic (which will be discussed later) shows that this response time is actually limited by the device RC time constant, where R is the impedance of the transmission line and C is the capacitance of the interdigitated structure. The capacitance of MSM diodes may be calculated with conformal mapping [23] and is approximately inversely proportional to the finger spacing for a given diode area. Depending on the substrate dielectric constant, its typical value is on the order of femtofarad. For example, a GaAs diode with finger spacing and width of 300 nm and an area of 10 × 10 μm² has a capacitance of ~10 fF.

Metal-semiconductor-metal diodes made on low-temperature grown (LT) GaAs to have a speed limited by carrier lifetimes were examined as well. Diodes with 100-, 200- and 300-nm finger spacing and width were tested. Due to smaller RC time constant, diodes with 300-nm finger spacing and width had the fastest response time, indicating effects of the device parasitics. The measured response of a 300-nm diode is shown in Fig. 4.7 to have a pulse full-width at half-maximum (FWHM) of 0.87 ps.
Fig. 4.6 A 100-nm MSM diode made on bulk GaAs was measured to have a response time of 1.5 ps.

Fig. 4.7 A subpicosecond response of a 300-nm MSM diode made on LT GaAs.
We have also tested the high-speed performance of InP diodes. For these diodes, semi-insulating Fe:InP substrates were used to have reliable Schottky contacts with Ti/Au. As in Fig. 4.8, a 2-ps electrical pulse was generated when a 500-nm InP MSM diode was activated by a laser pulse.

![Graph showing normalized amplitude versus time in ps](image)

**Fig. 4.8** A 2-ps electrical pulse was generated by a 500-nm InP MSM diode.

Our work on GaAs and InP diodes is summarized in Tab. 4.1. It shows that, with nanometer scaled finger spacing and width, MSM diodes made on bulk GaAs and semi-insulating Fe:InP are capable of generating picosecond electrical pulses. The corresponding 3-dB bandwidth of these diodes is as high as 300 GHz, suitable for ultrafast testing electronic circuits made on high quality substrates. On the other hand, MSM diodes made on LT GaAs were measured to have a response time of 0.87 ps and a corresponding bandwidth of 510 GHz, limited by the carrier lifetime. The external limitation of diode speed, the finite RC time constant, was also examined. Theoretical calculation assumed that the diodes have an infinitely small rise time and a RC-limited decay [15]. Therefore, the external pulse FWHM is ln2 times RC, as listed in Table 4.1. It shows that the speed of 100- and 200-nm diodes is actually limited by the
device RC time constant. This limitation, however, may be released with a smaller active area.

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>LT-GaAs</th>
<th>LT-GaAs</th>
<th>LT-GaAs</th>
<th>Bulk GaAs</th>
<th>Fe:InP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finger spacing/width (nm)</td>
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<td>200/200</td>
<td>300/300</td>
<td>100/100</td>
<td>500/500</td>
</tr>
<tr>
<td>Calculated intrinsic transit time (ps) [15]</td>
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<td>0.8</td>
<td>1.1</td>
<td>0.4</td>
<td>-</td>
</tr>
<tr>
<td>RC(ln2) time constant (ps)</td>
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<td>1.0</td>
<td>0.5</td>
<td>1.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Measured FWHM (ps)</td>
<td>1.6</td>
<td>1.0</td>
<td>0.87</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>3-dB bandwidth (GHz)</td>
<td>280</td>
<td>440</td>
<td>510</td>
<td>295</td>
<td>46</td>
</tr>
</tbody>
</table>

Tab. 4.1 Measured and calculated characteristics of MSM diodes made on bulk GaAs, LT GaAs, and Fe:InP.

4.3 Testing of silicon metal-semiconductor-metal photodiodes

We have demonstrated on bulk GaAs and InP that the mechanism for high-speed performance of metal-semiconductor-metal (MSM) diodes is independent of material. It implies that silicon MSM diodes should have an alike response time to compound diodes and can be useful for picosecond pulse generation. As in Fig. 4.3, Monte Carlo simulations confirm this idea and show that silicon MSM diodes with finger spacing of 200 and 300 nm have a response time of about 4 and 6 ps, respectively [15]. Furthermore, even compound diodes have a wide bandwidth due to the fast electron peak, the repetition rate of these diodes is actually low [19]. The diode recovery time is limited by the much longer hole tails, as illustrated in Fig. 4.2. For example, the response of an InP diode, as in Fig. 4.8, does not recover to zero within our observation time window. This disadvantage limits the practical applications of compound MSM diodes, because a photodetector has to fully recover to its original
state before it can resolve the next optical signal. On the other hand, silicon has a comparable electron and hole mobilities and should not have a hole tail. As a result, a faster overall recovery time for silicon MSM diodes is expected.

High-speed performance of these silicon MSM photodiodes with different finger spacing and width was tested using our electro-optic (EO) sampling system. As in Fig. 4.9, the response of a 300-nm silicon diode to a laser pulse with wavelength of 725 nm had a full-width at half-maximum of ~11 ps—much slower than III-V diodes and the Monte-Carlo predictions [16]. In addition, there was a long tail following the main peak. Similar responses were seen with excitation wavelengths of 750, 760, and 795 nm.

![Graph showing normalized amplitude vs time for different wavelengths](image)

**Fig. 4.9** A 300-nm silicon MSM diode has a response pulse width of 11 and 5.5 ps with red ($\lambda = 725$ nm) and blue ($\lambda = 465$ nm) light excitation, respectively. With blue light illumination, a 200-nm diode has a pulse width of 3.7 ps and recovers fully to its original state within 16.5 ps.

