A Study of Photoconductive Switching Phenomena and an Application in Ultrafast Electrical Pulse Shaping

By

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For my mother, XU Ruizhen

I wish she had lived to see it
Curriculum Vitae

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Abstract

This dissertation discusses some new developments in research and application of photoconductive semiconductor switches. How the dynamic response to laser illumination uniformity affects high-power GaAs photoconductive switching is studied. In linear switching operation, the electric fields within the switch redistribute themselves immediately after optical illumination. Asymmetric illumination creates a high field region on the nonilluminated side in about 100 ps. Illumination at the cathode compresses the field toward the anode, and illumination at the anode compresses the field toward the cathode. The nonlinear switching behaviors of GaAs photoconductive switches are investigated over a longer time scale. A nonlinear mode of repetitive-current-spikes was first observed in the experiment. The period for the repetitive-current-spikes is about 70-75 ns, or 13-14 MHz in frequency for a 6.9-mm long GaAs sample. The experiments suggest that Gunn oscillation could be a reason of this nonlinear switching mode.

A transmission-line discrete-circuit model was established to simulate the dynamic behavior of laser illumination uniformity in high-power GaAs photoconductive switches. There is a good agreement between the theoretical predictions and the experimental results.

A new conceptual method for sharpening the leading edge of an ultrafast electrical pulse is comprehensively studied in this dissertation. A relativistic moving ionization front induced by a ultrafast optical pulse with tilted-wave-front has been
experimentally proven to shape an incoming electrical pulse. The leading edge of the pulse was sharpened more than 30%. The experiments also confirmed that the degree of sharpening is determined by the speed of the ionization front. A very important result of these experiments is that the output electrical signal frequency, which corresponds to the rise time of electrical pulse leading edge, could be tuned by changing speed of the ionization front. When the speed of the moving ionization front increases by ~33%, the detected pulse rise time decreases ~30%. Theoretical simulations based on transmission line circuit model generally agree with the results of the experiments.

To detect the single-shot ultrafast electrical signal, a novel technique was developed to characterize such electrical pulses. In this method, a streak camera is used to image the temporal evolution of the surface electric field leading edge of the electrical pulse via the electro-optic effect. The streak camera imaging of the electrical pulse has increased the detection resolution to about 2 picoseconds even though the probe pulse had a duration of ~60 ps.
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List of Symbols

$\alpha = \text{absorption constant}$

$\beta(\omega) = \text{propagation constant}$

$\varepsilon_r = \text{dielectric constant of transmission line material}$

$\varepsilon_{\text{eff}} = \text{effective dielectric constant transmission line}$

$\phi_k(\vec{r}) = \text{Bloch function}$

$\mu_e, \mu_h = \text{electron mobility, hole mobility}$

$\sigma = \text{conductivity}$

$\omega_p = \text{plasma frequency}$

$a = \text{lattice constant}$

$c = \text{speed of light}$

$C = \text{capacitance}$

$E = \text{electric field}$

$E_g = \text{bandgap of material}$

$E_y(t) = \text{magnitude of local electric field at time } t$

$E_T = \text{electric field threshold for voltage controlled NDR}$

$G(t) = \text{conductance}$

$h = \text{thickness micro-stripline}$

$\hbar \omega = \text{energy of one photon}$

$I_0 = \text{incident light intensity}$
\[ I_y(t) = \text{light intensity measured at camera pixel (i, j) at a time delay } t \]

\[ I(t), I(t') = \text{current at time } t \text{ and } t' \]

\[ J = \text{current density} \]

\[ J_T = \text{current density threshold for current controlled NDR} \]

\[ k = \text{carrier momentum} \]

\[ K(k_e) = \text{complete elliptic integral of the first kind} \]

\[ l = \text{semiconductor device length} \]

\[ L = \text{inductance of length } dx \]

\[ m_e^*, m_h^* = \text{electron effective mass and hole effective mass} \]

\[ n_0 = \text{carrier density} \]

\[ N_e, N_h = \text{electron density, hole density} \]

\[ r_g = \text{gap resistance of coplanar-strip-lines} \]

\[ r_s = \text{resistance between two lines on coplanar-strip-lines} \]

\[ R = \text{reflectivity} \]

\[ T_y(t) = \text{transmission to 2-D detector array} \]

\[ V(t), V(t') = \text{voltage at time } t \text{ and } t' \]

\[ V_g = \text{voltage across switch gap} \]

\[ V_{\text{dom}} = \text{high-field domain drift velocity} \]

\[ Z = \text{characteristic impedance} \]

\[ W = \text{width of micro-stripline} \]
Chapter One

Introduction

1.1 Overview

Ultrafast optoelectronics has been a rapidly growing field of research in recent years. Ultrafast optical pulses used as sources of power and timing signals provide enormously greater flexibility in the application of high speed optics technology. They have enabled the development an entirely new class of devices and electronic measurements. In this field, the generation and detection of ultrafast electrical pulses has been a very interesting and active theme, around which a large amount of work has been performed. This is the topic addressed by this thesis. The physics and applications of photoconductive semiconductor switches are discussed, and various methods of ultrafast electrical signal generation and detection are illustrated.

The organization of this dissertation begins with a study of the fundamental physics of the photoconductive switching phenomena and some related effects and ends with a comprehensive investigation of the microwave pulse sharpening, a novel application of photoconductive semiconductor switch techniques. In the latter sections of this chapter, a general introduction to ultrafast electrical signal generation is given in terms of photoconductive switching process, and a brief historical review of this field is outlined. Starting in the second chapter, we present both experimental and theoretical analyses of photoconductive switching processes and their applications. The experiments were conducted at the High Power Switching Lab of the Laboratory
for Laser Energetics, University of Rochester. The effect of picosecond laser pulse illumination uniformity on high electric field photoconductive switch has been a long standing open question. We have experimentally investigated the surface electric fields of GaAs photoconductive switches and developed a picture of the dynamic behavior of this effect. The study of nonlinear phenomena in direct bandgap semiconductor switch is of wide interest and currently a hot topic in the today's high-power switch community. In Chapter Two, a relationship between the laser illumination uniformity and the nonlinear phenomena is pointed out. In Chapter Three, we establish a transmission line model using distributed-circuit elements to simulate the photoconductive switching process. There is a good agreement between the theoretical predictions and the experimental results that described in Chapter Two. In Chapter Four, a novel method of ultrafast electrical pulse shaping by using photoconductive switching technique is experimentally demonstrated. A theoretical analysis on this application is given in Chapter Five. Our results indicate this electrical pulse sharpening method has a promising future in the ultra-wide bandwidth microwave pulse generation.

1.2 Concept of photoconductive switching

The definition of photoconductive switching is simple: the conductance between two terminals on a piece of semiconductor material is modulated by the absorption of optical radiation in the gap between the electrodes. But, in order to draw a clear sketch of a photoconductive semiconductor switch, some descriptions of the basic concepts and physics are needed. These concepts include optical absorption,
materials for ultrafast optoelectronics, electrical contacts, and electrical signal transmission. A general mathematical description of a photoconductive switch is given at the end of this section.

1.2.1 Optical absorption

Optical absorption is an important process in photoconductivity, which includes optical absorption, photocarrier transport and recombination. In the point of view of electron band transition, the optical absorption can be roughly divided into two kinds: intrinsic absorption and extrinsic absorption. The intrinsic optical absorption in Fig. 1.1a(1) corresponds to the raising of an electron from the valence band to the conduction band. The extrinsic optical absorption corresponds to the raising of an electron from an imperfection to the conduction band as in Fig. 1.1a(2), or the raising of an electron from the valence band to an imperfection in Fig. 1.1a(3).²

For intrinsic optical absorption, if the minimum of the conduction band is at the same point in k-space as the maximum of the valence band, as shown in Fig. 1.1b, a vertical transition occurs involving only the absorption of a photon. Such a transition is called a direct optical transition. The minimum photon energy for absorption obeys \( \hbar \omega_{\text{min}} = E_{gd} \), where \( E_{gd} \) is the direct bandgap of the material. If the minimum of the conduction band is at a different point in k-space from the maximum of the valence band, as shown in Fig. 1.1c, an optical transition from the top of the valence band to the bottom of the conduction band must involve the absorption of a
Fig. 1.1 Optical transitions in homogeneous semiconductors. (a): (1) Intrinsic absorption, (2) extrinsic absorption, (3) capture and recombination. (b) Intrinsic direct absorption. (c) Intrinsic indirect absorption. (After R. H. Bube, Ref. 2.)
photon and a simultaneous absorption or emission a phonon. In this case
\[ E_{gl} = \hbar \omega_{\text{min}} \pm E_{\text{phonon}}, \]
where \( E_{gl} \) is the indirect bandgap of the material and \( E_{\text{phonon}} \)
is the energy of the phonon involved in the process. Comparing direct bandgap
materials with indirect bandgap materials, in a direct bandgap material (such as GaAs
or CdTe) optical absorption occurs near the surface of a material; for an indirect
bandgap material (such as Si and GaP) light penetrates much deeper into the material.

Both intrinsic and extrinsic semiconductor samples were used in the
experiments which will be discussed in later chapters. Intrinsic Si and GaAs are the
primary semiconductors used in the switches. In the bulk switch experiments,
Cr:GaAs extrinsic material was particularly used, because Cr-doping of GaAs
decreases the carrier lifetime (\(-300 \) ps) as the Cr traps act as recombination centers.\(^3\)

Optical absorption is described quantitatively through the absorption constant
\( \alpha \). In the simplest case that reflection or interference effects are neglected, if light of
intensity \( I_0 \) is incident on a material of thickness \( d \) with absorption constant \( \alpha \), the
intensity of the transmitted light, \( I \), is given by:

\[ I = I_0 e^{-\alpha d}. \]  \hspace{1cm} (1.1)

The constant \( \alpha \) depends on material and optical light wavelength. For an intrinsic
material, \( \alpha \) increases at shorter wavelength in general.

1.2.2 Materials for ultrafast optoelectronics

A wide variety of materials have been used for ultrafast photoconductive
switches. There are number of reports on the use of Si,\(^4\) GaAs,\(^5.6\) Cr:GaAs,\(^7\) GaP,\(^8\)
Diamond, InP, and many other materials in the photoconductive switching or other ultrafast optoelectronics applications. Among them, Si and GaAs (including Cr:GaAs) are the most commonly used photoconductive materials. Since the experiments described in this dissertation were based on these two semiconductors, the following description will concentrate on the Si and GaAs.

The properties of the semiconductors are mainly determined by their energy bands (Fig. 1.2). Si has diamond crystal structure, and GaAs has zincblende crystal structure. Notice that for any semiconductor there is a forbidden energy region in which allowed states can not exist. Energy regions or energy bands are permitted above and below this energy gap. The upper bands are called the conduction bands; the lower bands, the valence bands. The separation between the energy of the lowest conduction band and that of the highest valence band is called the bandgap, $E_k$. This is the most important parameter in the semiconductor physics. The band structure of a semiconductor, that is, the energy-momentum ($E-k$) relationship, is usually obtained by solving the Schrödinger equation of an approximate one-electron problem:

$$\left[ -\frac{\hbar^2}{2m_0} \nabla^2 + V(r) \right] \phi_k(\vec{r}) = E_k \phi_k(\vec{r}),$$  \hspace{1cm} (1.2)

where $V(r)$ is potential energy, $V(r)$ is periodic with the periodicity of lattice constant $a$: $V(r) = V(r + a)$. Therefore, $\phi_k(\vec{r})$, are of the form

$$\phi_k(\vec{r}) = u_k(r)e^{i\vec{k}\cdot\vec{r}} = \text{Bloch function}$$ \hspace{1cm} (1.3)
Fig. 1.2. Energy-band structures of Silicon (a) and GaAs (b), where $E_g$ is the energy bandgap. Plus (+) indicate holes in the valence bands and minus (-) signs indicate electrons in the conduction bands. (After S. M. Sze, Ref. 10.)
where the relation $u_k(r) = u_k(r + a)$ is also satisfied. Eq. 1.2 can be rewritten as,

$$
\left[-\frac{\hbar^2}{2m_0}(\nabla + k)^2 + V(r)\right]u_k(r) = E_k u_k(r).
$$

(1.4)

Applying perturbation theory and expanding $E_k$ in a power series about $k = 0$ ($E_0 = E_{k=0}$), we can obtain an $E_k$ expression:

$$
E_k = E_0 + \frac{\hbar^2 k^2}{2m^*},
$$

(1.5)

where $m^*$ is effective mass. The effective mass is also an important parameter, the carrier mobility is determined by the effective mass. Electrons, light holes and heavy holes have different effective masses.

At room temperature and under normal atmosphere, the values of the bandgap are 1.12 eV for Si, and 1.42 eV for GaAs. These values are for high-purity materials. For highly doped materials the bandgaps become smaller. Experimental results show that the bandgaps of most semiconductors decrease with increasing temperature.\(^{11}\)

In the study of photoconductivity, mobility and resistivity are two major parameters. At low electric field, drift velocity $v_d$ is proportional to the electric field strength $E$, and the proportionality constant is defined as the mobility $\mu$ in cm\(^2\)/V-s, or $v_d = \mu E$. In general, the mobility decreases as the effective mass increases, and the mobility increases when the temperature increases. Thus, for a semiconductor with given impurity concentration, the electron mobilities are larger than the hole mobilities since the effective masses for electrons are lighter than that of holes.
The resistivity $\rho$ is defined as the proportionality constant between the electric field $E$ and the current density $J$, $E = \rho J$. Its reciprocal value is the conductivity, $\sigma = 1/\rho$. For semiconductors with both electrons and holes as carriers, the conductivity is

$$\sigma = \frac{1}{\rho} = q\left(\mu_e N_n + \mu_h N_p\right).$$  \hspace{1cm} (1.6)

When illuminated by laser pulses, the semiconductor conductivity is dominated by the photocarrier densities $N_n$ and $N_p$.

A summary of the key properties of Si and GaAs can be find in Table 1.1. Absorption of a photon by a semiconductor and the subsequent generation of an electron-hole pair is an intrinsically fast process, being limited by the uncertainty principle and the requirement that the frequency spectrum of the optical pulse falls within the absorption bands corresponding to electronic transitions from bound to free states.\textsuperscript{12} Since the width of these bands are a few eV, this time can in principle be as short as $10^{-15}$ s, and consequently does not limit the rise time of the photocurrent. Although the onset of photoconduction is very rapid, the response speed of photoconductive switches are limited by several effects that can influence the subsequent evolution of the current following excitation by a very short optical pulse. One effect is that the mobility increases as the excitation density increases.\textsuperscript{13} For a high-power switch, the switch geometry design is also a critical factor in determining the response speed.
<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>Si</th>
<th>GaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atoms</td>
<td>cm⁻³</td>
<td>5.0×10²²</td>
<td>4.42×10²²</td>
</tr>
<tr>
<td>Breakdown field</td>
<td>V/cm</td>
<td>~3×10⁵</td>
<td>~4×10⁵</td>
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<td>Crystal structure</td>
<td></td>
<td>Diamond</td>
<td>Zincblende</td>
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<tr>
<td>Density</td>
<td>g/cm³</td>
<td>2.328</td>
<td>5.32</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td></td>
<td>11.9</td>
<td>13.1</td>
</tr>
<tr>
<td>Effective mass, Electrons Holes</td>
<td>m⁺/m₀</td>
<td>m⁺=0.98</td>
<td>m⁺=0.067</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m⁺=0.19</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>m⁺ₜₙ=0.16</td>
<td>m⁺ₜₙ=0.082</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m⁺ₜₜ=0.49</td>
<td>m⁺ₜₜ=0.45</td>
</tr>
<tr>
<td>Energy gap at 300 °K</td>
<td>eV</td>
<td>1.12</td>
<td>1.424</td>
</tr>
<tr>
<td>Intrinsic carrier concentration</td>
<td>cm⁻³</td>
<td>1.45×10¹⁰</td>
<td>1.79×10⁶</td>
</tr>
<tr>
<td>Lattice constant</td>
<td>Å</td>
<td>5.43095</td>
<td>5.6533</td>
</tr>
<tr>
<td>Melting point</td>
<td>°C</td>
<td>1415</td>
<td>1238</td>
</tr>
<tr>
<td>Minority carrier lifetime</td>
<td>s</td>
<td>2.5×10⁻³</td>
<td>~10⁻⁸</td>
</tr>
<tr>
<td>Drift mobility</td>
<td>cm²/V·s</td>
<td>1500</td>
<td>8500</td>
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<tr>
<td>Optical-phonon energy</td>
<td>eV</td>
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<td>0.035</td>
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<tr>
<td>Thermal conductivity at 300 °K</td>
<td>W/cm·°C</td>
<td>1.5</td>
<td>0.46</td>
</tr>
<tr>
<td>Thermal diffusivity</td>
<td>cm²/s</td>
<td>0.9</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Table 1.1. Properties of Silicon and GaAs at temperature of 300 K. (After S. M. Sze, Ref. 10.)
High electric field effects in direct bandgap semiconductor are important in the studies of high-power photoconductive switches. If the applied bias voltage is very large, the photo generated carriers will be heated by the electric field and produce a non-equilibrium distribution which can induce a number of effects that strongly influence the dynamic and steady-state properties of photoconductors. On longer time scales, once an equilibrium carrier distribution has been established, high electric fields can produce a substantially lower mobility due to saturation of the drift velocity. In GaAs and other materials having satellite valleys in their conduction bands, the steady-state drift velocity reaches a maximum at a field of approximately 3 kV/cm, and then decreases at higher fields. This negative differential resistivity (NDR) property can lead to electric field instabilities due to the Gunn effect. There are number of references on discussion of NDR and Gunn effect.\textsuperscript{10, 14, 15} A very good review is given by Esther Conwell in ref. [15].

1.2.3 Electrical ohmic contact

In the applications of high power photoconductive switch and ultrafast electrical pulse generation and processing, the quality of electrical contacts is critical. An understanding of the physical situation of electrical current flow under illumination is essential to the switch design.

