Electrical Characterization of Gold-doped Hg$_{0.8}$Cd$_{0.2}$Te Photodiodes

by

Michael D. Falcon

Submitted to the Department of Electrical Engineering and Computer Science in Partial Fulfillment of the Requirements for the Degree of Master of Science in Electrical Engineering at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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ABSTRACT

This experimental study characterizes both thick (> 50 microns) and thin (10 microns) gold-doped n-on-p Hg_{0.8}Cd_{0.2}Te photodiodes. Current-voltage measurements over a range of temperatures have been conducted on detectors with and without operational guard diodes. The minority carrier electron lifetime in the p-type base layer is estimated from measured dark current densities. Additionally, comparisons are carried out between gold-doped photodiodes and standard vacancy-doped infrared detectors fabricated at Texas Instruments, Inc. The planar gold-doped photodiodes were fabricated by ion-implantation into p-Hg_{0.8}Cd_{0.2}Te grown by liquid phase epitaxy.

Experiments show that with a reversed-bias guard diode, dark current densities on thick gold-doped photodiodes averaged 0.25 mA/cm^2 while equivalent thin photodiodes exhibited dark current densities of 0.15 mA/cm^2. In dark current comparisons between thin gold- and vacancy-doped photodiodes, the dark current density for gold-doped detectors with operational guard diodes measured two to three times less than vacancy-doped detectors. Minority carrier lifetimes in gold-doped devices were estimated to vary from 3 nanoseconds for a 3.4x10^{16} (cm^{-3}) acceptor concentration to 40 nanoseconds for a 4.4x10^{15} (cm^{-3}) acceptor concentration. In similar measurements conducted on vacancy-doped devices, minority carrier lifetimes are roughly three times shorter than gold-doped detectors for equivalent acceptor concentrations. It is concluded that the longer lifetimes in gold-doped photodiodes, in turn, lead to lower dark current at 77K and better device performance.

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\( d \) \hspace{1cm} \text{length of a diode (cm)}
\( D_n \) \hspace{1cm} \text{electron diffusion constant (cm}^2/\text{sec)}
\( D_p \) \hspace{1cm} \text{hole diffusion constant (cm}^2/\text{sec)}
\( E_a \) \hspace{1cm} \text{activation energy associated with an energy level in the bandgap (eV)}
\( E_g \) \hspace{1cm} \text{bandgap energy (eV)}
\( G_1 \) \hspace{1cm} \text{approximately half the distance between guard diode and photodiode (cm)}
\( J_{\text{dark}} \) \hspace{1cm} \text{total dark current density (A/cm}^2\text{)}
\( J_{\text{diff}} \) \hspace{1cm} \text{diffusion current density (A/cm}^2\text{)}
\( J_{\text{g-r}} \) \hspace{1cm} \text{generation-recombination current density (A/cm}^2\text{)}
\( J_s \) \hspace{1cm} \text{surface leakage current density (A/cm}^2\text{)}
\( J_{\text{tunn}} \) \hspace{1cm} \text{tunnel current density (A/cm}^2\text{)}
\( J_{1\text{diff}} \) \hspace{1cm} \text{diffusion current density from region one of Figure 10 (A/cm}^2\text{)}
\( J_{2\text{diff}} \) \hspace{1cm} \text{diffusion current density from region two of Figure 10 (A/cm}^2\text{)}
\( J_{3\text{diff}} \) \hspace{1cm} \text{diffusion current density from region three of Figure 10 (A/cm}^2\text{)}
\( k \) \hspace{1cm} \text{Boltzmann's constant (eV/K)}
\( L_n \) \hspace{1cm} \text{electron minority carrier diffusion length (cm)}
\( L_p \) \hspace{1cm} \text{hole minority carrier diffusion length (cm)}
\( L_{N-\text{thickness}} \) \hspace{1cm} \text{depth of a photodiode's n-region (cm)}
\( L_{P-\text{thickness}} \) \hspace{1cm} \text{depth of a photodiode's p-region base layer (cm)}
\( n \) \hspace{1cm} \text{electron concentration (#/cm}^3\text{)}
\( N_a \) \hspace{1cm} \text{total acceptor concentration (#/cm}^3\text{)}
\( N_d \) \hspace{1cm} \text{total donor concentration (#/cm}^3\text{)}
\( n_i \) \hspace{1cm} \text{intrinsic carrier concentration (#/cm}^3\text{)}
\( p \) \hspace{1cm} \text{hole concentration (#/cm}^3\text{)}
\( q \) \hspace{1cm} \text{magnitude of electron charge (Coulombs)}
\( R_{\text{tunn}} \) \hspace{1cm} \text{tunnel rate of carriers out of traps}
\( S_o \) \hspace{1cm} \text{surface recombination velocity (cm/sec)}
\( T \) \hspace{1cm} \text{temperature in degrees Kelvin (K)}
\( \tau_n \) \hspace{1cm} \text{electron minority carrier lifetime (sec)}
\( \tau_0 \) \hspace{1cm} \text{effective lifetime (sec)}
\( u_n \)  electron mobility (cm\(^2\)/V-sec)
\( V_a \)  diode applied voltage (V)
\( V_{bi} \)  junction built-in voltage (V)
\( V_F \)  dc value of applied forward voltage (V)
\( V_G \)  field plate bias (V)
\( V_{tunn} \)  empirically determined constant in the tunnel rate (V)
\( V_{oldiff} \)  diffusion volume in the p-region of a photodiode (cm\(^3\))
\( W \)  total width of the depletion region (cm)
\( x \)  mole fraction of cadmium
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Chapter 1