This slower response and the long tail with red light excitation are due to the deep-carrier effect. In silicon, light at a wavelength of 725 nm has a penetration depth
of ~5 μm, much longer than the finger spacing and width. As a result, photocarriers are generated deeply into the silicon substrate. These deep carriers have to diffuse through a long distance with a weak electric field before they can be collected by the metal electrodes.

In order to eliminate deep-carrier generation and to study the "intrinsic" response time of silicon MSM diodes, we used the frequency-doubled (blue) light as the excitation source, which has a penetration depth of ~150 nm in silicon. As shown in the same figure, the response pulse width of a 300-nm silicon diode is 11 ps with red-light (λ = 725 nm) illumination, but is reduced to 5.5 ps with blue-light (λ = 465 nm) excitation. For a 200-nm diode, excited with blue light, the response pulse width is 3.7 ps. More importantly, it fully recovers to its original, nonconductive state within 16.5 ps, implying that it can resolve optical information with a bit-rate as high as 60 Gb/s. The 3-dB bandwidth of this diode is about 110 GHz, as in Fig. 4.10. These results were measured with the configuration shown in Fig. 2.9 to minimize the propagation distortion of the electrical pulses.

![Normalized Amplitude](image)

**Fig. 4.10** The Fourier transform of a 200-nm diode response shows the 3-dB bandwidth is ~110 GHz.
Our study indicates that MSM diodes made on different semiconductor materials are capable of generating ultrashort pulses. The simple planar structure of MSM diodes makes them integrable with circuits to have a convenient optoelectronic interface. However, in order to have a useful tool for ultrafast testing of electronic circuits, whether the amplitude of the electrical pulses generated with MSM diodes is adjustable has to be examined. This problem has been explored with changing both the excitation light intensity and the bias voltage of MSM diodes.

![Graph](image)

**Fig. 4.11** Dependence of the pulse amplitude on the number of incident photons at 400 and 750 nm.

It can be seen in Fig. 4.11 that a 300-nm silicon MSM diode has a linear relationship between its peak amplitude and the amount of excitation photons. However, there are two distinct slopes for violet and red excitations. This characteristic is a further indication that deep carriers have significant effects on the diode response. With red light excitation, a large portion of the photocarriers are generated deeply in the substrate and do not reach the electrodes in the first few picoseconds to contribute to the main peak.
Fig. 4.12 (a) (b) The pulse amplitude and width as functions of the bias voltage of MSM diodes.
On the other hand, it is more complicated for the case of changing the bias voltage of MSM diodes, as in Fig. 4.12 where the response of a 200-nm silicon diode is shown. The first impression of Fig. 4.12 (a) is that the amplitude of pulses decreases with smaller bias voltages. However, a precise observation from Fig. 4.12 (b), showing the normalized amplitudes, indicates that the pulse width actually becomes wider when the bias becomes smaller. Figure 4.13 concludes these results and shows that the pulse width changes significantly with bias voltage smaller than ~1.5 V and then settles at higher bias. On the contrary, the pulse integral remains almost the same.

![Graph](image)

**Fig. 4.13** The pulse integral generated by an MSM diode remains almost the same with different bias voltages, while the pulse width changes significantly.

These results may be explained with the nature of MSM diodes. The pulse integral represents the total photocarriers excited by a laser pulse and should not be affected strongly by bias voltage. The pulse width, determined by the transit time or the traveling velocity of photocarriers, nevertheless is well known to be a function of
the average electric field between electrodes. For a given finger spacing of 200 nm, the average carrier velocity as a function of bias electric field is then deduced, as shown in Fig. 4.14.

![Graph showing average velocity vs. average electric field](image)

**Fig. 4.14** The average carrier velocity as a function of the average electric field.

Our study indicates that, different from edge illumination, changing the excitation light intensity on MSM diodes is a better way to modify the pulse amplitude. This amplitude may be adjusted linearly with light intensity, while the pulse shape remains the same, suitable for testing the response of circuits with different impulse amplitudes. Aided by computer simulation, this technique has been applied to study the nonlinear response of superconducting Josephson junctions, which will be presented in Ch. 5.

It should also be pointed out in passing that the velocity-field measurement (e.g. Fig. 4.14) provides a novel way of measuring the interesting phenomenon of the velocity overshoot in compound semiconductors [24]. Our initial effort on GaAs and
velocity overshoot in compound semiconductors [24]. Our initial effort on GaAs and InP was hampered by the large device RC time constant, and produced no useful conclusion yet.

4.4 Testing of metal-semiconductor-metal photodiodes made on silicon-on-sapphire

Our study on metal-semiconductor-metal (MSM) photodiodes is not only important for ultrafast testing electronics with our electro-optic sampling system, but also interesting in the applications of high-speed photodetectors. As a result, even we have demonstrated picosecond pulse generation with MSM diodes on different semiconductors, we have extended our study to diodes made on silicon-on-sapphire (SOS) to have silicon-based ultrafast photodetectors.

Conceptually, we have proved that the transit-time-limited performance of MSM photodiodes may be applied to silicon. However, the temporal performance of these silicon diodes is strongly dependent on the excitation wavelengths. To improve the speed of silicon-based MSM diodes at longer wavelengths, we suggest using silicon-on-insulator substrates. In this case, the thickness of the silicon layer limits the depth of photocarriers, thus the MSM diode should have a response time weakly dependent on the excitation wavelength. Specifically, MSM diodes made on SOS substrates were examined. For our samples, the thickness of silicon layer is 500 nm, comparable to the finger spacing and width. Both blue (λ = 400 nm) and red (λ = 720 nm) light were used to study the temporal response of SOS diodes.