The general effect of electrical contacts between a metal and a semiconductor under illumination can be described in terms of three classes of behavior. The first is a Blocking, or Schottky contact. A blocking contact is unable to replenish carriers created by photoexcitation when they are drawn out of the material by an applied
electric field. The second is an Ohmic contact. An ohmic contact is able to replenish carriers when they are drawn out of the material by an applied electric field. The contacts contribute negligible electrical resistance, and current varies linearly with applied voltage with a slope equal to the reciprocal of the resistance of the bulk semiconductor. The third is injecting contact. An injecting contact is an ohmic contact at low applied electric fields. At sufficiently high applied electric fields that carriers drawn in from the contact have time to cross the material in the electric field before the material is able to achieve charge neutrality by dielectric relaxation. Since an ohmic contact has a negligible contact resistance relative to the bulk or spreading resistance of the semiconductor, all of the electrical contacts on the semiconductor samples used in these experiments were designed to be ohmic contacts. But in the analyses of high voltage switching experiments, the effect of injecting contacts was considered. AuGe has been found to provide a good ohmic contacts to GaAs. All the bulk and surface switch experiments were based on this kind contacts. In the experiments when both GaAs and Si substrate coplanar-strip-lines were used, the contact metal was AuGe for GaAs, and Gold or Aluminum for Si. In practice, it is almost impossible to make a perfect ohmic contact on intrinsic materials, electrical signal energy loss due to imperfect ohmic contacts has been observed in our experiments.

1.2.4 Electrical signal transmission

Ultrafast electrical pulses require transmission lines which have extremely broadband, low dispersion and loss, and which can be readily interconnected to
optoelectronic and other devices. The frequency spectrum of ultrafast electrical pulses covers a range from dc to many hundreds of gigahertz. High voltage switch applications additionally require transmission lines having high breakdown levels. For these reasons, some transmission lines commonly selected are: coaxial, microstrip, coplanar-strip-lines. Coaxial cables have good bandwidth and low losses and dispersion. Both low power coaxial cables and high power cables were used in our experiments. Besides their wide bandwidth support, coaxial cables also have the advantages of easy connections to electrical measuring instruments and mechanical flexibility. On the other hand, coaxial cables are difficult to interconnect to other structures such as microstrip lines and coplanar-strip-lines. Since microstrip and coplanar transmission lines are naturally compatible with surface photoconductive switches and semiconductor substrate coplanar-strip-lines, they were frequently used in our experiments.

Dispersion is a major problem in transmission lines for ultrafast electrical pulses since it can easily produce a loss of speed due to pulse broadening. Some theoretical analyses of the dispersive broadening of pulses on microstrip and coplanar lines\(^{16,17}\) indicate that strong dispersion exists in these transmission lines when the pulse rise time is tens of picosecond. These calculations were experimentally confirmed.\(^{18}\) There are many factors that can introduce dispersion. The main contributions are from physical dimensions of the device, conductor and dielectric losses, and material resonances.\(^4\) In general, transmission lines designed for high voltage have larger dispersion for ultrafast pulses because of their larger physical
dimensions. It will be seen in Chapter Four that the dispersion of coplanar-strip-lines affects the electrical pulse sharpening.

1.2.5 Photoconductive switch

The optically activated switches to be discussed here have either bulk (vertical) or surface (lateral) semiconductor designs which consist of high-resistance Si or semi-insulating GaAs semiconductor medium, between two electrodes, that provides a large or insulator-like "off" resistance when not illuminated. Ideally, the voltage applied to a semiconductor switch is distributed uniformly between the electrodes across the switch medium. When a laser pulse illuminates the semiconductor between electrodes, the optical energy changes the conductivity of the inter-electrode switch medium in two ways: 1) the optically controlled, linear photoconductive mode in which each input photon produces one electron-hole pair, and 2) the nonlinear or optically initiated conducting mode in which each input photon initiates a nonlinear process within the switch that subsequently generates the required number of electron-hole pairs. In both cases, the time-varying conductance $G(t)$ can be derived from the rate of dissipation of electrical energy $^{12}$

$$G(t)V_g^2 = \int_E \cdot J d^3x$$  \hspace{1cm} (1.7)

where $V_g$ is the voltage across the gap, $E$ is the electric field, $J$ is the current density, and $E \cdot J$ is the power density. The integration over the entire active volume of the photoconductor represents a conversion of electromagnetic energy into mechanical or
thermal energy. When Ohm's law $J = \sigma E$ can be used to relate the current density and electric field, the conductance is

$$G(t) = \frac{1}{V_s^2} \int \sigma |E|^2 d^3x$$  \hspace{1cm} (1.8)

where $\sigma$ is the conductivity. By using Eq. 1.6, Eq. 1.8 can be written:

$$G(t) = \frac{1}{V_s^2} \int \left[ (N_e \mu_e + N_p \mu_p) |E|^2 \right] d^3x$$  \hspace{1cm} (1.9)

where $N_e$, $N_p$ and $\mu_e$, $\mu_p$ are the electron and hole densities and mobilities, respectively. In the linear photoconductive mode, the $N_e$ and $N_p$ have the same value at the beginning of the optical illumination:

$$N_e(t = 0^+) = N_p(t = 0^+) = \frac{(1 - R)\alpha A(x, y)e^{-\epsilon x}}{\hbar \omega}$$  \hspace{1cm} (1.10)

where $R$ is the reflectivity of the photoconductor surface, $\alpha$ is the optical absorption constant, $A(x, y)$ is the incident optical pulse energy per unit area, and $\hbar \omega$ is the energy of one photon. The carrier density for the nonlinear modes, which will be discussed in Chapter Two, could not be explicitly expressed because of lack of a complete understanding. In the linear photoconductive mode, the current carriers generated by the input photons recombine in a time determined by the material recombination time.

1.3 Research, applications and future trends

The research on ultrafast photoconductive phenomena can be roughly in two categories: high-voltage and low-voltage. In the former case, the device is required
to deliver as much power to the load as possible. The switch transfer efficiency should be near 100%. Speed is not the primary concern. In the latter case, the most important characteristic of the device is its high speed, it provides the main incentive for the proliferation of activity in this field. On the other hand, the switching efficiency is not crucial. A brief review of research on both high-voltage and low-voltage applications is given in this section, the most important and active topics are highlighted. At the end of this section, the future of photoconductive phenomena research, which will be more diversified and practical, is described based on the author’s knowledge. Terahertz imaging is likely to become one of future trends in the research of ultrafast optoelectronics.

1.3.1 High power optoelectronic switches

Photoconductors use the bulk properties of materials and consequently can be readily scaled to switch high voltages and currents. This has led to a number of important applications where extremely fast transients are required for switching high voltage instruments. In principal it is possible to have power gain in a photoconductor, i.e., to switch more electrical power than the input optical power.\(^{12}\)

Since the first experiment on photoconductive switch was reported in 1972, a large number of publications are related to the search for better switch geometry designs and suitable photoconductive materials. The design of photoconductors for high power applications requires a substantially different approach than for low powers. Electric field breakdown and thermal dissipation are two effects that greatly influence the choice of materials and geometry. It was found that the size of high
power photoconductors scales with the switching voltage. Therefore, careful attention to geometry and mounting are important to optimize the speed vs power trade-off. The size of a high power picosecond photoconductor is constrained by high field breakdown. This determines the gap size which scales linearly with voltage. Because the photo-conductance is proportional to the optical energy and inversely proportional to the square of the gap length, it follows that the required optical energy increases as the square of the operating voltage.\(^{12}\)

In a study of suitable semiconductors, silicon was found inadequate as a high repetition rate switch because of its long carrier lifetime.\(^3\) On the other hand, GaAs, which was used as a high-power switch,\(^{21}\) has much higher electric field breakdown threshold because of its high dark resistivity and short carrier lifetime. GaAs is also suitable for high repetition rate switching applications.

Thermal effects are also important considerations in high power photoconductors. Thermal runaway can limit the hold-off voltage. This effect occurs when the temperature rise due to the dark current is sufficient to create additional carriers by thermal generation of e-h pairs. Solutions to this problem that have been employed are use of high resistivity materials, low temperatures, and pulsed bias voltages. More detailed discussions of these and related aspects of high power photoconductors are given by the review articles by Mourou \textit{et al}\(^{21}\) and Nunnally and Hammond.\(^{22}\)

Electronic transport in semiconductors under high electric field conditions differs substantially from that at low fields. In silicon, for example the electron
velocity saturates at fields above 3-5 kV/cm at value of approximately $10^7$ cm/s. The behavior of holes is similar. In GaAs and related III-V direct-gap semiconductors the electron velocity reaches a maximum at a few kV/cm and then decreases at higher fields producing a negative differential mobility which can lead to instabilities of the Gunn type. These departures from linear behavior can influence the efficiency and stability of high power photoconductors. The study of these nonlinear phenomena in III-V direct-gap semiconductors, and further characterizing direct-gap photoconductive semiconductor switches has been a focal point of research in recent years.

Since the nonlinear photoconductive switching mode was first reported for GaAs by a research group in the Sandia National Lab in 1987, many papers have been published to study these nonlinear phenomena. It became the most active field in the research of high power photoconductive switches. High gain switching, or lock-on, is one of the most noticeable nonlinear modes. This switching mode distinguishes itself from linear switching mode in that the amount of light required to trigger it is much smaller when compared to triggering the same switch at low fields. It can be conveniently described in three phases: the first phase, “initiation phase”, occurs when a switch under high field stress is activated with a low energy short optical pulse; The second phase is called the “sustaining phase”, in which the switch continues to conduct as long as the circuit maintains this minimum field across the switch. This lock-on field is a few kV/cm depending upon material properties of the GaAs from which the switch is fabricated; The third phase of lock-on is the recovery phase. When the field across the switch drops below the lock-on field, the resistance
of the switch starts to recover. Current filamentation, which has been imaged with an infrared sensitive video camera, was found to be associated with the lock-on effect.\textsuperscript{27}\textsuperscript{,}28\textsuperscript{,}29 The experiments using localized triggering light indicated that the location and number of current filamentations are controllable.\textsuperscript{30} A lock-on switching mode scope trace and its corresponding pictures of current filamentations are shown in Fig. 1.3.

These lightning-like infrared radiation patterns of the current filamentation are similar to streamer formation and electrical breakdown in gases, this suggests a streamer model for ionization growth in a photoconductive power switch.\textsuperscript{31} This model uses iterative drift-diffusion equations, which includes effects of diffusion, drift, impact ionization, photo-ionization, and concentration dependent recombination. It successfully explains some experimental results related to the high gain nonlinear switch modes. In another theoretical analysis, which provides a qualitative overview of the nonlinear photoconductive switching mechanisms, several possible regimes have been identified.\textsuperscript{32} The low electric field regime (\textasciitilde10 kV/cm) could be described as the lock-on regime, with the characteristic oscillations of that phenomena. The medium electric field regime (\textasciitilde10-100 kV/cm) is dominated by the double injection and trap filling mechanisms. The high electric field regime (>100 kV/cm) is characterized by a true avalanche by impact ionization. Comparing these two models, it is noticed that the impact ionization effect quantitatively used in the streamer model seems also to be making contributions in the low electric field regime.

This dissertation explores the nonlinear switching modes in a wider view, the phenomena of persistent-conductivity, or lock-on, avalanching and repetitive-current-
Fig. 1.3 A GaAs photoconductive switch in a nonlinear mode: lock-on switching mode. (a) Scope traces, (b) the corresponding pictures of current filamentations. The experiments using localized triggering light triggering the switch. (After F. J. Zutavern et al., Ref. 30.)
spikes were examined in the experiments. An experimental method of electro-optic imaging the surface electric field\textsuperscript{33} was used to monitor the high-power photoconductive switches in both linear and nonlinear modes. A surface electric field map suggests that the Gunn oscillation could be a reason for the repetitive-current-spikes nonlinear mode. A transmission-line theoretical mode, which uses the distributed-circuit equations, is developed to explain some experimental results in high-power switches.

Many applications of the high-power photoconductive switches have been demonstrated. It is worth listing few: (1) Pockels cell driver. A GaAs switch, which generated electrical pulses of 3 kV, was used to drive a Pockels cell and measured rise and fall times as fast as 40 ps.\textsuperscript{34} (2) Synchronizing single shot streak camera. Mourou and Knox have used a high voltage silicon photoconductive to synchronize a streak camera so that greatly reduced timing jitter.\textsuperscript{35} (3) High-power microwave generation, ultra-wide-band radar, and high-voltage pulsers. Photoconductive switches mounted in a certain configuration and coupled with thin film dielectric material allow these applications implementation to become possible\textsuperscript{36}.

1.3.2 High-frequency electromagnetic wave applications

The ability to generate and measure extremely fast electrical signals by optoelectronic techniques has extremely important applications for the generation and detection of high-frequency electromagnetic waves. The frequency range spanned by optoelectronic devices is very large. For example, an electrical signal having a rise time of 1 ps has a base bandwidth which extends from dc to approximately 300 GHz.
One of the applications is microwave gating. Since photoconductive switches are designed to have large bandwidths, it is possible to produce short bursts of microwaves by the impulse excitation of dc-biased photoconductors which are mounted in tuned circuits or waveguides. This approach has the potential for producing much higher peak powers. The basic concept is to use the tuned circuit or waveguide to act as a frequency selective load so that a particular frequency component of the current pulse is extracted. The experiments results\textsuperscript{37, 38} showed the duration of these pulses to be approximately 50 ps.

Proud and Norman have applied the concept of a frozen-wave generator to picosecond optoelectronics\textsuperscript{39}. They used a sequence of photoconductive switches mounted in tandem in a microstrip-line. The line segments between the switches were independently biased. When the photoconductors were simultaneously illuminated, the frozen wave determined by the bias conditions was then launched down the line. The electrical pulse rise time is determined by the rise time of optical pulse and the frozen-wave generator configuration.

Before the technique of a tilted optical wave front was used to sharpen a microwave electrical pulse,\textsuperscript{40,41} to the author's knowledge, the temporal characteristics of ultrafast electrical pulses generated from photoconductive switches are mainly determined by the temporal profile of triggering optical pulses and the switch geometry. This electrical pulse sharpening technique using a tilted optical wavefront provides a unique method to generate shorter electrical pulses and hence
produce a source of higher frequency electromagnetic waves. The details of this topic will be discussed in Chapter Four and Chapter Five.

The methodology of ultrafast electrical pulse detection is another interesting topic in this thesis. Before this work, single-shot, ultrafast electrical pulse detection was limited by wide bandwidth digitizer and conventional e-o sampling. The streak camera method, which images an electrical pulse e-o modified optical pulse, provides a revolutionary method in the single-shot ultrafast electrical pulse detection, in which the temporal resolution is not limited by the optical pulse width. A temporal resolution as short as 2ps temporal resolution has been achieved in the experiments when the probe optical pulse width was about 60ps.

1.3.3 Future trends

The physics of all nonlinear switching modes in the high-power photoconductive switches is still not fully understood. In order to seek for practical applications of these high gain switching modes, and/or to avoid damaging ohmic contacts and semiconductors, increasing lifetimes of high-power switches, the experimental and theoretical studies on nonlinear switching modes will be continued in the future. As more compact and cheap ultrafast optical sources are developed and become gradually commercially available, the research of practical applications of both high-power and low-power ultrafast electrical signal generations will be an important part of this field.

Recently, terahertz-wave imaging has caught the eyes of the ultrafast science community. The terahertz-wave imaging is a technique based on terahertz time-
domain spectroscopy (THz-TDS). In their pioneering work, Hu and Nuss of Bell Labs\textsuperscript{42} demonstrated an imaging system using THz transients generated by standard optoelectronic methods. THz transients, which are generated from femtosecond optical pulses triggering a piece of GaAs wafer, are focused to a diffraction-limited spot on a sample, and the transmitted THz waveforms are acquired and processed in real time at each point of the sample while the sample is scanned in x and y directions. Since the sample chemical compounds absorption is highly specific frequency-dependent, the transmitted signals could be analyzed and imaged at every pixel of the sample by using THz-TDS method. Fig. 1.4 shows a schematic of their experiment setup and a THz image of a plastic packaged IC chip (Intel 8086). The temporal and spatial resolution of this imaging system are mainly limited by the laser pulse duration and the diffraction limit of the THz beam, respectively. An improved imaging system,\textsuperscript{43} which uses electro-optic, or Pockels, effect converting a far-infrared image into an optical image, was reported recently at Ultrafast Phenomena '96. The THz imaging could find applications in the package inspection and chemical content mapping.

1.4 Conclusion

An overview of the dissertation is outlined in this chapter. Some fundamental concepts of the photoconductive switching including optical absorption, materials for ultrafast optoelectronics, electrical contacts and ultrafast electrical transmission are highlighted. A brief historical review of the photoconductive switches researches and their applications is given, so that the position of this dissertation can be located.
Fig. 1.4 Terahertz imaging and an application by using ultrafast optical source. (a) Schematic of THz imaging system. (b) THz image of a packed semiconductor integrated circuit with plastic packaging. (After B.B. Hu and M. C. Nuss, Ref. 42.)
Reference


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(1991)


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Chapter Two

Surface Electric Fields of GaAs Photoconductive Switches

2.1 Introduction

Optically controlled, high-power photoconductive semiconductor switches have demonstrated their potential in pulsed power applications. Their three main advantages are: (1) the fast rise time, (2) the jitter-free response, and (3) the capability to switch at high voltage. These switches have many applications in picosecond, and even femtosecond, electronics. In the past decade, there have been published a large number of references related to the physics and design of a variety of laser or electron beam induced conductive semiconductor switches. However, in the field of high-power photoconductive switching, there has been very little investigation of the effect of illumination uniformity in linear switching mode at picosecond time scale. We also know that nonlinear switching phenomena, which only happen in direct bandgap semiconductor switches at nanosecond time scale, are not well understood. From the point view of switch lifetime, the electric field enhancements, which are caused by either nonuniform illumination or nonlinear switching phenomena, can result in the erosion of contacts, switch damage and further reduce their life times. In this chapter, we will examine the dynamic behavior of laser illumination uniformity that affects the high-power switch in its linear mode, and we will also study some nonlinear switching modes in nanosecond time scale. We believe this research will benefit GaAs switch designs and applications.
Since the switches that we are interested in operate at very high power, it is advantageous to have a current flow as uniformly as possible to avoid thermal damage. High-power switches tend to show spatial anisotropies. In the experiments of the bulk GaAs switches, the field enhancement around the contacts was reported to be due to the carrier transport and the rapid carrier sweep-out at the ohmic contacts. Zutavern et al have shown that nonuniform illumination of high-power photo-conductive GaAs switches can result in current filaments when operated in the avalanche mode. Those experiments demonstrated that very small amounts of light concentrated at one of the contacts could drive a GaAs switch into avalanche mode. Typically, such nonlinear switching mode needs several nanoseconds to develop.