Introduction

Semiconductor infrared detectors are based on the phenomenon that incident infrared radiation excites electrons from the valence band of the semiconductor across the energy bandgap into states in the conduction band. This process produces excess hole-electron pairs that modify the electrical properties of the semiconductor. Infrared detection primarily centers around two kinds of electrical changes to the semiconductor. A photoconductive detector senses infrared radiation by an increase in the semiconductor's electrical conductivity, whereas a photovoltaic detector senses infrared radiation as a photocurrent or photovoltage. This study will concentrate on the photovoltaic PN junction.

A number of elemental semiconductor materials can be used to adequately detect radiation wavelengths up to 8 microns. However, in order to detect wavelengths beyond this limit, mixed semiconductor alloys provide the best detector performance. In 1958, it was discovered that the bandgap of the semiconductor alloy Mercury-Cadmium-Telluride (Hg$_{1-x}$Cd$_x$Te) could be varied from 0.0 to 1.605 eV as $x$ increases from 0.17 to 1.0. This makes
Hg$_{1-x}$Cd$_x$Te ideal for infrared detection within the 8 to 14 micron atmospheric spectral window as well as other bands in the near and far infrared [1].

In a photovoltaic detector, the photocurrent adds to the normal reverse-biased diode current. It is important that nearly all photoexcited carriers reach the PN junction for best infrared detection. However, dark current (also referred to as leakage current) often degrades the detector's performance by competing with the photo-generated current.

Texas Instruments, Inc., fabricates high-performance infrared detectors using vacancy-doped Hg$_{0.8}$Cd$_{0.2}$Te gate-controlled photodiodes that have been ion-implanted to form an n-on-p planar homojunction. Efforts focus on producing devices that detect wavelengths above 10 microns with minimal dark current. Tests performed at 77 K on these photodiodes indicate that excess dark current can be comparable to photocurrent and hence, degrade performance. It is suspected that the short minority carrier lifetime of the vacancy-doped p-type Hg$_{0.8}$Cd$_{0.2}$Te causes the dark current to increase significantly [1-3]. Research in this thesis attempts to improve photodetector performance by using extrinsic p-doped Hg$_{0.8}$Cd$_{0.2}$Te to increase carrier lifetime and, thus, decrease dark current [2], [4-5]. Tests were conducted on photodiodes fabricated using gold(Au) as the extrinsic p-dopant in the Hg$_{0.8}$Cd$_{0.2}$Te crystal.

Dark current may be broken down into various components. This study focuses on dark current as the combination of diffusion current, generation-recombination current, and tunnel current. These three components have different temperature dependencies [1], [6-7];
for example, diffusion current is proportional to $\exp\left(-\frac{qE_g}{kT}\right)$, where $E_g$ is the bandgap, $k$ is Boltzmann's constant, $q$ is the magnitude of electronic charge, and $T$ is temperature. On the other hand, generation-recombination current is proportional to $\exp\left(-\frac{qE_r}{kT}\right)$ while tunnel current should be relatively temperature independent [8-10]. Overall, dark current is analyzed in extrinsic gold-doped photodiodes and compared to results for vacancy-doped $p$-type Hg$_{0.8}$Cd$_{0.2}$Te.