With red-light excitation, where the photon penetration depth is much larger than the finger spacing, typical response transients of 200-, 300-, and 500-nm SOS diodes are shown in Fig. 4.15. The pulse full-width at half maximum (FWHM) is only weakly dependent on the finger spacing, with values of 5.7, 6.6, and 7.5 ps, respectively. Comparing with the response transient of the 300-nm bulk-silicon diode, it clearly shows that limiting the photon penetration with SOS substrate improves the device speed, in this case by about a factor of two.
Fig. 4.15 Electrical pulses generated by illumination of 720-nm photons on SOS as well as bulk-silicon MSM diodes.

When the excitation source was changed to blue light (λ = 400 nm, penetration depth ~150 nm), the temporal response of SOS diodes was found to change only slightly. It is shown in Fig. 4.16(a) that the response of a 200-nm SOS diode has a FWHM of 4.5 and 5.7 ps with blue- and red-light excitation. In contrast, a 200-nm bulk-silicon diode shows more drastic change, as in Fig. 4.16(b) where the FWHM is now reduced from 7.0 to 3.7 ps with blue excitation. These results confirm the previous prediction that, for an MSM diode to have a fast temporal response over a wide range of wavelengths, the deep-photon penetration can be eliminated by using shallow substrates.
Fig. 4.16 (a) The response of a 200-nm SOS diode and (b) the response of a 200-nm bulk-silicon MSM diode subjected to red (dotted line) and blue (solid line) light.

The faster response of SOS diodes at longer wavelengths, however, comes with a penalty. While the deep carriers are now absent, the amount of photon absorption is likewise reduced. The SOS diodes therefore have reduced external
quantum efficiency at longer wavelengths. For example, the peak amplitude in Fig. 4.16(a) was 270 mV for 0.18 pJ of blue-light energy, but reduced to 94 mV for 0.62 pJ of red-light energy. We have examined the quantum efficiency of the SOS diodes over a wide range of wavelengths. A typical set of results are shown in Fig. 4.17. Because of the finite observation time-window and a residual tail response of the diode (see below), we have computed the external quantum efficiency by defining it to be the number of carriers in the main peak (pulse peak × pulse FWHM) divided by the number of excitation photons. In the same figure, solid line shows the photon absorption coefficient (inversely proportional to the penetration depth) [25].

![Graph showing external quantum efficiency and absorption coefficient vs. wavelength.](image)

**Fig. 4.17** The external quantum efficiency of our SOS diodes at several selected wavelengths. The solid line shows the absorption coefficient of silicon. The close fit indicates that the device quantum efficiency is dominated by the substrate absorption.

The result, shown in Fig. 4.17, is an external quantum efficiency, uncompensated for blocking of light by the fingers, reflection from silicon surfaces, and transmission through the silicon layer. The total absorption by the silicon layer of thickness \( t \) in this case is proportional to \((1 - e^{-\alpha t})\), where \( \alpha \) is the absorption coefficient. At longer wavelengths, where \( 1/\alpha \) is much larger than \( t \), one expects the
quantum efficiency to be linearly proportional to $\alpha$. On the other hand, at shorter wavelengths or larger $\alpha$, the quantum efficiency would lay down the curve of absorption coefficient with saturation occurring. These features are all indicated by the close similarity of the experimental results and the solid line in Fig. 4.17.

The slight difference between blue- and red-light excitation of the SOS diode in Fig. 4.16(a) is partially due to the thickness of the silicon layer, which is about three times larger than the penetration depth of blue light in silicon. A thinner silicon layer may reduce this effect and improve the temporal performance further at red light.

For these SOS diodes, following the main peak, there is a "tail" component in the diode response. This tail appears to be independent of the finger spacing of the diodes, as seen in Fig. 4.15, and can be reduced significantly at shorter wavelengths, where photons are absorbed by a shallow top layer of silicon, as seen in Fig. 4.16(a). It then seems reasonable to attribute this tail to imperfections at the interface between silicon and sapphire. Acting as carrier traps, these imperfections release carriers over a much longer time scale and contribute to a slow tail in the diode response. A better SOI material system, such as the bond and etch-back [26] substrate, could presumably be used to eliminate such tail responses.

Our study on MSM diodes made on silicon and SOS substrates is summarized in Tab. 4.2. These results point conclusively to the fact that the penetration depth of light is the determinant factor of the speed of silicon MSM diodes. Limiting the depth of photocarriers by either using SOI substrates or excitation photons with shorter wavelengths, silicon-base MSM diodes are shown to have a speed close to the Monte Carlo predictions and comparable to compound MSM diodes.
<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>SOS</th>
<th>SOS</th>
<th>SOS</th>
<th>Bulk Si</th>
<th>Bulk Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finger spacing/width (nm)</td>
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<td>300/300</td>
<td>500/500</td>
<td>200/200</td>
<td>300/300</td>
</tr>
<tr>
<td>Calculated intrinsic transit time (ps) [15]</td>
<td>4.0</td>
<td>5.5</td>
<td>7.0</td>
<td>4.0</td>
<td>5.5</td>
</tr>
<tr>
<td>FWHM with red light excitation (ps)</td>
<td>5.7</td>
<td>6.6</td>
<td>7.5</td>
<td>7.0</td>
<td>11.0</td>
</tr>
<tr>
<td>FWHM with blue light excitation (ps)</td>
<td>4.5</td>
<td>–</td>
<td>–</td>
<td>3.7</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Tab. 4.2 Measured response time of SOS and silicon MSM diodes with red and blue light excitation as a comparison of theoretical calculations.