We first look at the nonuniform illumination of high-power GaAs switches. Our purpose is to see whether the initial distribution of the optical radiation can act as a seed for structures that develop at later times. We operated the switches in the linear mode: that is, all the carriers were generated by the optical pulse. Our aim was to understand how the electromagnetic fields within the switch redistribute themselves immediately after optical illumination. This is a simpler case than the nonlinear dynamics presented by the nonlinear operation modes, which typically start to happen after the completion of linear photoconductive switching when the carriers beginning to recombine. From our experiences, the switches are generally in the linear switching mode in their first 2 ns after the laser illumination. To prevent damage to the GaAs
samples in any later nonlinear regime, these experiments were designed to investigate
the switch dynamics in an intermediate time and field regime.

We also looked into the switching behavior after the first 2 ns at higher field,
where the GaAs switches may operate in nonlinear modes. The nonlinear switching
modes were first found in LLE, University of Rochester, then further studied by a
group in Sandia National Laboratory.7, 8, 9 In these modes, a photoconductive switch
may be triggered by a laser pulse whose energy is much less than that used in an
ordinary manner. The low optical energy requirement has a great deal of attraction in
applications. However, the nonlinear switching could also physically damage the
switches. These reasons drove us to examine our switches in a longer time scale.

In the nonlinear switching mode experiments, we found the nonlinear
phenomena in photoconductive switches can be cataloged approximately into three
different effects: persistent-conductivity, avalanching, and repetitive-current-spikes.
Before these experiments, only the persistent-conductivity and avalanching were seen,
we were the first group who demonstrated the existence of the repetitive-current-
spikes in high-power GaAs photoconductive switches. All these nonlinear modes
were observed in our experiments.

The persistent-conductivity was first found in GaAs switches. When the
applied electric field reaches a certain value, the mode of persistent-conductivity can
be triggered with high energy laser pulses. In this particular mode, the current through
the switch does not decay exponentially with time, instead, the current flows from
tens of nanoseconds to hundred of nanoseconds. The second nonlinear switching
mode is the avalanching. In the mode of avalanching, the switches can be triggered with considerably lower energy than that required for ordinary conductivity. The third mode, the repetitive-current-spikes, was first appeared in a GaAs PIN bulk switch. In this mode, as many as two nonlinear current spikes were observed after the photo-induced current spike with a characteristic periodicity of about 70-75 ns for our 6.9-mm long GaAs bulk switch. This periodicity is consistent with the prediction of Gunn oscillation in the GaAs. This suggests that Gunn oscillations play an important role in the repetitive-current-spikes.

In this chapter, we will first briefly describe the experimental setup that we did our experiments, and the surface electric field detection. Then we discuss the effect of illumination uniformity on linear switching mode on the time scale of the first 2 ns and some phenomena of nonlinear switching on a longer time scale.

2.2 The experimental setup

Two kinds of GaAs switches, surface and bulk switches, were used in our experiments. Because of the simplicity of controlling the pump laser illumination position on the switch surface, the surface switch with active area of 2.5×2.5 mm was used in the study of the effect of illumination uniformity. Both types of switches were used in the research of nonlinear switching modes.

To better understand the physics of the high-power photoconductiveity, it is necessary to monitor a photoconductive switch during the switching process. This could be done by looking at the switched output waveform at the load with a conventional oscilloscope, or sampling oscilloscope. For switching speeds on
picosecond time scale, the bandwidth of the oscilloscope and the bandwidth of the experimental electrical setup limit the temporal resolution. Temporal resolution is greatly improved if the switched output is sampled electro-optically. The detection method, that we used in these experiments, is a two-dimensional electro-optical imaging the switch surface electric field. This technique was first developed by Valdmanis and Mourou,\textsuperscript{10} then improved by Donaldson and Kingsley.\textsuperscript{5,11,12} In this way, we have produced maps of the surface electric field between contacts of photoconductive switches. Such maps were used to determine the electric field configuration at different laser illuminations.

2.2.1 Surface electric field detection

Our experimental setup was a computer controlled system, which was designed to map the switch surface electric field by using the electro-optic effect. The electro-optic effect, or Pockels effect, is used to permit optical detection of the electric field. The electro-optic effect is the phenomenon whereby the birefringence of certain noncentro-symmetric crystals can be altered by an electric field. If a beam of polarized light traverses the crystal, the electrically induced birefringence will rotate this probe beam’s polarization. This rotation can be detected and used to measure the electric field present in the crystal where the probe beam traversed the crystal. The electric field in the crystal is not necessarily spatially nonuniform. If the probe only illuminates a small portion of the crystal, the electric field only in that region will be measured. The probe beam carries an optical analog of the spatial electric field distribution in the crystal. This is the essential operating principle of the two-
dimensional electro-optic probe. Temporal resolution is obtained by using a pulsed laser as the probe beam. To maximize the electro-optic effect, the crystal axis, optical polarization, and the electric field must all be properly aligned.

Fig. 2.1a shows the surface field probe setup to measure the field of a surface type switch, which has metallic contacts in the same plane on the surface of GaAs substrate. Fig. 2.1b show the probe setup to measure the field of a bulk GaAs switch, which has contacts on opposing faces of a rectangular slab of the semiconductor. For either type of switch, probe operation is the same, only the infrared pump geometry is different. When a bias voltage is applied to the metallic contacts, an electric field is established between the contacts. There is a fringing field which extends above the surface of the semiconductor. The electro-optic crystal is placed directly on top of the switch, covering the contact gap completely. The LiNbO$_3$, the e-o crystal we used in the experiments, has 532 nm AR dielectric coating on the top, and 532 nm HR dielectric coating at the bottom that contacts the surface of the semiconductor. The LiNbO$_3$ is immersed in the fringing electric field of the contacts above the surface of the GaAs and its birefringence is altered by this surface field. The 532 nm optical probe is polarized and directed onto the crystal and the switch. The probe beam diameter is greater than the contact gap so that the entire contact gap is illuminated. The beam traverses the crystal and is reflected back onto itself by the dielectric HR coating of the crystal. While the probe beam is in the crystal, the beam's polarization is modulated by the electrically induced crystal birefringence so that the polarization
Fig. 2.1 The probe setup for the Surface Switch (a) and Bulk Switch (b).
of the back-reflected beam contains the information of the local electric field. Any component of the back-reflected beam with polarization different from the incoming beam will be rejected by the polarizer. Each point in the rejected beam has sampled the local birefringence of the corresponding point in the crystal. Thus the intensity of the rejected beam is an optical replica of the electrically induced birefringence pattern in the crystal. The back-reflected beam is imaged onto a two-dimensional diode array, CID camera. The computer records the image from the camera for further analysis. Each pixel in the array image has a corresponding point in the crystal. The intensity at any given point in the cross section of the back-reflected beam will depend on the sine squared of the polarization rotation experienced by that particular beam element as it traverses the crystal. The transmission to the 2-D detector array element \((i,j)\) can be written

\[
T_y(t) = \frac{I_y(t)}{I_y^0} = \sin^2(\alpha_y E_y(t) + \phi_y)
\]  

(2.1)

where \(I_y(t)\) is the light intensity measured at camera pixel \((i,j)\) at a time delay \(t\) between the pump and probe pulse; \(I_y^0\) is the intensity that appears at the camera if 100% of the light is imaged onto the camera without bias voltage applied; \(E_y(t)\) is the magnitude of the local electric field at time \(t\); \(\alpha_y\) is a constant for each point \((i,j)\), which relates the electro-optic coefficient\(^{13}\) to the local electric field and whose value depends on material parameters, optical path length in the crystal, electrode geometry, and frequency of applied optical field; and \(\phi_y\) is a constant optical rotation due to
static birefringence in the e-o crystal and the $\lambda/2$ waveplate. The $\lambda/4$ waveplate chooses where the probe beam sits on the sine-squared transmission (Eq. 2.1) curve with no voltage applied. By measuring the intensity at the camera for several applied voltages with the pump beam blocked, the constants in Eq. 2.1 can be determined and the optical image can be inverted to obtained the local electric field.

2.2.2 The system

Fig. 2.2 is the layout of the entire computer controlled system, which consists of a GaAs photoconductive switch, an LiNbO$_3$ (or LiTaO$_3$) electro-optic crystal, high voltage supply and pulsar, a 512×512 CID camera and an optical delay translation stage. A conventional oscilloscope is attached at the load to measure the switching current. The pump beam is a 1064 nm Nd:YAG laser with pulse width of 100-200 ps, and 30 Hz repetition rate. The probe beam is a frequency doubled pump laser with wavelength of 532 nm. The temporal resolution of this system is better than 140 ps. By changing the length of the optical delay line in the IR arm, we can get snapshot of the electric field at different times relative to the switching event.

One difference between the surface switch and bulk switch setup was how the switch was mounted. For the surface switch, the sample was connected to a 50-Ω microstrip transmission lines. The sample was a 2.5×2.5 mm, 0.5-mm-thick piece of GaAs. Parallel ohmic metal contacts (NiAu:Ge) were coated on the semiconductor surface. The input and output transmission lines consisted of coaxial feeders transitioning to the microstrip on which the surface switch was mounted. For the bulk
Fig. 2.2 The systematic layout of the computer-controlled photoconductive switching and surface electric field detection. The infrared optical pulse is split into two pulses by a 10/90 beamsplitter, the stronger optical pulse functions as pump beam for photoconductive carrier generation, the weaker is converted to 532 nm green for surface electric field mapping. The dc bias for the switch is supplied by the high voltage pulser.
switch, two connectors connected the high voltage input and output transmission lines to the GaAs switch ohmic metal contacts\textsuperscript{14} (NiAu:Ge) by uniformly pressing the connectors. For both cases, the propagation lengths of input and output charging lines were about 2 ns. The switch chamber was filled with high-pressure SF\textsubscript{6} to prevent air breakdown inducing switch breakdown.

The experiment was to study the effect of illumination uniformity of surface switches. A microwave tube was used to pulse bias the switch at 1 kV. This value was chosen to minimize the possibility of electrical damage the switch and to keep argument of the sine function (Eq. 2.1) less \(\pi/2\) for the electric field values generated in the experiment. This removed any ambiguity in determining the electric field due to the periodic nature of the optical transmission function. The half-wave field for the particular electro-optic sampling setup was \(\sim 10\) kV/cm. Larger fields could not be measured. The 1064-nm pump laser pulse had an energy of \(\sim 75\) \(\mu\)J. The IR-beam spot size was measured by scanning a razor across the beam. Eighty percent of the beam energy was contained in a 1.5 mm diameter spot at the switch surface. The illumination was from the top side of the switch. The ratio of the main pulse to the laser prepulse was greater than 1000:1. For the particular set of the data that we used here, the IR beam size was unchanged. An IR viewer was used to position the pump laser beam. A current probe was attached to the load, and the signal was measured with a 450-MHz oscilloscope. The position of the pump laser pulse was determined by maximizing the voltage switched to the load. The IR pulse had a duration of 200 ps, and the green probe had a duration of 140 ps. The electro-optic images were taken
at time delays starting at 200 ps before the peak of the IR pulse to 1800 ps after the peak of the IR pulse. Each acquired image was taken with a single laser pulse, and the image was screened to ensure that the probe pulse energy was within 5% of the accepted mean, otherwise, the image was rejected and a new image was acquired. All these techniques used in the investigation of linear switching mode were also used in the study of nonlinear switching modes.

2.3 Effect of illumination uniformity on linear switching mode

Images of the electric field profile within the active area of the switch bounded by the edges of the GaAs surface switch contact pads are shown in Fig. 2.3. These images were taken at different optical illuminations: uniform illumination, illumination at cathode and illumination at anode. The raw images were inverted using the inverse of Eq. 2.1. Fourier transforms were applied to the data to removed the interference fringes due to probe laser spatial coherence, and a four-point sliding smoothing function was used to eliminate most of noise caused by speckles.\textsuperscript{15}

The image of top left of Fig. 2.3a represents the uniform field before activation. The rest of images of Fig. 2.3a shows the surface electric field at different time after the peak of IR pulse triggering. In uniformly illuminated case, the field is initially compressed toward the anode as the central region becomes conductive. By the time the IR laser pulse has finished (400 ps), the field has completely collapsed as uniform dark images, and the entire volume of the switch becomes conducting. The images of Fig. 2.3b and Fig 2.3c corresponds to moving IR laser beam, as determined with an IR viewer, to the edge of the cathode and anode respectively. In the later two
(a) Uniform illumination

(b) Illumination at the cathode
Fig. 2.3 The images of the electric field profile within the active area of the GaAs surface switch at three different cases of optical light illumination: (a) Uniform illumination; (b) illumination at cathode; and (c) illumination at anode. It is found that the uniform illumination can result in the complete collapse of the electric field followed by a slow recovery. Illuminating at the cathode compresses the field toward the anode and illuminating at the anode compresses the field toward the cathode.
cases, the electric fields are pushed away from the illuminated contact and compressed toward the opposite contact. At 400 ps, when most of the light has already interacted with the switch, the field has collapsed at the illuminated contact but has significantly increased at the opposite contact.

To illustrate this point, the two-dimensional images were reduced to one dimension by averaging the electric field across the width of the switch. This was done to facilitate comparison with the computer simulations, which will be described in detail in the Chapter Three, and to provide a more quantitative examination of the results. As shown in Fig. 2.3, the fields are approximately uniform across the 2.5-mm width of the switch in this operating regime. Therefore averaging over the width of the switch does not result in the loss of significant amounts of information. Fig. 2.4 and Fig. 2.5 show the averaged electric fields of the images in the Fig. 2.3a and Fig. 2.3c, respectively. Fig. 2.4 presents the electric field collapsing completely in ~400 ps after the laser triggering for uniform illumination. The field slowly recovers with the recombination time of the optically generated carriers. At later times, ~1200 ps, a field enhancement starts to develop at the anode. Compared to the uniform case, the asymmetric illumination at the ground contact (Fig. 2.5) creates a high field region on the nonilluminated sides. A similar graph, not shown, results when the cathode is illuminated. To demonstrate the effect of field strong compression in the case of asymmetric illumination, several bulk GaAs switch samples were tested. The Fig. 2.6, which shows the electric fields for all three cases at 200 ps after the IR triggering in another experiment, is one of our typical data to demonstrate such field compression.
Fig. 2.4 The plot of the average electric field across the switch width in the case of the uniform illumination (Fig. 2.3a). The field completely collapses at the time about 400 ps after the optical light triggering.
Fig. 2.5 The plot of the average electric field across the switch width in the case of the illumination the anode contact (Fig. 2.3c). It shows a rapid compression of the electric field followed by period of stagnation.
Fig. 2.6 The electric fields distribution across the switch width for all three cases at 200 ps after the infrared laser pulse triggering. The uniform illumination makes electric field collapse completely. The asymmetric illuminations induce significant electric field enhancement and compression.
in asymmetric illuminations. The uniform illumination makes electric field collapse completely. Illuminating at the cathode compresses the field toward the anode and illuminating at the anode compresses the field toward the cathode.

2.4 Study of nonlinear switching modes

The nonlinear switching modes are photoconductive switching phenomena in which the electrons and holes can also be generated non-optically. They only happened in some direct bandgap semiconductors, such as GaAs and InP, in a high electric field. Since bulk configuration GaAs switches are capable of holding higher voltage, an essential requirement to run the switch in the nonlinear modes, some of these experiments on nonlinear switching were conducted in bulk switches. Intrinsic GaAs switches and PIN doping GaAs switches were studied. Several nonlinear phenomena have been found in GaAs and InP photoconductive switches in other groups.\textsuperscript{1} Three different kinds of nonlinear modes were observed in our experiments, persistent-conductivity, avalanching and repetitive-current-spikes. Comparing with the linear switching mode, the durations of these nonlinear phenomena are much longer. They were from several nanoseconds to more than a hundred nanoseconds in our experiments.

We used the same experimental setup as shown in Fig. 2.2, both the surface switch and bulk GaAs switch were used. In order to operate the switch in different nonlinear modes, we carefully chose the switch bias voltage, the intensity of IR triggering light, IR illumination position and switch bias voltage polarization. Since the nonlinear switching is long time-scale phenomena, it is very convenient to use an
analog oscilloscope monitoring the switching process. The oscilloscope traces enable us to examine the temporal characteristics of the switching. In the following section, we will show some of the scope traces. They present a novel picture of nonlinear switching mode. To investigate the physics behind these nonlinear phenomena, looking only at the scope traces is inadequate. The surface electric field in nonlinear mode is analyzed.