1.1 The Mercury-Cadmium-Telluride System

To fabricate a quality photodiode, a controlled way of incorporating dopants into the Hg$_{1-x}$Cd$_x$Te crystal is essential. In a II-VI semiconductor, Group I and III elements should act as extrinsic acceptors and donors, respectively, which substitute for the mercury/cadmium metal sites. Group V and VII impurity atoms should behave as acceptors and donors on tellurium sites [4]. The most common means of doping Hg$_{1-x}$Cd$_x$Te material does not rely upon impurity dopants but, instead, is based on an intrinsic process involving the in-diffusion and out-diffusion of mercury. When Hg is out-diffused, mercury vacancy sites remain in the lattice and correspond to two acceptor levels for $x = 0.23$ (12-13 meV and 0.39 $E_g$ above the valence band), causing the semiconductor to behave as $p$-type [11]. Conversely, mercury interstitials can be introduced into the lattice to fill and reduce the concentration of Hg vacancy sites, causing the material to convert from $p$-type to $n$-type [12]. The mercury in-diffusion/out-diffusion process is done through a controlled anneal of the Hg$_{1-x}$Cd$_x$Te film.
1.2 Thesis Organization

The thesis body is divided into three main parts, represented by Chapters 2, 3, and 4 respectively. The first part, Chapter 2, discusses the theory surrounding an ideal PN junction photodiode and the gate-controlled photodiode. Dark current behavior and current mechanisms are also reviewed. In the latter part of Chapter 2, changes in dark current due to a guard diode and the rationale for thick and thin p-region detectors are outlined. The end of Chapter 2 defines a model to calculate minority carrier (electron) lifetime from a photodiode's experimentally measured dark current.

In Chapter 3, the PN homojunction formation process is defined for vacancy-doped and extrinsic gold-doped photodiodes. Next, the layout and geometry of the test devices are presented. The current-voltage measurement technique for device characterization is discussed in the last part of Chapter 3.

Chapter 4 presents the results collected on the gold-doped photodiodes. Several different dark current comparisons are made. First, dark current in thick gold-doped photodiodes are compared to equivalent thin detectors. Dark current measurements are also compared between photodiodes surrounded by a guard diode and photodiodes without a guard diode. Additionally, this study compares current-voltage measurements between gold-doped photodiodes and vacancy-doped detectors. Variable temperature dark current measurements are discussed to determine the dominant current mechanisms in gold-doped
test structures. The final section of Chapter 4 applies the diffusion current model derived in Chapter 2 to estimate a minority carrier lifetime for both gold- and vacancy-doped infrared detectors. Qualitative lifetime comparisons are then made between the deduced minority carrier lifetimes and experimentally measured lifetimes determined by the microwave reflection technique.
Chapter 2

Theory

2.1 Introduction

This chapter reviews the basic theory of a PN junction photodiode and a gate-controlled photodiode. In addition, dark current and its fundamental components are outlined. Changes in dark current when a guard diode surrounds a photodiode are discussed along with differences in dark current for a thick and thin photodiode. The last section in Chapter 2 defines a diffusion current model to estimate an electron lifetime.

2.2 PN Junction Photodiode

A diode is a semiconductor device comprised of a single PN junction. The p-type material on one side of the junction contains a larger number of holes compared to the intrinsic carrier concentration, due to acceptors in the Mercury-Cadmium-Telluride lattice. Due to donors such as indium atoms or mercury interstitials, the junction's n-type region has a greater concentration of electrons than the intrinsic carrier concentration. The transition
from $n$ to $p$-type material forms a depletion region, which has a built-in potential (see Figure 1-a). This junction is the basis for a photodiode’s useful electrical qualities.

In the laboratory experiments for this study, a $p$-type Hg$_{0.8}$Cd$_{0.2}$Te film doped with gold atoms is used as the junction’s base layer (see Figure 1-b). The $p$-type material undergoes ion implantation in a vacuum chamber, which damages the lattice. During the ion-implantation process, the damaged region converts the surrounding $p$-type material to $n$-type, thus forming a complete $PN$ junction (see Figure 1-b). For simplicity, this junction is ideally modeled in one dimension in Figure 1-c.