4.4 Cryogenic metal-semiconductor-metal photodiodes

To serve as optoelectronic switches in superconducting electronics, metal-semiconductor metal (MSM) diodes operating at cryogenic temperature have been studied. These diodes were made of Al/Nb bilayer on silicon substrates to have a convenient interfacing with niobium-based superconducting electronics. Typically, these diodes have an active area of 30×30 μm² and electrode spacing and width of 1 μm. Both undoped and lightly doped silicon substrates were tried to form Schottky contacts, the key issue of fabricating MSM photodiodes. At room temperature, an MSM diode made on n-type silicon (with a resistivity of 10-20 ohms-cm) was measured to have a response pulse width of 21 ps, as in Fig. 4.18(a). On the other hand, a diode made on silicon with a resistivity of 1200-1800 ohms-cm had a much slower response, as in Fig. 4.18(b), due to the poor Schottky contacts.
Fig. 4.18 (a) Al/Nb bilayer on n-type silicon makes reliable Schottky contacts and results in a desired high-speed performance of an MSM diode at room temperature. (b) MSM diodes made on undoped silicon with Al/Nb bilayer have slower response.
However, at cryogenic temperature, thermal carriers are frozen and the metal-semiconductor contacts are "forced" to be Schottky on both doped and undoped silicon substrates. As a result, the temporal response had no significant difference.

![Graph](image.png)

Fig. 4.19 A 1-μm MSM diode made of Al/Nb on silicon operating at 2 K has a pulse width of 10 ps and a recovery time of ~25 ps.

A typical result acquired at 2K is shown in Fig. 4.19 to have a saw-tooth like waveform with a subpicosecond rise time and a pulse width of 10 ps. Most importantly, it recovers fully to its original state within ~25 ps, corresponding to an operational speed of ~40 Gb/s. The response of these diodes at low temperature was measured using the cryogenic electro-optic sampling system described in section 2.4.
Summary

We have demonstrated the high speed performance of metal-semiconductor-metal (MSM) photodiodes made on different semiconductors. Transit-time-limited diodes on GaAs and InP are capable of producing picosecond electrical pulses with 3-dB bandwidth as high as 300 GHz. Silicon MSM diodes are shown to have a desirable high-speed performance as predicted by Monte Carlo simulations. For a 200-nm silicon MSM diode, the response time is demonstrated to be 3.7 ps and the fully recovery time is about 16.5 ps, corresponding to a resolvable-bit-rate as high as 60 Gb/s. Furthermore, a cryogenic MSM diode is presented to be an ultrafast optoelectronic interface to test high-speed superconducting circuits.

Moreover, acting as picosecond pulse generators, MSM diodes have simple planar structure and are integrable with devices to deliver picosecond electrical pulses synchronously to laser pulses. These electrical pulses are adjustable in amplitude and useful to characterize the device under test with different parameters, which will be presented in Ch. 5.

Our study on MSM diodes is not only useful for our further experiments, it is also significant by itself in the applications of high speed photodetectors. A low-temperature-grown GaAs diode was presented to have a response pulse width of 0.87 ps and a corresponding bandwidth of 510 GHz, limited by the carrier lifetime. On the other hand, silicon-based MSM diodes are more interesting in practical applications. They are compatible with silicon-based electronics and have a fast overall recovery time caused by a comparable electron and hole mobilities. These characteristics make silicon MSM diodes very useful as integrable, optical-communication receivers. Thus, an ultrafast photodetector compatible with the existing, silicon-base electronics is demonstrated.
References


[22] The Cornell Nanofabrication Facility at Cornell University, supported by NSF under grant ESC 8619049.


Chapter Five
Observation of Single-Flux-Quantum Pulses—
Impulse and Response Measurement of Josephson Junctions

The techniques of impulse and response measurement have been applied to measure the nonlinear response of superconducting Josephson junctions. In this chapter, the direct observation of magnetic single-flux-quantum (SFQ) pulses is described. These SFQ pulses were generated by switching nonhysteretic Josephson junctions with picosecond impulse signals. The experimental requirements for optoelectronically generation and detection of SFQ pulses will be discussed, as well as the experimental set-up to achieve this measurement. Finally, measured results will be presented along with computer simulations. In addition to an impressive demonstration of the impulse and response measurement, our experimental results are important by themselves as the first direct observation of a magnetic flux quantum pulse. This study also opens a way to test ultrafast superconducting electronics.
5.1 Introduction to single-flux-quantum electronics

The tunneling of super electrons between two closely spaced superconductors (a Josephson junction) was proposed by B. D. Josephson to be possible even without potential difference [1]. Microscopically, this tunneling (the Josephson effect) is related to the phases of the electron wave-function in superconductors. On the other hand, the macroscopic current-voltage relationship of a Josephson junction may be expressed as

$$ I = I_c \sin \phi $$

$$ \frac{\partial \phi}{\partial t} = \frac{2e}{\hbar} V, $$

where $I$ is the current flowing through the junction, $\phi$ is the relative phase difference of the electron wavefunction between superconductors, and $I_c$ indicates the critical current. The critical current of a Josephson junction is the maximum among of current under which electrons tunnel with no potential difference across the junction. When the tunneling current exceeds the critical current, the voltage across the junction is then proportional to the time derivative of the phase difference. The Plank constant is denoted by $\hbar$ and $e$ is the electron charge.

For fabricating a tunneling Josephson junction, a typical method is to deposit a thin layer of insulator in between two superconductors to have a sandwich-type structure. In nowadays, techniques based on Nb-AlO-Nb routinely allow the fabrication of reliable Josephson junctions for practical applications.