2.4.1 Three nonlinear switching modes

In order to analyze the nonlinear mode, we first briefly describe the behavior of a linear switching mode, as shown the Fig. 2.7. When the switch is illuminated by a laser triggering pulse with appropriate energy, a large amount of photoconductive carriers can be generated to induce the semiconductor conduct. The electric field inside the switch suddenly collapses to a minimum in tens of picoseconds to few hundred picoseconds, depending on the size of the switch, the laser pulse width, and the intensity of the light. After the optical pulse vanishes, the electric field starts to recover due to carrier recombination. This band-to-band recombination time is determined only by the carrier lifetime. For GaAs bulk switches, this entire switching process takes few nanoseconds because of normal carrier recombination. In the linear switching mode, the conducting carriers are generated only from the triggering optical light, the electric field will be completely recovered when all the photoconductive carriers have recombined.

Nonlinear modes generate the conductive carriers in a different way. When we biased the GaAs PIN bulk switch with -1.3 kV at its N side, and triggered the switch
Fig. 2.7 The scope trace of a typical linear switching process of a GaAs switch. All the conductive carriers are generated by the triggering optical light. The electric field inside the switch collapses to minimum in tens of picoseconds to few hundred picoseconds, depending on the size of the switch, laser pulse width, and intensity of the light. After the optical pulse vanishes, the electric field starts to recover due to carrier band-to-band recombination.
Fig. 2.8 The scope trace of the persistent-conductivity nonlinear switching mode. The bias voltage was -1.3 kV on the N side, the IR pulse energy was ~171 μJ. When the applied electric field reaches a certain value, the mode of persistent-conductivity can be triggered with high energy laser pulses. After few nanoseconds of optical triggering, the current does not decay to zero, but keeps a constant for few tens of nanoseconds to hundreds of nanoseconds.
by IR pulse energy of about 171 $\mu$J, the first nonlinear mode, persistent-conductivity, was observed on the scope screen, as shown in Fig. 2.8. In this mode, the current through the switch does not decay exponentially with time, instead, the current flows for tens of nanoseconds to hundreds of nanoseconds. After few nanoseconds of optical triggering, the majority of photoconductive carriers have vanished from normal recombination process, the carriers contributing to the persistent-conductivity may come from trap filling effect, which says that carriers can flow freely after the traps are filled.$^{16}$

As we increased the applied voltage to -8.0 kV on the N side of the switch, and decreased the IR pulse energy to as low as 42 $\mu$J, we noticed the second nonlinear mode, the photoconductive avalanching switching, as it is shown in Fig. 2.9. There are two conductive spikes in this mode, one is the laser induced photoconductive switching spike, which has a sharp falling edge due to short laser pulse induced electric field collapse. The other is a wider and irregular current spike, which may occur 10 to 20 nanoseconds after the IR trigger pulse peak. The appearance time of the second current spike is unpredictable. Whenever it starts, the electric field collapses uncontrollably to minimum like an avalanching process. The recovery time of the avalanching switching mode is much longer than that of the linear mode. It is interesting that the field does not recover back to its original bias value, it locks on a plateau and stays at this plateau as long as the bias voltage applied. This is the so called lock-on. Compared with other switching modes, it is found that the avalanching mode can be triggered with considerably lower energy than that required for ordinary
Fig. 2.9 The scope trace of avalanching switching mode of a bulk GaAs switch. The bias voltage was -8.0 kV on the N side, and IR pulse energy was 42 μJ. The avalanching mode has a wider and irregular current spike. When it starts, the electric field collapses uncontrollably to a minimum. Its recovery process is slow, and current does not go back to zero but is locked on a plateau.
conductivity. Several explanations for the avalanching or lock-on have been proposed. Current filamentation is one of the possibilities.

The third nonlinear mode we observed in the experiments is repetitive-current-spikes. When the high voltage on the N side biased switch was -4.5 to -5.5 kV, two current spikes in sequence were seen, as shown in Fig. 2.10. The repetitive-current-spikes are different from the persistent-conductivity and avalanching switching in: (1) There is no lock-on. Each current spike recovers completely after a switching event; (2) The occurrence time is periodic. The first nonlinear current spike appears a few tens of nanoseconds after the IR peak, then after another almost the same time period, the second nonlinear current spike is observed; (3) The peak current intensity is weaker than the avalanching mode, but stronger than the persistent-conductivity; (4) It is very sensitive on both bias voltage and IR illumination pulse energy. When the switch N side bias voltage was -4.5 kV, it needed ~140 μJ of optical energy to trigger the repetitive-current-spikes (Fig. 2.10a), but it only required a pulse of energy ~68 μJ to trigger when the high voltage increased to -5.5 kV (Fig. 2.10b). If voltage and IR light energy was not optimally selected, we could not find such repetitive-current-spikes.

Fig. 2.11 is a plot of the appearance time of the repetitive-current-spikes vs. the IR optical pulse energy. The appearance time was measured from the oscilloscope traces. The test sample was 6.9 mm long GaAs PIN bulk switch, bias voltage was -4.5 kV. A repetitive period of about 70 ns was observed. This periodicity is consistent with the theory of Gunn oscillation in the GaAs, which describes a phenomenon of
Fig. 2.10 The scope trace of repetitive-current-spikes. (a) The bias voltage was -4.5 kV on N side, and IR optical energy was ~140 μJ. (b) The bias voltage was -5.5 kV on N side, and IR optical energy was ~68 μJ.
Fig. 2.11 The repetitive-current-spikes appearance time measured from the scope traces for a GaAs PIN bulk switch. The bias voltage was -4.5 kV applied on the N side of the sample. A period is about 70 ns, which suggests Gunn oscillations play a role in this nonlinear switching mode.
high field domains formation and propagation periodically in a high electric field biased, direct-bandgap, semiconductor. This suggests that Gunn oscillation play an important rule in the repetitive-current-spikes. In next section, we will find the surface electric field pattern, which was obtained when the switching was occurring in the repetitive-current-spikes mode.

2.4.2 Surface electric field of the switch in nonlinear modes

The Fig. 2.12 is a 3D plot of an e-o image of the surface switch electric field at 5.5 ns after the optical triggering. The switch had an active area of 2.5×2.5 mm, the external field was along the length of the switch, the anode was on the left. This field map was taken when the switch was biased at -4 kV and operated in the repetitive-current-spikes nonlinear mode. Because almost all of the photoconductive carriers have recombined by 5.5 ns after the optical pulse, the high electric field region between the edge of the flat plateau and the low-field valley in Fig. 2.12 must come from some non-optically generated electron-hole carriers. We tried to map several low-field valleys at different times to find the speed of the low-field valley, but unfortunately the laser pulse-to-pulse energy variation prevented us from obtaining precise value of the speed. However, the period of repetitive-current-spikes of the 6.9-mm bulk switch suggest that the nonlinear valley moving velocity have an order of

\[ V = \frac{0.69 \text{cm}}{70 \text{ns}} = 1 \times 10^7 \text{cm/s}, \]

that implies Gunn oscillation might be the reason of the repetitive-current-spikes of the high-power GaAs photoconductive switch.
Fig. 2.12 A 3D plot of an electric field of surface switch at 5.5 ns after the optical triggering when the switch was biased at -4.0 kV and operated in the repetitive-current-spikes nonlinear mode. The active area is 2.5×2.5 mm, and the external field is along the length of the switch, the anode was on the left of the plot
2.4.3 Negative differential resistivity and Gunn oscillation

In 1963, Gunn discovered that coherent microwave output was generated when a high dc electric field was applied to a sample of direct bandgap semiconductor like GaAs. The frequency of oscillation was approximately equal to the reciprocal of the carrier transit time across the length of the sample. Later, Gunn oscillation was proved to be consistent with theory of negative differential resistance (NDR). The mechanism responsible for the NDR is a field-induced transfer of conduction-band electrons from a low-energy, high-mobility valley to higher-energy, low-mobility satellite valleys.\(^\text{17}\)

In the NDR regime, the current density falls with increasing electric field. Bulk negative differential resistivity devices can be classified into two groups: voltage controlled NDR (N-shaped) and current controlled NDR (S-shaped). The current density versus electric field characteristics for these two groups are shown in Fig. 2.13. In voltage controlled NDR, the electric field can be multivalued, and in current controlled NDR, the current can be multivalued. For both kinds of NDR, there exists a threshold value \(E_T\) for the voltage controlled, or \(J_T\) for the current controlled. A semiconductor exhibiting bulk NDR is inherently unstable, because a random fluctuation of the carrier density at any point in the semiconductor produces a momentary space charge that grows exponentially in time. By the NDR theory,\(^\text{18}\) the voltage controlled NDR can cause an electric field discontinuity and the current controlled NDR can cause a current filamentation. In practice, the sample may exhibit the hybrid characteristics of combining the N- and S- shaped features,\(^\text{18}\) which agrees
Fig. 2.13 The current density versus electric field characteristics for N-shaped voltage controlled NDR (a) and S-shaped current controlled NDR (b). $E_T$ is the field threshold for the voltage controlled NDR, and $J_T$ is the current density threshold for the current controlled NDR. (After S. M. Sze, Ref. 18)
Fig. 2.14 Energy-band structures of GaAs at room temperature. The lower conduction valley is at \( k=0 \) (\( \Gamma \)); the high valley is along the \( <111> \) axis (L). (After S. M. Sze, Ref. 18)
with our experimental electric field maps in some cases.

The transferred electron effect due to intervalley carrier transport is the most likely mechanism to cause NDR in GaAs. The transfer of conduction electrons from a high-mobility, low-energy valley to low-mobility, high-energy in momentary space causes the velocity to decrease. Fig. 2.14 gives the one dimensional dispersion relationship of GaAs. The conduction band consists of three sub-bands: the $\Gamma$ valley has a minimum located at $k=0$, 1.424 eV higher than the top of valence band; the L valley is located along the $<111>$ direction, and is 0.31 eV higher than the $\Gamma$ point; the X valley is located along the $<100>$ direction, and is 0.36 eV higher than the $\Gamma$ point. Under the influence of a high electric field, the electrons are accelerated and scattered from $\Gamma$ valley into the L valley because L valley has lower energy.

The formation of a strong space-charge instability has a criterion: the product of carrier density $n_0$ and the length $l$ must be greater than $10^{12} \text{ cm}^2$, or $n_0l > 10^{12} \text{ cm}^2$. The perturbation will increase to form dipole layers that propagate toward the anode with the high-field domain drift velocity $V_{\text{dom}}$, which is about the order of $10^7 \text{ cm/s}$ for the GaAs at an electric field of $-15 \text{ kV/cm}$. The exact drift speed and drift mobility depend on the instantaneous electron distribution between all of the conduction valleys. Outside the high-field domain, the carrier concentration and fields are constant values given by $n=n_0$ and $E=E_T$, respectively. When the dipole layer domain reaches the electrode, the current in the external circuit increases and the electric fields in the sample readjust themselves, creating a new domain. Then a
current oscillation is formed, that is called Gunn oscillation. The oscillation frequency is determined by $\frac{V_{dom}}{l}$. The repetitive-current-spikes in Fig. 2.10 and the electric field map Fig. 2.12 can be considered to be the results from voltage controlled NDR induced Gunn oscillation. The high-field Gunn domain is the leading edge of the valley of the Fig. 2.12. The field recovery from carrier recombination forms the other side of the valley.

2.5 Conclusion

The dynamic behavior of high-power GaAs photoconductive switching dependence on the laser illumination uniformity has been studied. A computer controlled experimental setup was designed to map the switch surface electric field by using the electro-optic effect. This has made it possible for us to monitor the switch electric fields and their evolution. In linear switching operation, which typically happens in the first 2 nanoseconds after laser pulse triggering in our experiments, the electric fields within the switch are found to redistribute themselves immediately after optical illumination. The patterns of the redistribution are correlated with the type of the laser illumination. Uniform illumination makes electric field collapse completely and the field recovery process is slow. A field enhancement starts to develop at the anode about 1.4 ns after the optical triggering. Asymmetric illumination creates a high field region on the nonilluminated side in about 100 ps. Compared with the case of uniform illumination, the field enhancement effect in asymmetric illumination is
faster and stronger. Illumination at the cathode compresses the field toward the anode, and illumination at the anode compresses the field toward the cathode.

The nonlinear switching behaviors of GaAs photoconductive switches are investigated in a longer time scale. Three different kinds of nonlinear modes have been seen: persistent-conductivity, avalanching, and repetitive-current-spikes. Repetitive-current-spikes were first observed in this experiment. The period for the repetitive-current-spikes is about 70-75 ns, or 13-14 MHz in frequency for a 6.9-mm long GaAs sample. The conditions for repetitive-current-spikes mode operation are stringent in terms of bias voltage and optical light energy. A surface electric field map, which was imaged when the switch was in the mode of repetitive-current-spikes, shows an electric field valley between the electrodes at 5.5 ns after laser triggering. Both the oscilloscope measured period and the electro-optic image mapped electric field suggest the Gunn oscillation could be a reason of the repetitive-current-spikes nonlinear switching mode.

The optical light non-uniform distribution on the surface of a GaAs switch, that can come from asymmetric illumination or from laser inherent beam pointing instability, can significantly influence the switch surface electric field structures. These initial field structures could act as seeds for further nonlinear switching modes.
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Chapter Three

Simulating Photoconductive Switches In A Microwave

Transmission Line

3.1 Introduction

In the first few nanoseconds after closing, the behavior of photoconductive semiconductor switches is determined by the properties of the semiconductor, the pump laser, and the switch device geometry. The experimental results of these phenomena have been discussed in Chapter Two. The generation of optical-induced electron-hole pairs in GaAs is well understood. A model to simulate GaAs photoconductive switch is developed in this chapter to explain these experimental results. The model is derived from theory of microwave devices. The solid-state photoconductive switch can be treated as a one dimensional distributed-circuit, which describes the switching behaviors within the context of a microwave transmission line. The electromagnetic dynamics are described by the distributed-circuit equations. A significant advantage of the transmission-line model is the smooth integration of external circuits into the model. The boundary and initial conditions of the electromagnetic field within the switch are determined by the external circuits. The distributed-circuit theory and the Maxwell’s field equations formation are equivalent, but the distributed circuit model provides easier correspondence with experimentally measured quantities. When a transmission line is analyzed using the time varying one-dimensional Maxwell’s field equations, it requires that the transmission line be
spatially symmetric, and only the electric field with TEM mode could be considered. All the high order modes are ignored. Otherwise, a full-wave analysis requires the fully three-dimensional Maxwell's curl equations. The distributed-circuit method, which involves only one space variable and the time variable, is capable of analyzing a transmission line in various conditions.

There are a number of references related to the asymmetric illumination\(^2,3\) and the electric field enhancement in photoconductive switches\(^4\). In a silicon-based, coplanar transmission line in the Ref. 1, the detected 5% asymmetry of the electric field in the silicon resulted from the asymmetric illumination of a 70 fs laser pulse, and method of full-wave analysis was used to discuss the experimental results.\(^3\) In the experiments on the bulk GaAs switches,\(^4\) the field enhancement around the contacts due the carrier transport, such as the rapid carrier sweep-out at the ohmic contacts, was reported.

In this chapter, we look at asymmetric illumination over the entire length of a GaAs switch. Symmetric and asymmetric illumination conditions are compared to the experimental results described in Chapter Two. We found significant field compression and enhancement in the regions of low carrier density by using the transmission-line discrete-circuit model. This was confirmed experimentally on the electro-optic imaging system in Chapter Two. The field enhancement may be due to the transient, optical ionization front compressing the electric field. Our model was chosen to simulate a surface GaAs switch in this calculation, by simply changing circuit configurations and some input parameters, this model can also be used to study
bulk switches, semiconductor substrate coplanar-strip-lines, or any other similar designs which use any kind of semiconductors.

3.2 Transmission line modeling photoconductive switch

The solid-state photoconductive switch, either the bulk switch or surface switch, can be treated as a distributed circuit.\textsuperscript{5} The source transmission line, semiconductor, and load transmission line each are modeled as the discrete elements: resistors, capacitors and inductors. The distributed circuit, as shown in Fig. 3.1, models a surface switch. Each circuit element is given by the local physical properties. The capacitances and the inductances are distributed along the length of the line and depend only on the device geometry. The characteristic impedance $Z$, the capacitance $C$, and the inductance $L$ of length $dx$ for the microstrip with $\frac{W}{h} > 1$ are calculated as\textsuperscript{6}

$$Z = \frac{120\pi}{\sqrt{\varepsilon_{eff}}} \left( \frac{W}{h} + 1.393 + 0.667 \ln\left(\frac{W}{h} + 1.44\right) \right)$$

(ohm) \hspace{1cm} (3.1)

$$C = \varepsilon_{eff} W \frac{dx}{h}$$

(farad) \hspace{1cm} (3.2)

$$L = Z^2 C$$

(henry) \hspace{1cm} (3.3)

and

$$\varepsilon_{eff} = \frac{1}{2} \left( \varepsilon_r + 1 \right) + \frac{\varepsilon_r - 1}{2 \left( 1 + 12 \frac{h}{W} \right)^{1/2}}.$$ \hspace{1cm} (3.4)
Fig. 3.1 The distributed-circuit model uses resistors, capacitors, and inductors to simulate the electromagnetic transients within the photoconductive switch. The entire transmission line is divided into 513 nodes, where the switch has 256 discrete nodes. Each circuit element is given by the local physical properties. The resistor $R_t$ is calculated from the local optical intensity, absorption depth, recombination lifetime, and carrier transport.
where $\varepsilon_r$ is the dielectric constant of the transmission line material. $W$ is the width of the micro- stripline, and $h$ is the thickness of the line. The resistivity of a part of the line corresponding to the switch is a function of position and time given by

$$\rho_i = \frac{1}{e \left[ N_e(x,t)\mu_e(E) + N_p(x,t)\mu_p(E) \right]}$$  \hspace{1cm} (3.5)$$

where the carrier densities $N_e$ and $N_p$ are calculated from the local optical intensity, absorption depth, recombination lifetime, and carrier transport.\(^7\) The electron mobility $\mu_e$ and the hole mobility $\mu_p$ are determined by the local electric field.\(^8\) By using the average mobility at a given field, we assume that all the femtosecond dynamics of intervalley transfer happens instantaneously and can be otherwise ignored on these time scales. The electron and hole drift velocities (given by $\mu_e E$ and $\mu_p E$, respectively) were used to calculate the carrier transport into and out each circuit cell. Carrier diffusion was ignored because of the large drift component and it also made the model mathematical unstable.\(^9\) Each absorbed photon was assumed to create an electron-hole pair. Since the optical radiation was sub-bandgap, carrier generation was assumed to proceed by neutralizing or ionizing an EL2 defect site with each site being continuously available through recycling via the inverse process.\(^10\) We checked this assumption by measuring the absorption coefficient of the sample as a function of incident intensity up to a level used in our experiments. The absorption coefficient was constant at 1.4 cm\(^{-1}\) ±10\%, indicating no nonlinear processes such as 2-photon absorption or saturation were taking place.\(^11\) The recombination was
assumed to be simple electron-hole recombination with a recombination life time of 500 ps. Within the switch portion of the transmission line, there is a capacitance in parallel with each element corresponding to the nonconducting state of the semiconductor. Each section of the switch is treated as a dielectric slab and the capacitance is

\[ C_s = \varepsilon_r \frac{Wl}{dx}, \tag{3.6} \]

where \( \varepsilon_r \) is the dielectric constant of the semiconductor, \( l \) is the thickness of the semiconductor, and \( dx \) is the length of each section. Since the semiconductor sits above the transmission line substrate, \( l \) is distinct from \( h \). We can thus describe the switching process in terms of electric field, current, and impedance.