When a small positive voltage ($V_F > +0.7$ Volts for a silicon diode at room temperature) is applied to the $p$-region with respect to the $n$-side of a diode, large current flow occurs (see Figure 2-a & b). This condition is referred to as forward bias. In the test circuit seen in Figure 2-b, the electric field across the depletion region is reduced, and a large number of electrons in the $n$-region are able to diffuse across the junction, producing a positive current. Holes from the $p$-region readily diffuse across the depletion region producing a positive current, similarly to those for electrons. However, if a negative bias is applied to the $p$-region, a different event occurs (see Figure 2-c). The holes in the $p$-region are attracted away from the junction and toward the negative terminal. Simultaneously, electrons in the $n$-type material are attracted to the positive battery terminal, creating a larger depletion region. Very few electrons or holes diffuse across the depletion region because of the larger potential barrier. Thus, very little current flows through the diode, which is
Figure 1: The Photodiode

(a) PN junction structure

(b) actual structure

(c) idealized one-dimensional model
Figure 2: Diode: [Neudeck, 1989, p. 13]
(a) current-voltage characteristics for a silicon diode at room temperature
(b) forward bias sample circuit
(c) reverse-bias sample circuit
considered to be in the reverse-bias state. However, the small reverse-bias current that does flow is referred to as leakage current or dark current; the magnitude of this dark current is of concern in this study. Ultimately, if an extreme reverse-bias voltage is applied, breakdown occurs due to a phenomenon called avalanching or tunneling (see Figure 2-a).

2.3 Gate-controlled Photodiode

A gate-controlled diode is similar to a single $PN$ diode, except that the device has a field plate (also called a gate) on top of the insulator above the $p$-region and slightly overlapping the $n$-region (see Figure 3-a & b). When a negative voltage is applied to the field plate, holes in the $p$-type material are attracted to the potential. These positive charges are concentrated near the insulator/Hg$_{1-x}$Cd$_x$Te interface and form an "accumulation region" (see Figure 4-a). If a small, positive voltage is placed on the field plate, holes in the $p$-type material will be repelled from the insulator surface, leaving a surface depletion region (see Figure 4-b). If the positive potential applied to the gate is increased, the width of the surface depletion region increases proportionally until a sudden increase in electron concentration is observed near the interface, forming a narrow $n$-type surface inversion layer (see Figure 4-c).

Gate-controlled diodes are unique because the various surface space-charge regions (accumulation, depletion, and inversion) can be established by application of a particular potential to the field plate. This ability becomes significant when minimizing dark current for a photodiode. When the surface under the field plate is accumulated, electric field-induced
Figure 3: The gate-controlled diode [Neudeck, 1989, pp. 290, 298]
(a) gate-controlled diode structure
(b) idealized representation of (a)
negative voltage applied to field plate ($-V_G$)

(a) accumulation

small positive voltage applied to field plate ($V_G$)

(b) depletion

large positive voltage applied to field plate ($V_G$)

(c) inversion

Figure 4: Variations of the surface space-charge region at reverse-bias.
[Grove, 1967, p. 229]
tunneling increases. If the potential on the field plate is adjusted to a point between accumulation and depletion (also known as the flatband condition), dark current drops to a minimum (see Figure 5). Determining the lowest dark current as a function of field plate bias is often referred to as "optimizing the field plate bias."

Photodiodes are similar to normal diodes, except that light is allowed to illuminate the $PN$ junction. When the junction is in darkness, only dark current is present within the photodetector. When the detector is exposed to light, excess electrons and holes are generated in the photodiode and cross the depletion region to produce additional reverse current, known as photocurrent. The photocurrent is proportional to the amount of light striking the junction and is the key factor that allows infrared detection. Photodetectors may be placed in an array and connected to a microprocessor that senses currents. An image similar to a black and white picture can be formed. An advantage of such an infrared image is that objects can be identified in darkness or through smoke because smoke is transmissive to infrared radiation (see Figure 6). This technology is especially important in military applications where infrared detection can achieve "night vision" and enhance an army's function. However, if the microprocessor in a focal plane array system senses unwanted dark current, the image can lose contrast.
Figure 5: Experimentally measured field plate bias versus current plot for a 9 mil\(^2\) HgCdTe photodiode at 77 Kelvin. (semi-log scale)
Figure 6: Infrared photography.
(portrait of a bust made in total darkness by the heat from two flatirons.)
2.4 Dark Current Behavior

As mentioned above, a limiting factor in a photovoltaic detector is the magnitude of dark current that competes with photo-generated current. This thesis will define dark current density \( J_{\text{dark}} \) as

\[
J_{\text{dark}} = J_{\text{diff}} + J_{\text{g-r}} + J_{\text{tunn}} + J_s,
\]

which is the sum of diffusion current density \( J_{\text{diff}} \), generation-recombination current density \( J_{\text{g-r}} \), tunnel current density \( J_{\text{tunn}} \), and surface leakage current density \( J_s \). Each of these current components have different fundamental behaviors.