For single-flux-quantum (SFQ) electronics, it is required to have nonhysteretic Josephson junctions, which are produced by shunting the junctions properly. The current-voltage relation of a nonhysteretic junction is

$$ I = I_c \sin \phi + \frac{\hbar G}{2e} \frac{d\phi}{dt} + \frac{\hbar C}{2e} \frac{d^2 \phi}{dt^2}, $$

5.2
where $G$ is the shunting conductance, and $C$ is the capacitance of the sandwich structure. Such a current-voltage characteristic may be seen in Fig. 5.1, where the dash line indicates the load line for biasing the junction. When a current pulse is applied to a biased junction to exceed the critical current, that junction is switched to its voltage state. While this junction relaxes to its original state, the wave-function of electrons recovers with a phase-slip of $2\pi$ and an SFQ voltage pulse is generated. The area of an SFQ pulse is quantized: the integral of the voltage over time is equal to one flux quantum, $h/2e$, or $2.07$ mV $\times$ ps. Depending on the junction parameters, these SFQ pulses may have different pulse amplitude and width to have a total content of a flux quantum. For example, a $3 \times 3$-μm$^2$ junction may produce an SFQ pulse of $-0.3$ mV $\times$ 6 ps, and a $0.3 \times 0.3$-μm$^2$ junction may be switched to have a pulse of $-6$ mV $\times$ 0.3 ps.

![Fig. 5.1](image)

Fig. 5.1 The current-voltage curve of a nonhysteretic Josephson junction. When the junction is switched by a current pulse, a single-flux-quantum voltage pulse is generated.

Superconducting circuits based on SFQ pulses provide a new family of digital electronics with ultrahigh speed and very-low-power dissipation. Many logic gates based on the processing of SFQ pulses have been presented [2]. This family of digital
logic currently has a clock rate exceeding 10 GHz and is a promising technology for hundreds-of-gigahertz operation speed, much faster than any semiconductor logic [3]. In these superconducting digital circuits, an SFQ pulse is the fundamental information carrier: SFQ pulses represent logical "1" while their absence denotes logical "0", as in Fig. 5.1.

Single-flux-quantum pulses are regularly generated, processed, and detected in many different superconducting circuits. In addition, a solitonian fluxon propagating in a Josephson transmission line has been measured by a Josephson sampler [4-5], by means of pulse convolution with the sampler's internal response (of the order of a few picoseconds). However, because of its small amplitude and the picosecond time scale, an SFQ pulse has never been directly observed, i.e., having its voltage and temporal evolution accurately determined. As a result, until recently, the characterization of these high-speed circuits has been performed on a chip scale to test the operation of a whole chip. The design and optimization of these circuits are then relied on computer simulations, since circuit parameters could not be directly measured. However, simulations are not accurate enough in many cases [6-7]. In order to experimentally characterize these ultrafast superconducting circuits, the first step is to observe SFQ pulses with high temporal resolution. This task was achieved in this study and will be described in this chapter.

5.2 Experimental requirements and solution

Because an SFQ pulse has only a pulse content of 2.07 mV × ps, it is necessary to have a measuring technique carrying cryogenic testing with subpicosecond temporal resolution and submillivolt sensitivity. This requirement can not be achieved even with modern sampling oscilloscopes. Furthermore, due to the small energy content in an SFQ pulse, a noninvasive testing is required. It is obvious that this is a difficult task, not to mention that on-chip testing is desired. Because of the problem of impedance matching between testing equipment and low-impedance superconducting microstrip lines, ex situ experiments are impossible.
To achieve this measurement, we have developed a cryogenic electro-optic (EO) sampling system, as described in Ch. 2. It has a temporal resolution of ~250 fs and a voltage sensitivity less than 100 microvolt, as shown in section 2.3. Because only the fringing field of the microstrip line is probed, EO sampling is ideal for noninvasive, on-chip measurement.

The remaining problem is that SFQ pulses have to be generated synchronously to laser pulses so that they may be sampled by delayed probing pulses. In other words, these SFQ pulses have to be generated optoelectronically. Because we have developed reliable optoelectronic switches to generate picosecond electrical transients, the task is then to develop a superconducting circuit that converts these electrical transients to SFQ pulses. There are two circuits proposed by us, a dc-to-SFQ converter [8] and a two-junction "pulse shaper" [9]. The advantage of a dc-to-SFQ converter is that an SFQ pulse may be generated with a large margin for the current bias of junctions and the impulse amplitude. However, in order to restore and generate a flux quantum, the circuit parameters have to be precise. As a result, the design and fabrication are more restricted. On the other hand, the pulse shaper consisting of just two parallel junctions is simpler in operation.

In this study, the two-junction pulse shaper was used. Intuitively, these parallel junctions can be switched by a picosecond electrical pulse to generate SFQ pulses, if a proper current bias is applied. When the impulse amplitude gets smaller, fewer SFQ pulses are switched and finally one single SFQ pulse may be produced.

5.3 Simulated performance of the pulse shaper

The performance of this proposed circuit to generate SFQ pulses has been simulated with JSPICE [10]. Because a superconducting metal-semiconductor-metal (MSM) diode has a response shown in Fig. 4.19, the impulse for this simulation was focused on a saw-tooth like waveform. It is interesting to note that, according to our simulation, the two-junction pulse shaper can be switched by an impulse with arbitrary waveform to generate just one SFQ pulse. Impulse signals with a width from 1 ps to even 50 ps can be shaped to an SFQ pulse as long as the amplitude is
adjusted properly. As a result, this simple two-junction pulse shaper is powerful for generating a single SFQ pulse with different optoelectronic switches.