To derive the circuit equations for each cell, we first linearize the expressions for the current in the inductors and capacitors. \( V(t) \) is the voltage across the inductor at time \( t \); \( V(t') \) is the voltage at the previous time \( t' \). We integrate by Simpson's rule to get

\[
\frac{1}{2} [V(t) + V(t')] = L_i \frac{dI}{dt} \\
\approx \frac{L_i}{\Delta t} [I(t) - I(t')],
\tag{3.7}
\]

where \( L_i \) is the inductance. Similarly, the current of the capacitor can be written as

\[ I(t) \approx C \frac{V(t) - V(t')}{\Delta t} \tag{3.8} \]
where $C$ is the capacitance of a section of line of length $\Delta x$. In the simulation, we divided the entire line, including the source, the switch, and the load into 513 nodes, where the switch has 256 discrete nodes. The even nodes and odd nodes each generate a different set of equations. When node number $k$ is even, the circuit equation for a node within the switch is

$$\frac{1}{R_{k/2}}(V_{k+1} - V_k) + \frac{C_s}{\Delta t}[V_{k+1} - V_k - (V_{k+1} - V_k')] + \frac{C_e}{\Delta t}(-V_k + V_k') + \frac{C_i}{\Delta t}[(V_{k-1} - V_k) - (V_{k-1} - V_k')]$$

$$= I' + \frac{\Delta t}{2L_s} [(V_k - V_{k-1}) + (V_k' - V_{k-1}')]$$

where $I$ and $I'$ indicate the current at $t$ and $t'$, respectively (the same convention is used for the voltage). If the node number $k$ is odd, we have

$$\frac{1}{R_{k+1/2}}(V_{k-1} - V_k) + \frac{C_s}{\Delta t}[(V_{k-1} - V_k) - (V_k' - V_k')] + \frac{C_e}{\Delta t}[(V_{k+1} - V_k) - (V_{k+1} - V_k')]$$

$$= I_k' + \frac{\Delta t}{2L_s} [(V_k - V_{k+1}) + (V_k' - V_{k+1}')]$$

These equations are derived by applying Kirchhoff's law of currents continuity at each node. The current through the inductor must equal the sum of the capacitor currents and the variable resistor current. The equations of the source line and the load line are similar but lack the variable resistance and the parallel capacitance terms. In order we can program the computer to calculate, the above two equations are rewritten in the form of a temporal sequence,
\[
\left( \frac{2C_s}{\Delta t} + \frac{C_s}{\Delta t} \frac{\Delta t}{2L_s} + \frac{1}{R_{\Delta t}} \right) V_k - \left( \frac{C_s}{\Delta t} + \frac{1}{R_{\Delta t}} \right) V_{k+1} - \left( \frac{C_s}{\Delta t} + \frac{\Delta t}{2L_s} \right) V_{k-1}
\]
\[
= -I_k' + \left( \frac{2C_s}{\Delta t} + \frac{C_s}{\Delta t} + \frac{\Delta t}{2L_s} \right) V_k' - \left( \frac{C_s}{\Delta t} - \frac{\Delta t}{R_{\Delta t}} \right) V_{k+1}' - \left( \frac{C_s}{\Delta t} - \frac{\Delta t}{2L_s} \right) V_{k-1}'
\]

and

\[
\left( \frac{2C_s}{\Delta t} + \frac{\Delta t}{2L_s} + \frac{1}{R_{\Delta t}} \frac{1}{\Delta t} \right) V_k - \left( \frac{C_s}{\Delta t} + \frac{\Delta t}{2L_s} \right) V_{k+1} - \left( \frac{C_s}{\Delta t} + \frac{1}{R_{\Delta t}} \frac{1}{\Delta t} \right) V_{k-1}
\]
\[
= -I_k' + \left( \frac{2C_s}{\Delta t} - \frac{\Delta t}{2L_s} \right) V_k' - \left( \frac{C_s}{\Delta t} - \frac{\Delta t}{2L_s} \right) V_{k+1}' - \left( \frac{C_s}{\Delta t} - \frac{\Delta t}{R_{\Delta t}} \right) V_{k-1}'
\]

If we write the equations in matrix format, the matrix is tridiagonal. The tridiagonal matrix makes it possible to solve the circuit equations numerically in a fast and efficient manner using standard algorithms.\(^\text{12}\)

3.3 Simulation results

The model parameters were chosen to match switches we tested. The switch used in simulation was a 2.5×2.5 mm, 0.5 mm thick GaAs surface switch. For calculating the illumination on the switch, we selected a 1064 nm optical pulse with both temporal and spatial Gaussian profile, the pulse temporal FWHM was 180 ps and the spatial FWHM was 1.5 mm. Although 75 \(\mu\)J was incident on the switch, when reflection losses and the small absorption coefficient of GaAs at 1.06 \(\mu\)m were taken into account, only 4.42 \(\mu\)J were actually absorbed into the switch. The charging resistor was chosen to be 300 \(\Omega\), which is the on-state resistance of the microwave hard tube to charge the line. The load was 50 \(\Omega\). A radiative recombination time of
500 ps was used. This is faster than is normally assigned to radiative recombination in semi-insulating GaAs\(^7\) and probably indicates that some other process was involved. The ohmic metal contacts were assumed in the modeling.

The three different illumination conditions were simulated, determined by different positions of the center of the spatial Gaussian profile. The corresponding electron density profile is as shown in Fig. 3.2. The simulated result of the symmetric illumination, as shown in Fig. 3.3, shows the most effective switching process. The field collapses rapidly in center of the switch with the field at the contacts remaining higher or being slightly enhanced. Comparing the experimental results of Fig. 2.4, there is a quantitative agreement between the simulation and the experiments.

In another simulation which focused on physical phenomena at a longer time scale, high-field effects were considered. As shown in Fig. 3.4, a very high value of the field in the simulation of center illumination case can be traced to the formation of a space charge domain associated with a Gunn domain near each of the contacts. These Gunn domains can be clearly seen by looking at the carrier distribution that give rise to them. At 1050 ps, the electron still bears the imprint of the Gaussian laser pulse that generated them. At 1300 ps, kinks develop in the electron distribution near the contacts. These kinks, or high-field domains, become larger and more asymmetric at later times because of injection at the contact and the different mobilities of electrons and holes. Thus the detailed dynamics of these high-field regions depends on how the charge moves in and out of the contacts. Such disturbances of electron distribution can be seeds for the formation of high-field Gunn domains, which
Fig. 3.2 The three different illumination conditions were simulated, determined by different positions of the center of the spatial Gaussian profile. The plots are three corresponded electron density profiles.
Fig. 3.3 Uniform illumination results in a simple collapse of the electric field followed by a slow recovery.
Fig. 3.4 The distribution of free electrons within the switch follows the Gaussian profile of the generating optical pulse until about 1 ns after illumination. Shortly after 1 ns, space-charge domains form and propagate. These domains are not symmetric with respect to the applied field.
propagate to the anode. Experimentally, the repetitive current spikes in Fig. 2.10 and the electric field map, Fig. 2.12, can be considered to be the results from these severe electron distribution turbulences, which induce high-field Gunn domain and Gunn oscillation. The high-field Gunn domain is the leading edge of the valley of Fig. 2.12.

Asymmetric illumination was obtained by moving the centroid of the Gaussian to the edge of either the anode or cathode contact. Thus, half of the light intensity was lost. Asymmetric illumination caused the electric field to be significantly compressed and enhanced toward the region of low carrier density. Fig. 3.5 is a field distribution for the case of a beam placed near the anode or ground contact for comparison with Fig. 2.5. Initially, the optically induced carriers push the field down on the illuminated side. Correspondingly the electric field rises at the opposite end of the switch. Since the field compression occurs on a subnanosecond time scale, carrier transport does not play a role in the field compression. The field compression is caused by moving of the laser-induced ionization front in the semiconductor. After ~300 ps of illumination (Fig. 3.5), it can be seen that the amplitude of the electric field increases over the bias on the non-illuminated side of the switch. The effect of the light induced charge carriers is only to change the value of the series resistance of each cell. Charge exchange between cells is negligible. The electromagnetic wave propagation is dominated by the capacitive and inductive elements. At this point, a stagnant field distribution develops, with a low field at the anode and a high field at the cathode. Comparing to the experimental results of Fig. 2.5, agreement between the simulation and experiments is qualitatively quite good.
Fig. 3.5 The model predicts the temporal development of the electric field within the switch for the anode illumination case. This is be compared to the experimental measurements in Fig. 2.5.
The switching efficiency depends on the position of the illumination spot. Fig. 3.6 shows the simulated voltage at the load for three different cases of illumination. Asymmetric illumination significantly reduced the switching efficiency as well as increasing the field rise time. The optically generated plasma near the contact effectively decreased the electrode spacing. However, due to field compression, much of the electrical energy remained stored in the switch, thus, resulting in reducing the switching efficiency. This agrees with the experimental results. The small spikes shown in Fig. 3.6 at the beginning of the pulse for the asymmetrically illuminated cases came from dielectric current induced by the discharge of the capacitors $C_s$.

3.4 Conclusion

There is an agreement between the theoretical predictions and the experimental results. The transmission-line model shows rapid field compression away from the illumination contact followed by a period of stagnation; the experiments on the electro-optic imaging sampling in Chapter Two confirmed the simulations. By using the resistors, capacitors, and inductors, the transmission line gives a new way to analyze the photoconductive semiconductor switches. The method of discrete-circuit equations analyzing photoconductive phenomena is powerful, a GaAs substrate coplanar-strip-line will be studied by using a different discrete-circuit will be presented in Chapter Five. Based on our findings with the e-o sampling system, we have endeavored to model the general behavior of photoconductive switches mounted in transmission-line geometry. Those interested in these switches are primarily interested in the voltage that delivered to the load. Fig. 3.6 shows
Fig. 3.6 The simulated switching efficiency depends on the position of the illumination spot. The off-center illumination produces less efficient pulses, but it induces shorter pulses. The shape of the curves reveals that different type of switching mechanisms are involved.
voltage delivered to the load for the three illumination schemes. Not only does off-center illumination produce less efficient pulses, but it produces shorter pulses. The shape of the curves reveals that different type of switching mechanisms are involved. The rise time for the center illumination case is determined by the FWHM of the laser pulse. The faster rise times of the off-center illumination pulses are due to the discharge of the switch-gap capacitance. This capacitance is very small, and the associated RC time constant is much shorter than the RC time constant in the transmission line. A smaller capacitance also means that less energy is stored, resulting in less efficient switching. Our results are also consistent with the full-wave analysis by E. Sano and T. Shibata\textsuperscript{3} on silicon-on-sapphire substrate coplanar transmission line. The important result for the high-power switching community is that, roughly 1 ns after illumination, the electric field within the switch can develop hot spots. The position and magnitude of the hot spots can be influenced by the optical illumination, but they occur even with relatively uniform illumination. These hot spots have the capability of seeding some of the long-term nonlinearities seen in high-power GaAs photoconductive switches.
References


Chapter Four

Microwave Pulse Sharpening - Experiments

4.1 Introduction

High-frequency microwave sources have many applications. In general, it is convenient to obtain high-frequency microwave sources by direct generation, such as high-frequency microwave cavity oscillation or short rise time electrical pulse creation. In certain circumstance, it is very difficult to directly generate high-frequency microwave signal, so novel techniques of microwave signal frequency up-shift are needed. As early as middle of the 1970s, intense relativistic, electron-beams were used to reflect and frequency up-shift counterstream electromagnetic waves. A signal with frequency of 9.3 GHz was scattered from the electron beam to produce an output electromagnetic wave at frequency of 38 GHz. Almost at the same time period, an alternative method for microwave frequency upshifting was developed, that the electron-beam did not directly scatter electromagnetic waves, but instead, the electron-beam ionized a stationary gas to generate relativistic moving ionization wave front. The oncoming electromagnetic wave was reflected by the ionization front to accomplish a frequency shift. In recent years, several groups have demonstrated that optically induced, ionization-fronts frequency up-shift microwave radiation. C. Joshi et al applied 30 mJ, 15 ns fourth harmonic generation of Nd:YAG laser pulse (266 nm) to a cylindrical microwave resonant cavity, which filled with azulene (C_{10}H_{8}) vapor. The incident 33.3 GHz RF wave frequency was up-shifted 5% by shortening
the resonant cavity length with moving ionization front. The efficiency was only 10% in this case.\textsuperscript{4} With a similar setup, another group at UCLA using shorter UV laser pulses with pulse width of 50 ps and energy of 50 mJ displayed a better result, a 35 GHz radiation was shifted to more than 116 GHz in an microwave gas resonator.\textsuperscript{5,6}

Although gaseous plasmas, used as the reflection media, can change electromagnetic signal to higher frequency in an microwave resonator, the gaseous plasma technique has a disadvantage that it needs extremely high-energy lasers or electron beam accelerators. The high energy is required because the gas must be sufficiently ionized to ensure that the plasma frequency \( \omega_p = \left( \frac{4\pi n e^2}{m_e^*} \right)^{1/2} \) would greater than the impinging microwave frequency. From the point of view of optical energy requirement, on the other hand, a semiconductor is considered to be an ideal candidate for high density electric carriers generation with moderate laser energy.

Since the photoconductive semiconductor switch was invented, ultrafast optical pulses have been used to generate short electrical pulses. But in the high-power electrical pulse applications, large electrode gaps, which are required to hold off the high voltage, limit the ultrafast rise time of the electrical pulses generation. In order to produce high voltage electrical pulses with ultrafast rise time, the techniques of electrical pulse shaping are needed.

The pulsed microwave signal frequency can be modified by different pulse shaping methods. T. Motet \textit{et al} reported that ultrafast laser pulses are capable of sharpening electrical pulses.\textsuperscript{7} In their experiments, a 150-fs optical pulse was used to
illuminate a pulse-biased low-temperature-grown GaAs substrate coplanar-strip-lines. The optical pulse shorted the circuit creating a sharp edge notch, which had a rise time of 1.4 ps, on the bias electrical pulse. In this electrical pulse method, the rise time of the notch was determined by the rise time of the optical pulse as well as the geometry of coplanar-strip-lines.

This portion of the thesis will explore a novel electrical pulse shaping method to shorten an electrical pulse. In this method, an optical pulse with tilted-wave-front is used to produce relativistic ionization front in a semiconductor substrate coplanar-strip-lines. This moving ionization front can reflect and shorten an oncoming microwave pulse rise time.8,9

In the past two years, a number of experiments had been done at LLE studying the techniques of optical pulse shortening electrical pulse rise time in a semiconductor substrate microwave transmission lines. The design philosophy for the experiments was based on the photoconductive switching generating an electrical pulse and then reflection and shortening this electrical pulse rise time by a wave-front-tilted optical pulse. Two different methods were used to generate such electrical pulses. In the first method, electrical pulses were generated on a GaAs substrate coplanar-strip-lines, which had a 20-μm gap in the one of the lines. In the second method, a separate microwave stripline pulse generator was used to generate the electrical pulses. Based on these two methods, two series of experiments were conducted.

Utilizing an optical pulse with a tilted-wave-front is the key to these experiments and distinguishes it from the gaseous plasma experiments and the
experiments by T. Motet et al on coplanar-strip-lines. Those experiments could not tune the output microwave signal frequency. In this tilted optical wave front method, an optical transmission grating created a wave front that has a linear time delay across the beam in the transverse direction, as shown in Fig. 4.1. When this modified laser pulse illuminates the semiconductor, photocarriers are instantaneously created as the photons reach the GaAs surface, the boundary of the photo-induced ionization can move relativistically along the surface. By rotating the optical grating, the speed of the ionization front is controlled; hence, the frequency of the electromagnetic radiation can be tuned. In the following sections of this chapter, two series of experiments, i.e., a series of experiments of electrical pulse generation and shortening on the same DC biased, 20-μm gaped coplanar-strip-lines and a series of experiments of microstripline electrical pulse generation and coplanar-strip-lines pulse shortening, will be discussed including details of the design, operation and detection. The experimental results from both series of experiments will be analyzed in Chapter Five.