Dark currents may also be categorized as either "lateral" or "bulk" currents. Lateral currents are dark currents that originate near the sides and front surface of the photodiode. This type of current is proportional to the perimeter of the photodiode. Bulk currents are any dark currents that originate from directly underneath the \( pn \) junction. Bulk currents can be identified by their dependence on a photodiode's implant area.

2.4.1 Diffusion Current Component

The most common current mechanism in a photodiode is diffusion current. Diffusion current is due to a carrier concentration gradient. Thermally-generated electron-hole pairs within a minority-carrier diffusion length of the depletion region diffuse across the space-
charge region to reach equilibrium. Diffusion current density for a thick (long-base) diode is determined by the Shockley equation

\[ J_{\text{diff}} = \left[ \frac{qD_p n_p}{L_p} + \frac{qD_n n_p}{L_n} \right] \exp\left( \frac{qV_a}{kT} \right) - 1. \]  

(2)

During infrared detection, the photodiode often operates at temperatures near 77 K in the reverse-bias state where the n-region is biased positive with respect to the p-side. (Reverse-biasing the diode corresponds to a negative \( V_a \) value in eqn. 1.) In most cases, the magnitude of \( V_a \) is much larger than \( kT/q \), and \( J_{\text{diff}} \) reduces to

\[ J_{\text{diff}} = -n_i^2 \left[ \frac{qD_p}{L_p N_d} + \frac{qD_n}{L_n N_a} \right], \]  

(3)

where \( \frac{n_i^2}{N_d} \) and \( \frac{n_i^2}{N_a} \) have been substituted for the equilibrium minority carrier concentrations, \( p_n \) and \( n_p \), respectively (\( n_i \) corresponds to the intrinsic carrier concentration while \( N_a \) and \( N_d \) are acceptor and donor concentrations for the p- and n-regions).

The n-on-p Hg\(_{0.8}\)Cd\(_{0.2}\)Te photodiodes fabricated at Texas Instruments are believed to be dominated by diffusion current from the p-side. With the thicknesses of the n- and p-regions approximately three microns and at least ten microns thick, respectively, geometry suggests that p-side (electron) diffusion current dominates. Studies by Tredwell and Long [12] also indicate that the diffusion current on the n-side should be negligible compared to the p-side diffusion current since the minority carrier lifetime of n-type Hg\(_{0.8}\)Cd\(_{0.2}\)Te is limited by the Auger electron-electron collision generation rate [1]. With this assumption, \( J_{\text{diff}} \) can be further reduced to
Similarly, the electron diffusion current can be written as a function of minority carrier lifetime $\tau_n$ because of the relationship $L_n = \sqrt{D_n \tau_n}$; diffusion current density for a thick photodiode, thus, becomes

$$J_{\text{diff}} = -n_i^2 \frac{q D_n}{L_n N_a \tau_n}.$$  \hfill (4)

For a thin (short-base) photodiode, the electron diffusion current density is equal to

$$J_{\text{diff}} = -n_i^2 \frac{q \sqrt{D_n}}{N_a \tau_n} = -n_i^2 \frac{q L_n}{N_a \tau_n},$$ \hfill (5)

where $L_{P\text{-thickness}}$ is the base layer thickness (see Figure 1-b). The difference in diffusion current between thick and thin photodiodes lies in the fact that the thickness of a short-base diode may be smaller than the minority carrier diffusion length ($L_{P\text{-thickness}} < L_n$).

Part of the temperature dependence of $J_{\text{diff}}$ can be seen by simply substituting $kT u_n/q$ in place of the diffusion constant $D_n$ ($u_n$ is defined as electron mobility).

However, the dominant temperature dependence of $J_{\text{diff}}$ comes from the $n_i^2$, which is proportional to $\exp(-\frac{E_g}{kT})$. This implies that a semilog plot of dark current versus inverse temperature should be a straight line with a slope of approximately $E_g/kT$ [1]. Similarly an "activation energy" can be calculated by fitting the variable temperature dark current measurements with an Arrhenius-type equation of the form $-E_a/kT$, where $E_a$ is assigned to an activation energy associated with an energy level in the gap. This unique temperature dependence allows for diffusion current to be extracted from the total dark current.
2.4.2 Generation-Recombination Current