Fig. 5.2  A two-junction pulse shaper is used to shape the impulse with a saw-tooth like waveform from an MSM diode to an SFQ pulse. The circuit parameters are shown as well.

The circuit diagram of the pulse shaper can be seen in Fig. 5.2 to have parallel junctions connected by an inductor. The operational principle of this circuit can be understood with the intuitive picture given above, or a more popular language in the field of SFQ electronics—flipping of flux quantum in the circuit loop. According to this concept, the performance of the pulse shaper can be explained as follow. The impulse and the current bias exceed the critical current $I_c$ of the first junction and introduce a counterclockwise circulating current in the loop. Because the product of the inductance and the junction critical current is chosen to be about half of the flux quantum, there is a "negative" half-flux-quantum restored in the loop. After the exceeding current pulse switches the first junction to generate a voltage pulse, that voltage pulse is delivered by the inductor to switch the second junction. There is then a clockwise circulating current in the loop and a "positive" half-flux-quantum is restored. In other words, the magnetic flux in the loop is flipped by a flux quantum and an SFQ voltage pulse is generated.
Circuit parameters used in this simulation are approximated to practical conditions. Junction parameters are chosen to have a size of $4 \times 4 \ \mu\text{m}^2$, critical current density of 1000 A/cm$^2$, junction capacitance of 38 fF/\mu m$^2$. The inductance of 6.5 pH is actually contributed by the microstrip line used to connect junctions, which has a width of 15 \mu m, a length of 100 \mu m, and a separation from the ground plane of 0.85 \mu m. These parameters are chosen according to the design rules of a foundry process [11].

![Graph showing response of first and second junctions over time](image)

**Fig. 5.3** After two parallel junctions, a saw-tooth-like waveform is shaped to an SFQ pulse.

A typical result can be seen in Fig. 5.3 that, after two junctions, a saw-tooth-like electrical signal with an amplitude of 0.8 $I_c$ is shaped to an SFQ pulse. It is also interesting to notice that two junctions are required to shape an arbitrary waveform to an SFQ pulse. The wide impulse is still reflected in the response of the first junction. It then implies that the picture of the flipping of flux quantum is more accurate for this pulse shaper. This simulation confirms the possibility of generating an SFQ
pulse optoelectronically, and lead to the design and fabrication of our sample for observing SFQ pulses.

5.4 Sample fabrication and experimental set-up

In the test circuit, a silicon metal-semiconductor-metal (MSM) diode is used to generate the electrical transients. The diode is followed by a two-junction pulse shaper which converts the impulse transients to SFQ pulses. By adjusting the amplitude of the impulse with light intensity, as demonstrated in Fig. 4.11, a single SFQ pulse may be generated. This SFQ pulse is then propagated on a superconducting microstrip line, where the pulse is measured electro-optically.

Sample chips were fabricated using conventional Nb technology [11]. The whole process consists of ten layers, as in Fig. 5.4. An Al/Nb bilayer is deposited on n-type silicon to make both the MSM diode (see section 4.4) and the ground plane. The MSM diode sits in an open via of the ground plane. A layer of SiO₂ is then put on the ground plane as the insulating layer of a microstrip line, on which most superconducting circuits are based. A Nb/AlO/Nb trilayer is used to define Josephson junctions. On top of the trilayer, a SiO₂ insulating layer, a layer of shunting resistance, and another SiO₂ layer are deposited sequentially. Usually, the bottom layer of the junctions sits on the ground plane and the top layer is connected to the shunted resistor through a via of the SiO₂ layer, as in Fig. 5.4. A thick Nb metalization is used for connections, including junctions to resistors and resistors to the ground plane. Finally, a layer of SiO₂ and the top Nb layer are deposited. The latter forms the microstrip line and is used to connect the MSM diodes to junctions.
Fig. 5.4 The cross section of an MSM diode and a junction.

A microphotograph in Fig. 5.5 shows our experimental sample. The MSM diode with an area of $30 \times 30 \ \mu m^2$ and an electrode separation of $2 \ \mu m$ was mounted in-line on a Nb superconducting microstrip line (SML) and connected to the two-junction pulse shaper.

Each junction of the pulse shaper had a critical current $I_c$ of 150 $\mu A$ at 2 K and the McCumber parameter $\beta_c$ of 1.5 [12]. The inductance between junctions was estimated to be 6.5 pH. To generate SFQ pulses, the junctions were biased at $0.7 \ I_c$, and the MSM diode was biased at 5 V and illuminated with blue light. By changing the light intensity, impulse with different amplitudes from the MSM diode was generated and subsequently fed into the pulse shaper. As a result, different numbers of SFQ pulses were generated.
Fig. 5.5  Microphotograph of the sample, showing an MSM photodiode coupled to a microstrip line and followed by a two-junction pulse shaper.

The time-domain observation of SFQ pulses was made using an EO sampling system. In its cryogenic version, reflective sampling was made by attaching a lithium tantalate (LiTaO₃) crystal to cover the superconducting circuit, as described in section 2.4. The crystal had a high-reflectivity (HR) dielectric coating facing the device under test (DUT). The frequency-doubled (blue) light penetrating the dielectric coating was used as the switching beam to activate the MSM diode mounted in-line on the DUT, as shown in Fig. 5.5. The fundamental light, serving as the sampling beam, passed through the LiTaO₃ crystal, experienced the refractive-index change caused by the fringe electric field from the SML, and was reflected by the HR coating to the analyzer. Both the switching and sampling beams were focused by a single microscope objective and delivered through an optical window to the DUT which was immersed in superfluid helium.