![Diagram](image)

Fig. 4.1 Tilted optical wave front generates relativistic moving ionization front, which reflects and sharpening oncoming electrical pulse leading edge.
4.2 The laser system

Visible laser light with energy of few microjoules can efficiently generate the photo carriers with densities of $10^{14}$-$10^{16}$ cm$^{-3}$ to the depth of 5 μm in the GaAs. Because of their high electron densities and high resistivities, GaAs and Si are ideal substrates for the coplanar-strip-lines used for frequency upconversion of microwave pulses. For practical applications, two requirements must be met in order to obtain higher reflection coefficients and better electrical pulse shortening effects. First, the optically generated plasma density should be high enough so that the plasma frequency $\omega_p$ is higher than the signal frequency. With moderate laser energy, it is possible to generate high-density, electron-hole plasma in semiconductors like GaAs or Si. Second, the plasma density profile should have a sharp transition to minimize the impinging electromagnetic wave penetrating in the plasma. For this purpose, Stimulated Raman Scattering (SRS) was used to shape laser pulses to have sharp rise time. Compared to the gaseous plasma techniques, it is obvious that the semiconductor methods use considerable less laser energy.$^{10}$

All the experiments were conducted on the Nd:YAG laser system in the Lab 184 of the LLE. The system consists of a 100 MHz mode-locked Nd:YAG optical oscillator, cavity-dumped regenerative amplifier, up to 5-Hz power amplifier and SRS cell for optical pulse shaping, as it is shown in the Fig. 4.2. After a piece of optical fiber, Pockels Cell pulse selector, and pulse injecting wedge, the mode-locked pulses with ~100 ps pulsewidth and energy less a nanojoule were seeded to the regenerative
Fig. 4.2 The experiment system schematic
amplifier, which could operate at the repetition rate from single-shot to kilohertz. The amplified pulses were extracted with a cavity dumper. Typically, pulses from the regen have more than 150 μJ optical energy and almost the same pulsewidth as the oscillator pulses. For the electrical pulse shortening experiments, 150 μJ was a sufficient amount of energy. But, the infrared pulses with a rise time longer than 90 ps made it almost impossible to observe a clear electrical pulse shortening effect. An electrical pulse generated by a 90-ps long optical pulse needs at least 9-cm long semiconductor substrate transmission line to conduct, hence this also requires the tilted wavefront optical pulse with larger than 9-cm beam size to interact the electrical pulse. Such requirements were impractical in the experiments. A shorter visible optical pulse is needed.

In order to obtain a visible optical pulse with a fast rise time and appropriate optical energy, the pulses from the regen were amplified to more than 15 mJ in a double-pass Nd:YAG power amplifier. Then, a 1.5-cm-thick KD*P frequency doubler converted the infrared to 532 nm green light and shortened the optical pulse to ~70 ps FWHM, or about 60 ps rise time. The green pulse had energy of ~5 mJ. To further steepen the optical pulse rise time, Stimulated Raman Scattering (SRS) is efficient method for picosecond optical pulses.11 When the green pulse was focused into an ethanol SRS cell, the stokes SRS optical pulse wavelength was shifted to 630 nm. This red optical pulse had a rise time of ~25 ps (Fig. 4.3) and energy of ~500 μJ. In order to avoid the second SRS in which the 630 nm light can be stimulated Raman
Fig. 4.3 The streak camera measured the Stimulated Raman Scattering Sharpening the pulse rise time. A 61 ps rise time frequency doubled Nd:YAG pulse was stimulated Raman scattered by liquid ethanol, and generated 630 nm red, coherent optical pulse with rise time of 26 ps. The SRS pulse rise time was sharper than its fall time, that agrees the SRS theory.
scattered, the lens before the cell had a long focal length of 2 m, so that a large scattering volume could be achieved. Two prisms separated the green light from the red SRS beam path. This optical pulse rise time sharpening by using SHG and SRS made it possible to implement microwave pulse shortening experiments.

4.3. Experiments - I

To demonstrate the optical induced electrical pulse shortening effect in a semiconductor microwave device, two steps are needed in the experiments. First, it is necessary to generate a microwave signal, which should have a rise time short enough so that the signal entire leading edge could be reflected by the optically-generated ionization front. Second, the optical pulses shaped by SRS must have an appropriate spatial tilted-wave-front. This gives the speed of ionization front matched to speed of the electrical signal propagation speed in the coplanar-strip-lines. For this purpose, two series of experiments have been implemented. The differences between the two series are the manner of microwave signal generation and method of detection.

4.3.1 Electrical pulse generation on coplanar-strip-lines

In the first series of experiments, the microwave step signal was generated and sharpened in the same coplanar-strip-lines, and detected by a wide bandwidth digitizer. The GaAs substrate coplanar-strip-lines had a 20-μm gap in one of the lines, as shown in Fig. 4.4. There were two synchronized SRS optical pulses with a wavelength of 630 nm. The first pulse, with a normal wave front, illuminated the GaAs in the 20-μm gap, which was DC biased. This produced two identical traveling step signals: one propagated directly to the digitizer scope, the other propagated to the
Fig. 4.4 Electrical step pulse generation and sharpening detected by a wide bandwidth digitizer. With accurate timing delay control, a 630 nm SRS optical pulse illuminates the 20-μm gap of the GaAs substrate coplanar-strip-lines, two identical traveling electrical step pulses are generated and propagate in opposite directions along the transmission lines. The other SRS optical pulse diffracted from a transmission grating having tilted wavefront generates relativistic ionization front, which meets and shortens the oncoming step electrical pulse. A wide bandwidth digitizer like Tektronix SCD5000 or Tektronix 7250 compares the step signals before and after the pulse shortening.
opposite direction where it was reflected with a shortened pulse rise time. After a precise time delay, determined by a mechanical delay line, the second, or the main laser pulse illuminated the GaAs between the metal lines creating a short circuit. The main laser pulse passed through an optical transmission grating (50,000 grooves per inch, from Holoteck Ltd.), obtained a wave front tilted to an appropriate angle to the surface of the transmission line. As this tilted wavefront optical pulse reached the GaAs substrate, a relativistic moving ionization front was generated and collided with the incoming step signal. The degree of frequency upconversion due to the moving ionization front shortening the electrical pulse effect depended on the electron-hole plasma density, the plasma boundary profile, and the most importantly, the speed of ionization boundary. In this configuration, the ionization front has no momentum in the direction of the microwave signal propagation, so it is different from the case of a moving mirror. The photo-generated carriers have no longitudinal component of momentum.

If the grating is adjusted so that the angle between the wave front and transmission lines less than 68°, the speed of the ionization front will be higher than the speed of the signal in the GaAs transmission line, which is about 0.38c (c is the speed of light in free space). In this case, a highly dispersive shock wave will be formed, and most of the electromagnetic wave energy will be converted to heat in the plasma. When the speed of the moving ionization front is too slow, ionization front looks stationary so that no electrical pulse shortening effect will occur. Therefore, the
speed of the ionization front was always kept approximately the same as the speed of microwave signal in transmission line.

The transmission line was a gold-coated coplanar-strip-lines with a spacing of 44 \textmu m. The line impedance was 50 \Omega, and the loss was approximately 0.3 dB/cm at 10 GHz.\textsuperscript{8} A fast digitizer such as SCD5000 or Tektronix 7250 was connected to the transmission line to compare rise times of the step signals before and after the reflection. To avoid DC bias at the digitizer, a capacitive microwave isolator (Mini-Circuits, Model ZFSC-2.10G) with bandwidth of 10 GHz was placed between the DC power supply and the scope. A 50 ohm resistor was connected to the other end of the line to eliminate any unwanted reflections.

4.3.2 Wide bandwidth digitizer detection

The detection of fast electrical signals with high signal-to-noise ratio is very critical to the experiments. The detection of single-shot, picosecond-rise-time electrical signals can not be accomplished with conventional methods. For high repetition rate fast electrical signal detection, either a fast sampling oscilloscope or conventional electro-optic sampling is possible. But for a single-shot event, a sampling oscilloscope can not efficiently sample an entire pulse shape, and the ordinary electro-optic sampling introduces too much noise which overwhelms any weak signals. In order to measure the signals with acceptable resolution and signal-to-noise ratio, two signal detection methods were used in the experiments. The first method directly measured the reflected pulse rise time by using a wide bandwidth digitizer; The second method, which will be discussed later, approached the
measurement in another way. The coplanar-strip-lines surface electric fields were imaged in a streak camera by using electro-optic modulation.

Connecting the coplanar-strip-lines to a wide bandwidth digitizer was the most convenient detection method. The Tektronix SCD5000 with 4.5 GHz bandwidth and Tektronix 7250 Digitizing Oscilloscope with 6 GHz bandwidth were used to trace the electrical pulse shape. To insure all the electrical connections extremely clean was a essential in the experiments. The semi-flex coaxial cables (from QMI Inc.) with 18 GHz bandwidth were used to connect each electronic device. Two SMA connectors, which support more than 24 GHz bandwidth signals, were mounted at the ends of the coplanar-strip-lines. Silver paint functioned as solder to connect the SMA connectors and the gold coated lines. A SMA to N converter linked the coaxial cable to the digitizer. All the experimental data on the 20-μm one-line-gaped coplanar-strip-lines were taken by the digitizers. The computer retrieved the scope traces for further analysis. Because of bandwidth limit of the digitizer, Tek SCD5000 could not resolve any pulses with rise time faster than 80 ps, Tek 7250 could not resolve any signal faster than 60 ps rise time pulses.

4.3.3 Analysis

The Fig. 4.5 shows a scope trace (Tektronix SCD5000 digitizer) of the generated microwave electrical pulse before and after the reflection. The incident angle of the SRS beam to the grating was about 71 degrees, or the speed of the ionization front was about 0.4c, and the coplanar-strip-lines were biased at 1.5 V. The electrical pulse rise time sharpening ratio, which is the ratio of two rise times of a step
Fig. 4.5 The Tektronix SCD5000 digitizer scope trace shows an electrical pulse rise time sharpening and strong reflection. The reflected pulse rise time was measured sharpening ratio of 0.63, and the reflection coefficient of 0.9. The coplanar-strip-lines was biased at 1.5 V, the incident angle of the SRS beam to the grating was about 71 degrees, or the speed of the ionization front was about 0.4c. The SCD5000 was at Time Window = 5 ns and Display = $\times$ 2.
Fig. 4.6 The SCD5000 scope trace shows a reflected electrical signal was sharpened. (a) The scope trace of a single electrical pulse generation-sharpening event. (b) Both pulses were normalized and plotted together to show the leading edge was faster after the sharpening. The rise time was measured 127 ps before the reflection and 88 ps after the reflection. The pulse sharpening ratio was 0.69 and reflection coefficient was 0.6. The grating and the scope settings were the same as the data in Fig. 4.5.
pulse before and after reflection, was measured 0.63. The reflection coefficient was 0.9, the largest measured reflection coefficient. In the same experiment, Fig. 4.6a shows another scope trace of electrical pulse generation-sharpening event, amplitude was measured in volts. The reflected step signal rise time was 88 ps comparison to 127 ps before the reflection. The sharpening ratio was 0.69 and reflection coefficient was 0.6. After normalizing the two steps from Fig. 4.6a, the sharpening effect that changed the signal shape, is clearly shown in Fig. 4.6b.

The sharpening ratio and reflection coefficient depend on the SRS pulse intensity and pulse rise time. The higher the light intensity, the higher reflection coefficient can be measured; the sharper the optical pulse rising edge, the better the electrical pulse sharpening ratio can be achieved. In practice, a SRS pulse could not be obtained with both high light intensity and good pulse shape. When the green pulse intensity in the SRS cell was too high, the generated 630 nm pulse experienced the second SRS process, which removed energy from the peak of 630 nm pulse. The output 630 nm pulse became a double-peak pulse, which could be measured on a streak camera. So to obtain optimum electrical pulse sharpening ratio and reflection coefficient, the energy of 532 nm green optical pulse was kept just below the second SRS threshold.

The main advantage of the digitizer direct measurement was that it could be made in real-time, clearly monitoring the step pulse shape before and after the reflection with extremely high signal-to-noise ratio. By adjusting the timing between the optical pump pulse and probe pulse, the reflection of electrical pulse by the
relativistic moving ionization front was under precise control. The disadvantage of the digitizer detection is that the measurement accuracy was limited by the bandwidth of the instrument.

4.4. Experiments - II

To increase the temporal resolution, a second series of experiments was performed by using the streak camera to image a replica of the sharpened electrical pulse leading edge. In this series, microwave step signals were generated in a separate microstrip line, which could produce electrical pulses with amplitudes of more than 100 volts. Such high voltage microwave signals transmitted to the coplanar-strip-lines for reflection and rise time sharpening, as shown in Fig. 4.7. This setup was designed with use of a single-shot pump-probe method. The reflected pulse was probed by using electro-optical effect and imaged in a streak camera. In order to increase detected signal-to-noise ratio, it was necessary to obtain high-level electro-optic modulations of the reflected pulse electric field on the optical probe pulse in LiTaO₃, the e-o crystal used in the experiments. If the crystal was properly coated and set in correct orientation, the e-o modulation was determined by the strength of the electric field and the penetration depth of the surface electric field in the crystal. Since the crystal was on top of the coplanar-strip-lines, the effective surface electric field penetration in the crystal was only the order of distance between two strip lines, which was 44 μm. A strong surface electric field was inevitably necessary for a detectable e-o modulation. The micro stripline with a Si photoconductive surface switch built in the middle of the line was an ideal generator of such large amplitude
Fig. 4.7 Layout of the streak camera imaging system. Three optical pulses with appropriate timing delay are in the same window. An electrical pulse (~100 volts) transmitting to the semiconductor substrate coplanar-strip-lines is then reflected and sharpened by the ionization front induced by a 630 nm optical pulse with tilted wavefront. A green probe pulse e-o samples the reflected electrical pulse.
ultrafast electrical pulses. Because the bandwidth of digitizers in today’s technology prevents us from detecting electrical pulses with rise time less than 50 ps, using the electro-optic effect to produce a replica of the electrical signal in a streak camera was a savvy choice.

After reto-reflection from the e-o crystal, the probe pulse carried the information of the surface electric field in the terms of the temporal varying polarization retardation. By using optical polarization compensator and polarizer combination to compensate the static retardation, caused by the crystal’s inherent birefringence, the desired information in the form of polarization could be expressed in terms of the temporal light intensity.

There are a number of pump-probe methods based on the electro-optic effect to temporally characterize electrical signal. The technique of streak camera imaging the e-o modified optical signal distinguishes itself from other methods, because the detection resolution is not determined by the probe pulsewidth but by the streak camera temporal resolution. The previous streak camera e-o sampling experiment sampled 85 MHz repetition rate picosecond electrical pulse train by using CW HeNe probe light. The principal disadvantage of this system was the small number of photons in the sampling window. The method described here improves the previous method by using a pulsed source to increase the light intensity. Compared to conventional e-o sampling techniques, the advantage of streak camera method is that it can be used in single-shot mode since it samples each waveform in its entirety. In this series of experiments, the optical setup for electrical pulse rise time sharpening
arm, which produced the tilted optical wave front, remained the same as the first series of experiments.

4.4.1 The setup

The optical and electronic setup of the second series of experiments was more complicated, and required an accurate systematically timing control. The generation of electrical pulses was from a separated micro-stripline which has a photoconductive semiconductor surface switch in the middle. The reflected electrical pulses were characterized with an optical detection scheme. The streak camera recorded the probe pulse light intensities which were modulated by electro-optic effect. The entire system must be under the computer control, as shown in Fig. 4.8. When a RUN command was sent to the EG&G 1461 Optical Multi-channel Analyzer (OMA) from the computer via GPIB, an OMA main trigger TTL met one of the kilohertz TTL pulses from the RF Divider in the Coincidence Box, then, a new TTL timing signal generated from the Coincidence Box made the Stanford Research Systems DG535 Digital Delay/Pulse Generator task the timing laser firing and other electronic controls. Finally, the computer read the Hamamatsu Streak Camera image and the Optical Shutter (Uniblitz Model D122) status data from the OMA. The computer was programmed in the Labview (National Instruments, version 3.0.1). Fig. 4.8 describes the details of this single-shot pump-probe experiments.

4.4.2 Streak camera imaging

A streak camera has an electron image converting tube, that via the photo-
Fig. 4.8 The system schematic. This entire data acquisition system was designed for computer (PC) control.
electric effect, converts an optical pulse to an electron pulse replica. This electron pulse is then be rapidly deflected, or streaked by a time-varying electric field. An electron pulse streaked in this manner has its time axis mapped along the direction of deflection onto a phosphor screen, where it can be recorded. Different streak cameras have different spectral response range, the streak camera that used in the experiments, Hamamatsu Model C1587, has a S-20 cathode which can respond in a spectral range of 200 - 850 nm. The probe pulse wavelength of 532 nm is right in this range.

The basic principal of the streak camera imaging method is: an optical pulse, which is electro-optically modulated by transient electrical pulse, is imaged on streak camera screen. The optical pulse shape carries the information of the electrical pulse. To obtain a clear e-o modulation, in the experiments, a total 3 optical pulses were imaged in the same streak camera screen, as shown in Fig. 4.9. The 532 nm optical pulse was first split into 2 pulses: a reference pulse and a probe pulse. The reference pulse went directly to the streak camera without any modulations. The probe pulse, on the other hand, traveled through on an e-o crystal, where the probe pulse was modulated by the field transient electrical pulse. Then, the probe pulse was further split into 2 pulses by a polarizing beamsplitter. Because of the e-o modulation, these 2 signal pulses had orthogonal polarizations, hence different pulse shapes. With appropriate time delay between each other, all 3 optical pulses were imaged in one streak camera screen. The timing jitters between the 3 optical pulses were measured by the distance variations between peaks of these pulses on the streak camera. The timing jitters were calculated ~ 0.5ps RMS at the streak time 2. Compare the temporal
Fig. 4.9 The principal of the streak camera imaging by using electro-optical effect. (a) A probe optical pulse is split into 2 pulses: reference pulse and probe pulse. The probe pulse is deformed by an e-o modulator. A polarizer beamsplitter further splits into 2 pulses with compensated modulation. All 3 pulses are imaged in the streak camera. (b) By decoupling the e-o modulation, the electrical pulse shape can be retrieved.
Fig. 4.10 (a) A typical averaged streak camera image of frequency doubled Nd:YAG oscillator pulse. (b) Three typical 50-shot average probe pulses, the first two pulses that were e-o modulated were signal pulses, the third pulse, that did not probe the surface electric field, was the reference pulse.
resolution of 2.6ps at the same streak camera setting, these timing jitters could be safely ignored.

Fig. 4.10a is a typical averaged streak camera image of the frequency doubled Nd:YAG pulse. Fig. 4.10b is a typical 50-shot average of the probe pulses, the first two signal pulses were e-o modulated, the third pulse, that did not probe the surface electric field, was the reference pulse. After the optical compensator and the polarizer, the e-o modulation of the two signals should be of equal of amplitude with opposite sign. The difference between the signals gives the relative e-o modulation, the absolute e-o modulation is given by:

$$\text{e-o modulation depth} = \frac{\text{Signal1} - \text{Signal2}}{\text{Reference}}$$

(4.1)

4.4.3 Timing electric and optical pulses

For all the experiments, the timing between the electrical pulse and the optical pulses was very important. Improper timing could cause the experiments to fail. In order to obtain reliable experimental results, two steps of timing control must be achieved: (1) The SRS optical pulse tilted wavefront must meet the electrical pulse leading edge so that electrical pulse rise time sharpening would occur; (2) The green optical probe pulse must meet the reflected electrical pulse leading edge so that the reflected electrical pulse leading edge could be detected. In practice, the second step was performed first.

The timing between green optical probe pulse and the reflected electrical pulse leading edge was very critical for the streak camera imaging experiments. In principle,
Fig. 4.11 Timing the probe pulse and SRS pulse by using photoconductive switching effect. (a) A DC bias can be switched by a weak green probe pulse, and a strong SRS pulse. (b) The scope trace of DC bias was switched by two pulses. By precisely timing the SRS pulse time delay, the two switching events could be synchronized.
this is equivalent to timing a SRS pulse generated electrical signal with the probe green pulse. A technique of photoconductive switching a low DC bias voltage by both probe pulse and SRS pulse was used to achieve an accurate timing. The Tek SCD5000 digitizer monitored the switching signals, as shown in Fig. 4.11a. The scope trace (Fig. 4.11b) was the probe pulse measured \(~130\) ps ahead of the SRS pulse. By precisely positing the SRS beam time delay stage, the two step pulses was overlapped. Hence, the probe green pulse leading edge met the SRS pulse generated electrical signal leading edge, i.e., probe green pulse should meet the SRS pulse reflected electrical pulse. The timing resolution of this method was limited by the temporal resolution of the Tek SCD5000, to approximately 67 ps.

Timing between the SRS optical pulse tilted wavefront with the generated electrical pulse was performed first by a rough timing adjustment and then by a fine timing adjustment. As the same as above, a method of photoconductive switching was used in the timing control. In the rough timing adjustment, as shown in Fig. 4.12a, an ordinary digital oscilloscope (HP54510A, 250 MHz bandwidth, 1Gs/s) was used to monitor the interaction of SRS optical pulse with the generated electrical pulse. To protect the scope, the electrical pulse had low voltage. Fig. 4.12b shows such scope traces. When the SRS pulse arrived too early, the electrical pulse could not propagate through the transmission line to the scope. When the SRS pulse arrived too late, the entire electrical pulse could be observed on the scope. If the SRS pulse met the leading edge of the electrical pulse, only a part of electrical pulse could propagate to the scope (0-ps marked scope trace). The temporal resolution of this method was only
Fig. 4.12 Rough timing the generated electrical pulse and SRS optical pulse by using oscilloscope. (a) Monitor the leakage electrical pulses which were switched off by SRS optical pulse when changing the optical time delay line. (b) Digital scope traces of electrical pulses from the load at different optical time delays. The scope was HP54510A (250 MHz bandwidth, 1Gs/s).
about 250 picoseconds, but the rough timing adjustment made it possible a fine timing control could be accomplished by the Tek SC5000 digitizer. The same photoconductive switching method was applied in the fine timing control. By adjusting optical delay of the pump green pulse, the digitizer accurately presented the interaction of the SRS optical pulse tilted wavefront with the generated electrical pulse leading edge.

4.4.4 Electro-optic sampling and optimization

A piece of 0.5-mm-thick e-o LiTaO₃ crystal, which had with 532 nm AR coating on the top and 532 nm HR coating at the bottom, was set on the top of the coplanar-strip-lines in the probe beam path. In order to achieve maximum e-o modulation, the z axis of the crystal was placed perpendicular to the lines, or in the direction of the surface electric field.

The change in the probe pulse polarization came from two different sources, the static phase retardation and the dynamic phase retardation. Due to the inherent crystal birefringence, the phase shift of static retardation only depended on the optical path length and the orientation of the crystal optical axis. The dynamic part of phase retardation was from the Pockels effect, the temporal modification of probe light polarization followed the variations of the coplanar-strip-lines surface electric fields. Obviously, the dynamic phase retardation of the green probe beam was to be detected. The probe beam, which was split from the main green beam, was split again by a polarizing beam splitter (Fig. 4.7), and then was focused by a 10× micro objective lens on the bottom of the LiTaO₃ crystal. After reflection from the HR coating, the
probe pulse, which carried information of the surface electric field, passed through a solid compensator before it was split into two optical pulses. The main purpose of the solid compensator was to compensate for the static retardation. At the input of the streak camera, there were total three optical pulses, two signal pulses and one reference pulse. Appropriate time delays between each of the three pulses were adjusted to fit within the streak camera image window.

It was necessary to optimize the e-o effect sensitivity in the probe setup. For this purpose, an experiment was setup by using two photo diodes, as shown in Fig. 4.13a. The coplanar-strip-lines was biased with 40 volts square pulse train, in the meanwhile, the probe optical pulses had the repetition rate as twice as that of the electrical pulses. On an analog oscilloscope screen, the subtraction of two PIN diode inputs (\(CH1 - CH2\)) recorded a double trace. The upper scope trace of Fig. 4.13b shows the 40 volts bias electric field modulated the probe pulse light intensity. By rotating both the half-waveplate and the compensator, the e-o effect was optimized. On the scope, it appeared as enlarging the distance between the two traces.

### 4.4.5 Streak camera calibration

Before the measurement, the streak camera was calibrated with an etalon. It was proved that the etalon calibration was the most precise calibration method. The etalon was a pair of mirrors with 532 nm AR coating on the outer sides, and 70% reflection coating on the inner sides, as shown in the Fig. 4.14. The separation of two inner sides was measured to be 35.60 mm, or 273.3 picosecond light round trip propagation time. With this setting, a single pulse was split into a pulse train with
Fig. 4.13 The optimization of the electro-optic effect of the probe setup by using two photo diodes. (a) The e-o probe setup with 40 volts toggled bias. (b) The analog scope traces of (Ch1-Ch2). The upper trace shows the coplanar-strip-lines was biased at 40 volts, the lower trace show no electric field applied. By adjust the half-waveplate and the compensator, the e-o effect can be optimized.
Fig. 4.14 Calibration the streak camera by using an etalon-pair. (a) The etalon has AF coating for 532 nm on the outer sides, 70% reflection coating on the inner sides. The separation of two inner sides is 35.60 mm. (b) The streak camera image at streak time=2. The calibration shows that the streak time 2 has 2.6 ps per pixel.
~50% light intensity difference. The streak camera recorded this pattern. The calibration was made by measuring the distances between the peaks. At the setting of streak time 2, which was used in the most experiments, the streak camera was calibrated 2.6 picosecond per pixel.

### 4.4.6 Streak camera imaging data analysis

Since the streak camera could probe the temporal variation of the surface electric field with high resolution (~2 ps), more experiments were conducted by using the streak camera for the purpose of understanding microwave pulse leading edge shortening in the coplanar-strip-lines. As it has been discussed, the experiments were designed to generate electrical pulses with tunable frequency. By adjusting the incident angle of the SRS pulse on the transmission grating, the speed of the electron-hole ionization front was changed, so that the rise time of the reflected electrical pulse leading edge was modified. In these experiments, data was taken at two different ionization front moving speeds, ~0.3c and ~0.4c, corresponding to ~77° and ~71° of the SRS pulse incident angle on the grating. The reason to choose these ionization front moving speed was because the propagation speed of electromagnetic wave along the coplanar-strip-lines was 0.38c for GaAs substrate, and 0.39c for Si substrate.

To demonstrate the electrical pulse leading edge sharpening and its tunability, two sets of data were taken at the ionization front moving speed of 0.3c and 0.4c, respectively. Single-shot data acquisition is known for high noise. To increase signal-to-noise ratio, a large quantity of single-shot images were needed for later computer data average analyses. In the experiments, as many as 2,500 images were stored for
each set. Considering the e-o crystal static retardation and other background noise, all
the experimental images were toggled between with the high surface electric field and
with no surface electric field. This toggling process was controlled by the optical
shutter in the path of pump green beam. In a data analysis, pixel 513 of the image was
used to tell the shutter status.

The noise caused by the signal-shot laser fluctuation can be almost filtered by
averaging a large number of images. In the experiments, it was found that the
sensitivity of the streak camera depends on incident light polarization. In order to
apply Eq. 4.1 for image data analysis, the two signal pulses on the streak camera had
to have comparable amplitudes. A half waveplate was used in one of the signal beam
path for this purpose. But on the other hand, this externally introduced polarization
deformed the analyzed data. Fortunately, since the waveplate setting was unchanged
in the experiment, such deformation could be eliminate by,

$$\text{e-o modulation} = \frac{\text{Signal}_1 - \text{Signal}_2}{\text{Reference}_{\text{Shutter-open}}} - \frac{\text{Signal}_1 - \text{Signal}_2}{\text{Reference}_{\text{Shutter-closed}}} \quad (4.2)$$

where shutter-open means the coplanar-strip-lines electrical pulse biased, shutter-
closed means no bias electric field.

Each raw image was segmented into three individual pulses in equal number
of pixels, and the e-o modulation by using Eq. 4.2 was calculated. A total of 1200
images have been analyzed individually in this way. By averaging 1200 analyzed
images, the electrical pulse rising edge is clearly shown in the Fig. 4.15.
(a) = average \left( \frac{\text{Signal 1 - Signal 2}}{\text{Reference}} \right)_{\text{shutter-open}}

(b) = average \left( \frac{\text{Signal 1 - Signal 2}}{\text{Reference}} \right)_{\text{shutter-closed}}

(c) = (a) - (b)

Fig. 4.15 After averaging 1200 individually analyzed images, the Eq. 4.2 analyzed data shows the electrical pulse leading edge. (a) The plot when electrical pulse was applied. (b) The plot when no bias electrical pulse was applied. (c) The plot of (a)-(b). The substrate was Silicon, moving ionization front speed was 0.4c.
In the experiments of study the tunability of the electrical pulse rise time, two sets of data were recorded at the SRS beam incident angles of \( \sim 71 \) and \( \sim 77 \) degrees, corresponding to the moving ionization front speed of 0.4c and 0.3c. When the pump green pulse had rise time of \( \sim 60 \) ps, a similar rise time electrical pulse was generated from the micro-stripline, this electrical pulse was further reflected on the coplanar-strip-lines. Fig. 4.16 shows the sharpening effect as well as the tunability. When the speed of the moving ionization front increased \( \sim 33\% \) from 0.3c to 0.4c, the detected pulse rise time decreased \( \sim 30\% \) from 56 ps to 43 ps.

In order to achieve higher gain of the reflected electrical signal, electron momentum was introduced in the direction of the ionization front movement by applying a magnetic field. The Lorentz force \( \mathbf{F} = -e(\mathbf{V} \times \mathbf{B}) / c \) accelerated electrons in the predetermined direction, where \( \mathbf{V} = \mu_e \mathbf{E} \sqrt{T_e / T} \) is the drift velocity\(^{13}\) of electrons across the two strip lines, \( \mathbf{B} \) is the magnetic field. In the experiments, the magnetic field was measured to be 1.95 kG at the surface the semiconductor, the drift velocity was \( \sim 10^7 \) cm/s at room temperature for both GaAs and Si when the electric field \( \mathbf{E} \) was about 20 kV/cm, or 90 volts of electrical pulse amplitude.\(^{13}\) The duration of the photo carrier generation and electrical signal reflection was \( \sim 25 \) ps, which was the rise time of the SRS pulse, the electrons in GaAs could reach the maximum speed of \( 1.27 \times 10^8 \) cm/s, or 0.004c under the Lorentz force acceleration. In Silicon, the electron velocity is slower because of its heavier effective electron mass.
Fig. 4.16 By changing the speed of the moving ionization front, the sharpened electrical pulse leading edges have different rise times. When the moving ionization front speed was set at 0.3c, the reflected electrical pulse had a rise time of 56 ps, this rise time decreased to 43 ps as the speed increased to 0.4c. This data was taken by using Silicon substrate coplanar-strip-lines, and there was no static magnetic field applied.
Experimental data was taken to measure the electrical pulse rise times in the cases with and without the magnetic field. At the ionization front speed of 0.4c, the both pulses had the similar rise time of ~45 ps, as shown in Fig. 4.17. When the ionization front speed was decreased to 0.3c, the electrical pulses had rise time of 55 ps (Fig. 4.18). Because the speed of the electrons in Si driven by the Lorentz force was less than 2.5×10^4c in this 1.95 kG field, it was very difficult to tell whether the reflected electrical pulses had higher amplitude when the magnetic field applied. Therefore, it was safe to plot Fig. 4.17 and 4.18 with normalized amplitudes. These plots proved that the electrical pulse leading edge sharpening effect was only determined by the speed of ionization front, not the magnetic field.

4.5 Discussion of dispersion in the coplanar-strip-lines

Dispersion is a major problem in transmission lines for ultrafast electrical pulses since it can easily produce a longer rise time due to pulse broadening. Theoretical calculations of the dispersive broadening of pulses on transmission lines have been made by Li et al. In their discussion, the Fourier transform of a short electrical pulse given by \( V(0, t) \) is given by

\[
V(0, \omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} V(0, t) e^{-i\omega t} dt
\]

(4.3)

At a distance \( L \), the pulse becomes

\[
V(L, \omega) = e^{-jB(\omega)L} V(0, \omega)
\]

(4.4)

where
Fig. 4.17 With and without magnetic field, the data presents almost the same degree of sharpening for Silicon substrate coplanar-strip-lines. The rise times of electrical pulses were measured 45 ps and 44 ps with and without the magnetic field, respectively. In the experiments, the static magnetic field at surface of the coplanar-strip-lines was 1.95 kG. The incident angle of the SRS pulse to the grating was ~71 degrees, or the speed of the moving ionization front was 0.4c.
Fig. 4.18 Reducing the ionization front speed from 0.4c to 0.3c, the rise times of the electrical pulses were measured 55 ps 56 ps with and without the magnetic field, respectively. Other experimental conditions were the same as in the Fig. 4.17. The degree of the electrical pulse leading edge sharpening was determined by the speed of the ionization front.
\[ \beta(\omega) = \sqrt{\epsilon} \frac{\omega}{c} \]  

(4.5)

is the propagation constant. For simplicity, attenuation is neglected. The inverse transform of Eq. (4.4) gives \( V(L, t) \) in the time domain:

\[ V(0, \omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} V(L, \omega)e^{i\omega t} d\omega \]  

(4.6)

Li et al calculated the dispersion of a 5 ps pulse width Gaussian pulse propagation in a micro-stripline.\(^1\) After only 10 mm of travel, the 5 ps pulse is seriously distorted because of the dispersion. For single pulse propagation in the transmission line, the dispersion is due to the fact that the low-frequency components of pulse propagate faster than the high-frequency components.

To examine to the dispersion caused by the coplanar-strip-lines, an experiment was conducted by generating a electrical pulse from an micro-stripline pulse generator, then measuring the pulse rise time before and after the 4-cm long coplanar-strip-lines, as shown in Fig. 4.19a. When a \( \sim 50 \) ps rise time green laser pulse illuminated on the GaAs photocondutive surface switch on the micro-stripline, a 55 ps rise time step pulse was measured before the coplanar-strip-lines. When the pulse propagated through the coplanar-strip-lines, the rise time became 162 ps (Fig. 4.19b). The difference of the rise times indicated the coplanar-strip-lines had strong dispersion.

To provide evidence further of the dispersion of an electrical signal propagating in the coplanar-strip-lines, a different experiment based on boxcar
Fig. 4.19 The coplanar-strip-lines had strong dispersion. The electrical pulses generated by \(-50 \text{ ps}\) pulse width green optical pulses were measured by Tek 7250 before and after the electrical pulse propagated through the 4 cm long coplanar-strip-lines. The pulse rise time was broadened from 55 ps to 162 ps after the coplanar-strip-lines.
average electro-optic sampling was designed and implemented. In order to achieve a high signal-to-noise ratio, the optical pulses from the regenerative amplifier were operated at 1 kHz repetition rate. The setup is shown in Fig. 4.20a. As the time delay of 1064 nm infrared pulses was scanned by a computer, the probe 532 nm green pulse sampled the surface electric field. Two PIN diode detectors ($Ch1$ and $Ch2$) monitored the green probe pulses. The signals from the diodes were sent to a SRS SR250 Boxcar Integrator and then further analyzed by computer. In this experiment, the IR pulsewidth was $\sim$100 ps, optical delay stage moving step was 5 ps, and the DC bias on the micro- stripline was 200 volts. A total of 200 laser shots were averaged by the boxcar integrator at each step of the delay stage. Fig. 4.20b is a plot of \[ \frac{Ch1 - Ch2}{Ch1 + Ch2} \], or the e-o modulation depth. A 260 ps step pulse rise time was detected.