Because only the fringe field of the microstrip line is probed, this measurement is noninvasive. However, calibration is required to convert the measured EO signal to the "real" voltage transient on the transmission line. This calibration process was accomplished using a passive SML that contained no
Josephson junctions and was separated from the DUT by 300 μm. A known electrical signal was applied to the passive transmission line to determine the voltage scale-factor. The sampling beam was then moved back to the DUT. Sensitivities at the two measurement points were assumed equal, justified by knowing that the crystal was in uniform contact with the chip to within 250 nm (as verified by interference fringes observed through the crystal).

5.5 Measured and simulated results

A series of the measured results is shown from Figs. 5.6 (a)-5.9 (a). The response of the MSM diode, i.e., the impulse to the pulse shaper, is shown in Fig. 5.6 (a) to have a saw-tooth-like waveform. Responses of the pulse shaper to different impulse amplitudes are shown in Figs. 5.7 (a)-5.9 (a). As a comparison, simulated results using JSPICE are shown in Figs. 5.6 (b)-5.9 (b). A waveform similar to the MSM diode response was used in these simulations, as shown in Fig. 5.6 (b). Experimental and simulation conditions are also shown in the insets, where the critical current, the bias current, and the impulse amplitude are represented by $I_c$, $I_b$, and $I_p$, respectively. Circuit parameters were chosen to approximate the experimental sample. It is seen that measured and simulated results are in qualitative agreement.

For a certain range of light intensity, only one SFQ pulse was generated, as in Fig. 5.7 (a) (solid line). The measured pulse had a width of ~3.2 ps and an amplitude of ~0.67 mV. The time-averaged integral of the measured SFQ pulse, as shown by the dashed line in the same figure, shows a total pulse content of 2.1±0.2 mV × ps, corresponding to a single quantum of magnetic flux. To reduce the noise level down to sub-hundred microvolt, the trace presented in Fig. 5.7 (a) represented ~15 minutes of data acquisition.
Fig. 5.6  (a) The impulse signal was generated by an MSM diode. (b) A saw-tooth-like waveform was used in simulations as the input signal to the pulse shaper.
Fig. 5.7  
(a) One SFQ pulse was measured. Dashed line shows the time-averaged integral to have a pulse content of 2.1±0.2 mV × ps. (b) According to simulation, one SFQ pulse is generated by the pulse shaper when the input has an amplitude of 0.8 $I_c$. 
Fig. 5.8  (a) Three SFQ pulses were obtained with a larger impulse. Dashed line shows the time-averaged integral. (b) Corresponding simulated result.
Fig. 5.9  (a) The “feed-through” of the impulse signal, followed by a single SFQ pulse.  (b) Simulation shows the pulse shaper may generate multiple pulses followed by one SFQ pulse.
With a larger impulse amplitude, three SFQ pulses were obtained; the first two were closely placed and the third entered about 6 ps after the second, as indicated by arrows in Fig. 5.8 (a). The time-averaged integral (dashed line) shows that the total content of pulses was \( \sim 6 \, \text{mV} \times \text{ps} \). For even larger input signals (e.g., the peak amplitude \( I_p = 4.3 \, I_C \)), the output begins to acquire the overall shape of the input with Josephson junction pulsing superimposed, as is visible in Fig. 5.9 (a). However, one SFQ pulse can still be clearly identified at the end of the transient [cf. Fig. 5.9 (b)].

The impulse and response measurement has been applied to characterize Josephson junctions with different parameters and for the first time that an SFQ pulse has been observed. This experiment is not only an impressive demonstration of ultrafast testing of electronics with EO sampling, but also opens a way to characterize high speed SFQ-based electronics. Single logic gates can be activated with an SFQ impulse, and their functional delay times and response times can be measured with picosecond accuracy. A wider range of applications requires the use of a clock, where sequential pulses are generated to test such issues as the setup time, hold time, and maximum speed that a given logic gate can operate. The scheme of two excitation beams, illustrated in Fig. 2.10, can be used to generate the sequential clock pulses with adjustable time delays. With this technique, generally, all failure-mode testing of circuits at high clock rates can be handled.
Reference


[8] Senior project of Willam Oliver, Department of Electrical Engineering, University of Rochester, advised by Prof. Roman Sobolewski.


Chapter Six Conclusions

Ultrafast testing of electronic/optoelectronic devices was a formidable, if not unachievable, task, even though tremendous efforts had been made. However, with the effort of this study, it has become possible. A powerful electro-optic (EO) sampling system has been developed to handle the subpicosecond testing of devices. Ultrafast photodetectors with bandwidths as high as 500 GHz were measured with this system. In this thesis, the technique of impulse and response measurement with an EO sampler is established to be applicable to devices made on different semiconductor substrates. All the requirements in using this technique are accomplished in this study. As a demonstration, this technique was applied to study the response of a high-speed superconducting device.

The commonest way for testing high-speed devices is to use sampling oscilloscopes. The testing bandwidth is then limited by the equipment to be less than 50 GHz. With microwave network analyzers, this bandwidth is slightly higher, but information can only be obtained at one single frequency at a time. Furthermore, it is impossible to determine the "intrinsic" performance of a device with these techniques, because probes connected the device and the testing tools always result in an external measurement. Especially, signal attenuation and distortion in probes and connections increase with frequency dramatically and decrease the testing accuracy. As a result, simulation and deconvolution are required to "extract" the real response of a device with these approaches [1]. Other sampling techniques with picosecond temporal resolution, for example superconducting sampling [2] and photoconductive sampling [3], are capable of on-chip testing and avoid connections. However, testing is limited to circuits based on superconductors or special substrates of which ultrafast photoconductive switches are made.

On the other hand, electro-optic sampling [4, 5] does not have these limitations. Its temporal resolution is basically determined by the response time of the EO crystal and the laser pulse width used in the system. For our system, it is estimated to be ~250 fs. The testing is performed with an external EO crystal to probe the fringing electric field of the signal and thus noninvasive. If a finger probe
is used, the testing is naturally on-chip and free from distortion, as in Fig. 2.9. However, there are other factors to be considered before an EO sampling system can be used for routine testing of high-speed electronic/optoelectronic devices. For example, dynamic range, spatial resolution, and operating temperature are crucial for a testing tool. Most importantly, reliable optoelectronic network that generates picosecond electrical pulses has to be developed for the impulse and response measurement of high-speed circuits. All the requirements in using an EO sampling system for ultrafast testing of electronics are fulfilled in this study.

With our EO sampling system, ultrafast photodetectors were tested, including photoconductive switches with novel operation scheme and submicrometer sized metal-semiconductor-metal (MSM) photodiodes. These photodetectors made on GaAs, InP, as well as Si are shown to have bandwidths of hundreds of gigahertz. The operation and speed limitation of these devices were also studied.

The displacement-current pulse generated by edge-illuminating a photoconductive switch is demonstrated to have a subpicosecond pulse width on different semiconductors. This pulse width is ultimately limited by the speed with which photocarriers screen the electric field across the photoconductive switch and is expected to be on the order of 100 fs [6]. The repetition rate, on the other hand, is determined by the carrier lifetime of semiconductors and is about 100 MHz. As a result, this technique is useful in resolving subpicosecond laser pulses with low repetition rate.

The development and operation of MSM diodes are reviewed in this thesis. The ballistic transport of photocarriers in nanometer-scaled MSM diodes results in the picosecond response and full-recovery times. Diodes made on silicon, in particular, are useful as integrable optical receivers for fiberoptical communications and optoelectronic interfacing [7, 8]. Superconducting MSM diodes were also tested with our cryogenic EO sampling system.

Applied as a reliable pulse generation network, these ultrafast photodetectors made on different semiconductors were then used in the impulse and response measurement of high-speed electronic circuits. The edge illumination technique has
been applied in our earlier work to measure the attenuation and dispersion characteristics of coplanar transmission lines for up to one terahertz [9]. With a cryogenic MSM diode, the response of Josephson junctions to picosecond electrical pulses with different amplitudes was measured in this study. This work is not only a successful demonstration of the impulse and response measurement of ultrafast circuits, but is also the first observation of magnetic single-flux-quantum (SFQ) pulses. Another significance of this observation of SFQ pulses is the application in design verification of SFQ circuits in the time-domain.

The accomplishments of this thesis can be concluded in three categories: the development of a versatile EO sampling system, the development and testing of ultrafast optoelectronic switches, and finally the observation of SFQ pulses. These are listed as follows.

**State-of-the-art electro-optic sampling system**

- A Ti:sapphire all-solid-state laser is used to provide laser pulses with a width of ~60 fs. The wavelength is fully tunable in red-infrared region and UV-green region with frequency doubling.
- The temporal resolution is ~250 fs. With excellent noise reduction schemes, the voltage sensitivity is ~100 μV on both coplanar and microstrip lines. The spatial resolution is < 5 μm with the ability of nodal analysis. The testing is noninvasive.
- The cryogenic electro-optic sampling system with operating temperature between 2 K and room temperature has been developed.
- Switching with an optical fiber enables practical testing on the chip scale. Switching through a finger probe, electro-optic sampling can be performed with minimal propagation and distortion of signals.

**Ultrafast photodetectors and optoelectronic generation of ultrashort pulses**

- Two powerful methods for generating ultrashort electrical pulses were developed: edge illumination of photoconductive switches and nanometer scaled MSM diodes. These methods are applicable to different semiconductor materials and compatible with circuit processing for monolithic integration. Pulses generated by these optoelectronic switches are adjustable in amplitude.
• The postulate of pulse generation by edge illumination is experimentally proven to be the redistribution of electric field and independent of materials. It is demonstrated that edge illumination enables the generation of 540 fs electrical pulses on GaAs and InP. On silicon, 800-fs pulses—the fastest pulses to date on bulk silicon—are shown.

• Based on ballistic transport of photocarriers, ultrafast operation of nanometer scaled MSM diodes is demonstrated on GaAs, InP, as well as on Si. Limited by carrier lifetime, a low-temperature-grown GaAs diode is shown to have a response pulse width of 0.87 ps and a corresponding bandwidth of 510 GHz.

• Deep carrier effect is presented to be a limitation of the high-speed operation of silicon MSM diodes. We demonstrated that this limitation can be eliminated with either silicon-on-insulator substrates or photons with shorter penetration depth. Diodes made on silicon-on-sapphire were measured to have improved temporal performance with red light excitation. With blue light excitation, a silicon diode with 200-nm finger spacing and width was measured to have a response pulse width of 3.7 ps and a resolvable bit rate as high as 60 Gb/s.

• Cryogenic MSM diodes were developed for optoelectronic interfacing superconducting circuits. A Nb-Si-Nb diode operating at 2 K is shown to have a response pulse width of 10 ps.

• These optoelectronic switches are useful in the application of ultrafast photodetectors.

First observation of single-flux-quantum pulses

• The technique of impulse and response measurement with an EO sampling system was applied to characterize superconducting Josephson junctions. Our measurements show that different numbers of SFQ pulses are generated with different impulse amplitudes.

• These measured results are qualitatively in agreement with computer simulations.

• This is for the first time that an SFQ pulse has been measured. This success also opens a way to characterize high-speed superconducting circuits.
References