4.6 Conclusion

Two detection methods were used to study the microwave electrical pulse leading edge sharpening. In the first method, a microwave step pulse was generated and its leading edge was sharpened in the same coplanar-stripe-lines, a wide bandwidth digitizer was used to measure the electrical signals. In the second detection method, an electrical step pulse was generated in a separated micro-stripline and then reflected on a coplanar-stripe-lines. A streak camera imaged the temporal evolution of the surface electric field of the electrical pulse leading edge via the electro-optic effect. The advantage of the digitizer measurement is that we could clearly monitor the pulse leading edge sharpening in real time with high signal-to-noise ratio, but its
Fig. 4.20 The e-o sampling IR generated electrical pulse leading edge by using 2 PIN detectors and boxcar integrator. (a) The setup layout. (b) The plot of \( \frac{Ch1 - Ch2}{Ch1 + Ch2} \).

The rise time of 260 ps was detected.
disadvantage is the measurement accuracy is limited by the bandwidth of the digitizer. Using streak camera imaging of the electrical pulse, on the other hand, increases the detected resolution to less than 3 ps even though the probe pulse had a duration of \( \sim 60 \) ps. These experiments have proven the existence of the electrical pulse leading edge sharpening effect. The most important is the frequency, which corresponds to the rise time of electrical pulse leading edge, could be tuned by the optical grating.

These experiments have demonstrated that relativistic moving ionization front induced by an optical pulse with tilted-wave-front could shape an incoming electrical pulse. The pulse leading edge could be sharpened more than 30% and the reflection coefficient could be as high as 90%. The experiments also confirmed the degree of sharpening is determined by the speed of the ionization front, when the speed of the moving ionization front increased \( \sim 33\% \), the detected pulse rise time decreased \( \sim 30\% \). Increasing the reflected electrical pulse intensity by introducing the Lorentz force induced electron momentum was attempted, but unfortunately, the magnetic field was not strong enough, and the experimental noise prevented us from obtaining the desired result.

The strong dispersion existing in the both GaAs and Si substrate coplanarstrip-lines was the major barrier which blocked the measurement of very short electrical pulses. The experiments have confirmed the dispersion of the coplanarstrip-lines setup. The electrical pulse leading edge measured at a distance from the reflection point had a slower rise time. Since the electrical pulses in Fig. 16 to Fig. 18
have similar rise times, few tens of the picoseconds, it is safe to assume that they had
experienced the similar dispersion.

This electrical pulse sharpening technique has some significant advantages
over the previous methods of pulse shaping. These include high-reflection coefficient,
low optical energy requirements, frequency tunability, and all-solid-state construction
make this device an interesting candidate for high-frequency radar applications.
References


Chapter Five

Microwave Pulse Sharpening - Theoretical Modeling

5.1 Introduction

In Chapter Four, experimental evidence that an ultrafast optical pulse with tilted wavefront can sharpen an electrical pulse leading edge has been shown. To understand the mechanism of the microwave pulse optical generation and pulse sharpening, and to further help us in a better opto-electronics design, a theoretical analysis is necessary. By using a similar technique to that was discussed in Chapter Three, the GaAs (or Si) substrate coplanar-strip-lines can be treated as a one dimensional distributed-circuit. To perform this theoretical analysis and make the simulation easier, we simulated the coplanar-strip-lines with a 20-μm gap, with which the first series of experiments of Chapter Four (Fig. 4.4) were conducted. Like the experiments, two optical pulses are applied to the transmission line. The first pulse, with a normal wave front, illuminates the GaAs at the 20-μm gap. The second pulse, which is much stronger and has tilted-wave-front, illuminates the GaAs between the metal lines creating a short circuit. The source transmission line, coplanar-strip-lines and the load transmission line each are modeled as the discrete elements: resistors, capacitors and inductors. These distributed-circuit elements are determined by the characteristics of the semiconductor, the shape of the transmission line, and the external optical energy source. The advantage of this model is that it can represent the
photoconductive process in the transmission line and has a smooth integration of the external circuit.

5.2 Coplanar-strip-lines transmission line model

The distributed-circuit, as shown in Fig. 5.1, models a coplanar-strip-lines with a 20-µm gap, which is dc biased.¹ The characteristic impedance $Z$, the coplanar-strip-lines capacitance $C_s$, the gap capacitance $C_g$, and the inductance $L$ of length $dx$ are determined by²

$$Z = \frac{120\pi}{\sqrt{\varepsilon_r + 1}} \frac{K(k_c)}{K'(k_c)} \quad \text{ (ohm)}$$

(5.1)

$$C_s = \varepsilon_0 (\varepsilon_r + 1) \frac{K(k_c)}{2K'(k_c)} dx \quad \text{ (farad)}$$

(5.2)

$$C_g = \varepsilon_0 (\varepsilon_r + 1) \frac{K(k_c)}{2K'(k_c)} g \quad \text{ (farad)}$$

(5.3)

$$L = Z^2 C \quad \text{ (henry)}$$

(5.4)

where $K(k_c)$ is the complete elliptic integral of the first kind,

$$K(k_c) = \int_0^{\frac{\pi}{2}} \frac{d\varphi}{\sqrt{1 - k_c^2 \sin^2 \varphi}}$$

(5.5)

and

$$K'(k_c) = \int_0^{\frac{\pi}{2}} \frac{d\varphi}{\sqrt{1 - \sin^2 \varphi + k_c^2 \sin^2 \varphi}}$$

(5.6)

and $k_c$ is given by
Fig. 5.1 The microwave transmission line model for the coplanar-strip-lines uses discrete elements. Where the load resistor $R_L=50\ W$, blocking capacitor $C_b=200\ nF$, $r_g = \frac{dx}{AN_{e1}\mu}$, $r_t = \frac{dx}{AN_{e2}\mu}$. The electron densities $N_{e1}, N_{e2}$ are determined by the laser pulses.
\[ k_c = \frac{S}{S + 2W} \]  

(5.7)

where \( \varepsilon_r \) is the dielectric constant of the transmission line material. \( W \) is the width of the coplanar strip, which is 44 \( \mu \text{m} \). \( S \) is the distance between the two strips, and \( g \) is the width of gap, 20 \( \mu \text{m} \). The resistivity of a part of the coplanar-strip-lines is the same as Eq. 3.5, which is a function of position and time. Rewriting Eq. 3.5,

\[ \rho = \frac{1}{\varepsilon \left[ N_e(x,t)\mu_e(E) + N_p(x,t)\mu_p(E) \right]} \]  

(5.8)

where the carrier densities \( N_e \) and \( N_p \) are calculated from the local optical intensity, absorption depth, recombination lifetime, and carrier transport. The resistances \( r_g \) and \( r_t \) are

\[ r_g = \rho \left( N_{e1}, N_{p1}, E_1 \right) g \]  

(5.9)

and

\[ r_t = \rho \left( N_{e2}, N_{p2}, E_2 \right) dx \]  

(5.10)

where subscripts 1 and 2 stand for the weaker trigger optical pulse and the tilted optical pulse, respectively.

By applying the linearized expressions for the current in the inductors and capacitors and the Kirchhoff’s law of currents continuity at each node, as in the Eq. 3.7 and Eq. 3.8, the discrete-circuit equations for this coplanar-strip-lines model could be derived from the circuit (Fig. 5.1). When the node number \( k \) is even, we have
where $V$ and $V'$ indicate the current at time $t$ and $t'$. $r_u$ is resistance of the metal line of distance $\Delta x$. If the node number $k$ is odd, the equation becomes

$$\frac{V_k - V_{k+1}}{r_{u+1/2}} = I'_{k-1} + \frac{\Delta t}{L} (V_{k-1} - V_k + V_{k-1}' - V_k').$$

At the gap, there are two connection equations for point A and point B. The point A equation is

$$\frac{V_A - V_B}{r_g} + \frac{C_g}{\Delta t} (V_B - V_A - V_B' + V_A') = I'_{A-1} + \frac{\Delta t}{2L} (V_{A-1} - V_A - V_{A-1}' + V_A').$$

and the connection equation at point B is

$$I'_B + \frac{\Delta t}{2L} (V_B - V_{B+1} + V_B' - V_{B+1}')$$

$$= \frac{V_A - V_B}{r_g} + \frac{C_g}{\Delta t} (V_B - V_A + V_B' - V_A') + \frac{C_l}{\Delta t} (V_B - V_B') - \frac{V_B}{r_l}.$$

The equations of the source line and the load line are similar but lack the variable resistance terms. In order to program a computer code, the above four equations are rewritten in a form of temporal sequence:

even node equation,

$$\left(\frac{\Delta t}{2L} + \frac{1}{r_{u+1/2}} - \frac{C_u}{\Delta t} + \frac{1}{r_{l+1/2}}\right) V_k - \Delta t \frac{V_{k+1}}{2L} - \frac{1}{r_{u+1/2}} V_{k-1} = -I'_k - \frac{\Delta t}{2L} (V_k' - V_{k+1}') - \frac{C_l}{\Delta t} V'_k.$$

(5.11)
odd node equation,

\[
\left( \frac{1}{r_{n+1}} + \frac{\Delta t}{2L} \right) V_k - \frac{1}{r_{n+1}} V_{k+1} - \frac{\Delta t}{2L} V_{k-1} = I_k + \frac{\Delta t}{2L} (V'_{k-1} - V'_k)
\]  

(5.12)

A point equation,

\[
\left( \frac{1}{r_g} - \frac{C_g}{\Delta t} + \frac{\Delta t}{2L} \right) V_A + \left( \frac{C_g}{\Delta t} - \frac{1}{r_g} \right) V_B - \frac{\Delta t}{2L} V_{A-1} = I_{A-1} - \frac{C_g}{\Delta t} (V'_A - V'_B) + \frac{\Delta t}{2L} (V'_{A-1} - V'_A)
\]  

(5.13)

B point equation,

\[
\left( \frac{\Delta t}{2L} + \frac{1}{r_g} - \frac{C_g}{\Delta t} + \frac{1}{r_r} \right) V_B - \frac{\Delta t}{2L} V_{B+1} - \left( \frac{1}{r_g} - \frac{C_g}{\Delta t} \right) V_A = -I'_B - \frac{\Delta t}{2L} (V'_B - V'_{B-1}) + \frac{C_g}{\Delta t} (V'_A - V'_B) - \frac{C_i}{\Delta t} V'_B
\]  

(5.14)

As we did in Chapter Three, Eq. 5.11 to Eq. 5.14 can be numerically solved by the tridiagonal matrix method.

5.3 Simulation results

We simulated the experimental conditions. The GaAs substrate coplanar-strip-lines had 4-cm length, the distance between two lines was 44 μm. One of the line had a 20-μm gap, which was located 1 cm from the end connector (Fig. 4.4). The GaAs substrate was 0.5-mm thick. The dc bias voltage was 8 volts. The charging resistor and load resistor were 50 Ω. Two 0.63 μm laser pulses with a rise time of 30 ps were used to illuminate the semiconductor. The trigger pulse, which had optical energy of
0.2 µJ, first fired the 20-µm gap switch so that two traveling step signals were generated. Then a delayed optical pulse, which had optical energy of 0.5 mJ and tilted-wave-front, reached the GaAs between the main coplanar-strip-lines, where the photocarrier boundaries collided with the incoming electromagnetic signal. The both optical pulses had temporal and spatial Gaussian profiles.

Fig. 5.2a is a step-signal generation and reflection in a 500 ps process simulation. Comparing with experimental result in Fig. 4.6a, the simulation has higher reflection coefficient of 0.88. This difference might come from loss and dispersion in the experiments. Like we did in Fig. 4.6b, the two steps from Fig. 5.2a were normalized and plotted together, as shown in Fig. 5.2b. As expected, the simulation results gave the same behavior as the experiments. Direct comparison is difficult because of bandwidth limitations of the scope and the dispersion of coplanar-strip-lines which is not modeled, but the simulated reflection-sharpened pulse has a rise time of about 20 ps less than that of the original pulse.

In order to demonstrate the concept that shorter optical pulses have advantages on the shortening an electrical pulse leading edge in the semiconductor substrate coplanar-strip-lines, we simulated a temporal Gaussian microwave pulse (not a step pulse) propagating along the coplanar-strip-lines and shortened by a tilted-wave-front optical pulse generated moving ionization fronts. When the angle between the optical wave front and the semiconductor surface was set above 70 degrees, the incoming microwave pulse could be effectively reflected and propagated out of the active plasma region. Both the shortening and the reflection coefficient vary for the different
Fig. 5.2 (a) The simulation result shows a process of both generation and reflection of a step signal. The speed of the ionization front was set $0.46c$. (b) The normalized rise time of each step of (a) shows that the rise time of the step signal was sharpened by a factor of 1.62. The simulations is to be compared to the experimental measurements in Fig. 4.6.
Fig. 5.3 Simulating a microwave pulse with pulse width of 30 ps which is reflected and shortened by a tilted wavefront optical pulse of 1 ps pulse width. After the reflection, the microwave is shortened more than 4.5 times while the reflection coefficient is about 0.75. This simulation implies the sharpening could be significantly improved if shorter optical pulse is used.
angles. As the angle increases, the speed of the ionization front becomes slower and the Doppler effect weakens, but the reflection gets stronger. Fig. 5.3 shows that a microwave pulse with pulse width of 30 ps is reflected and sharpened by an optical pulse which has pulse width of 1 ps, and energy of 0.2 mJ. The angle between the optical wave front and the semiconductor surface was 75 degrees. After the reflection, the microwave was shortened more than 4.5 times while the reflection coefficient is about 0.75.

5.4 Conclusion

A transmission line circuit model has been established to simulate the microwave coplanar-strip-lines for the purpose of optical pulse sharpening electrical pulse. These theoretical results generally agree with the experiments. In the simulating the first series of experiments described in Chapter Four, we found the calculated results have the same behaviors as the experiments, the sharpened step pulse was squeezed by a factor of 1.62. But both the generated and sharpened electrical pulses have faster rise time, this was because the experimental coplanar-strip-lines had significant dispersion, which broadened the propagation of the microwave pulses. The simulation implied that we could improve the sharpening performance if we could use low dispersion coplanar-strip-lines in the experiments. In another simulation, we have demonstrated a Gaussian electrical pulse can be significantly sharpened if a shorter optical pulse is applied. It suggests that a larger sharpening coefficient require sharp optical pulse rise time.
References


Chapter Six

Summary

Some new developments in research and application of photoconductive semiconductor switches are discussed. This thesis can be roughly divided into two parts: switching behavior research and switching phenomena application. The dynamic behavior of high-power GaAs photoconductive switching dependence on the laser illumination uniformity has been studied in the first part. A computer controlled experimental setup, which was designed to map the switch surface electric field by using electro-optic effect. In linear switching operation, the electric fields within the switch are found to redistribute themselves immediately after optical illumination. The patterns of the redistribution are correlated with the type of the laser illumination. Asymmetric illumination creates a high field region on the nonilluminated side in about 100 ps. Compared with the case of uniform illumination, the field enhancement effect in asymmetric illumination is faster and stronger. Illumination at the cathode compresses the field toward the anode, and illumination at the anode compresses the field toward the cathode. In nonlinear switching modes, the behaviors of GaAs photoconductive switches are investigated in a longer time scale. Three different kinds of nonlinear modes have been seen: persistent-conductivity, avalanching and repetitive-current-spikes. Repetitive-current-spikes were first observed in the experiment. The period for the repetitive-current-spikes is about 70-75 ns for a 6.9-mm long GaAs sample. A surface electric field was mapped when the switch was in
the mode of repetitive-current-spikes. Both the oscilloscope measured period and the
electro-optic image mapped electric field suggest the Gunn oscillation could be a
reason of the repetitive-current-spikes nonlinear switching mode.

A transmission-line model of discrete-circuit equations has been used to
simulate the switching behavior. There is a good agreement between the theoretical
predictions and the experimental results for linear mode switching. The model also
predicted Gunn domain in the nonlinear mode, which has been proven by the
experiments. The simulations suggest off-center illuminations have less efficiency,
but produce shorter pulses. The important result is that, roughly 1 ns after
illumination, the electric field within the switch can develop hot spots. The position
and magnitude of the hot spots can be influenced by the optical illumination. These
hot spots have the capability of seeding some of the long-term nonlinearities seen in
high-power GaAs photoconductive switches.

In the second part of the thesis, a new conceptual method of ultrafast electrical
pulse leading edge sharpening is comprehensively studied. A relativistic moving
ionization front induced by a ultrafast optical pulse with tilted-wave-front has been
experimentally proven to shape an incoming electrical pulse. Two detection methods
were used to study the microwave electrical pulse leading edge sharpening. In the first
method, a microwave step pulse was generated and its leading edge was sharpened in
the same coplanar-strip-lines, a wide bandwidth digitizer was used to measure the
electrical signals. In the second detection method, an electrical step pulse was
generated in a separated micro- stripline and then reflected on the coplanar-strip-lines.
A streak camera imaged the temporal evolution of the surface electric field of the electrical pulse leading edge via the electro-optic effect. The streak camera imaging method increases the detected resolution to less than 3 ps even though the probe pulse had a duration of ~60 ps. These experiments have proven the existence of the electrical pulse leading edge sharpening effect. The most important is the frequency, which corresponds to the rise time of electrical pulse leading edge, could be tuned by the optical grating. The experiments confirmed the degree of sharpening is determined by the speed of the ionization front, when the speed of the moving ionization front increased ~33%, the detected pulse rise time decreased ~30%. This electrical pulse sharpening technique has some significant advantages over the previous methods of pulse shaping. These include high-reflection coefficient, low optical energy requirements, frequency tunability, and all-solid-state construction make this device an interesting candidate for high-frequency radar applications.

To understand the mechanism of the microwave pulse optical generation and pulse sharpening, a theoretical analysis has been accomplished. A discrete-circuit equations based on the GaAs (or Si) substrate coplanar-strip-lines has been established to perform the simulation for the purpose of optical pulse sharpening electrical pulse. The theoretical results are found to have the same behaviors as the experimental results described in first series of experiments of Chapter Four. The simulation implied that it could improve the sharpening performance by using a low dispersion transmission line. It also suggested that a larger sharpening coefficient require sharp optical pulse rise time.