Generation-Recombination current (also called g-r current) is another current mechanism that limits infrared detection performance. The source of g-r current is due to generation-recombination centers (also referred to as Shockley-Read-Hall centers) scattered throughout the depletion region of a pn junction [14]. The number of generation-recombination centers depends on defects and impurities within the material. Under reverse-bias, excess dark current can cause generation of carriers in the depletion region. G-R current can be modeled as

\[ J_{g-r} = \frac{q n W}{\tau_o} \]  

(7)

where the most probable generation-recombination centers are assumed to be located at the intrinsic fermi energy level and the effective lifetime \( \tau_o \) is inversely proportional to the density of trapping states [14] (\( W \) is the total width of the depletion region). \( J_{g-r} \) also depends on the junction built-in voltage \( V_{bi} \) and the applied voltage \( V_a \) because \( W \) is proportional to the square root of the difference between \( V_{bi} \) and \( V_a \) for a step junction.

The temperature dependence of generation-recombination current varies mainly as a function of \( n_i \), \( \exp\left(-\frac{E_g}{2kT}\right) \), if the effective lifetime is assumed to be temperature insensitive. On a semilog plot of \( J_{g-r} \) versus 1/Temperature, the graph should have a slope of \( E_g/2kT \). Consequently, as temperature is lowered, \( J_{g-r} \) decreases less rapidly than diffusion current implying that generation-recombination current may dominate over diffusion current at lower temperatures. The different temperature dependencies of diffusion and generation-
recombination currents can help determine which current component dominates under varying conditions.

2.4.3 Tunnel Current Mechanism

As the temperature of a photodiode decreases, dark current does not continually decrease as anticipated by the temperature dependencies of diffusion and g-r current components. Instead, temperature-insensitive tunnel current dominates, especially in long wavelength (above 8 microns) photodetectors. At low temperatures, tunnel current is often broken down into two processes, direct interband tunneling and trap-assisted tunneling (see Figure 7-a & b). Direct interband tunneling occurs when a carrier in either the valence or conductance band approaches the depletion region, tunnels through the bandgap, and appears at the same energy in the opposite band [14]. Similarly, trap-assisted tunneling involves carriers that tunnel from a trap within the bandgap to the valence or conduction band. For direct interband tunneling, the probability of transmission of a carrier from one band to another depends strongly on the thickness of the barrier. Trap-assisted tunneling depends additionally upon the energy level of the trap in relation to the valence and conductance bands. For example, the probability of a trap-assisted carrier tunneling often increases when the trap is located near midgap. This study focuses on the trap-assisted tunnel process because the experimental photodiodes are assumed to be trap-dominated by the defects and impurities within the Hg_{0.8}Cd_{0.2}Te lattice.
Figure 7: Two tunneling processes in HgCdTe Photodiodes
Based on research by W.W. Anderson and Hoffman, trap-assisted tunnel current in a reversed-biased photodiode is of the form

\[ J_{\text{tunn}} = -A_t R_{\text{tunn}} W, \quad (8) \]

where \( A_t \) is a proportionality constant and \( R_{\text{tunn}} \) is the tunnel rate of carriers out of traps [6]. The tunnel rate \( R_{\text{tunn}} \) can be represented as an exponential, dependent upon some potential \( V_{\text{tunn}} \) divided by the width of the depletion region. \( J_{\text{tunn}} \) in Equation 8 can be rewritten as

\[ J_{\text{tunn}} = -A_t W \left[ \exp \left( -\frac{V_{\text{tunn}}}{W} \right) \right], \quad (9) \]

where \( W \) (total width of the depletion region) is determined by \( \sqrt{V_a - V_{bs}} \), based on a step junction.

Tunnel current dominates at low temperatures where thermally-activated diffusion and g-r currents become small. The above analysis implies that the magnitude of tunnel current depends on the number and position of traps within the bandgap as well as the tunneling path of the carrier and height of the barrier. Narrow bandgap Hg\(_{0.8}\)Cd\(_{0.2}\)Te material \((E_g = 0.12 \text{ eV})\) can be severely limited by tunnel current if care is not taken to reduce the density of defects.

### 2.4.4 Surface Leakage Current

A photodiode is typically dominated by dark currents due to carrier generation and recombination in the "bulk" regions and the depletion region. However, after actual
fabrication, photodiodes can exhibit additional dark current related to the surfaces of a device. In between the semiconductor surface and insulator, excess energy states in the bandgap (called fast surface states) act as g-r centers and as important sources of carriers and dark current [1]. This process is described by a surface recombination velocity. The surface current density component is given as

\[ J_s = qnS_o, \]  

(10)

where \( S_o \) is the surface recombination velocity. The quality of the device fabrication process has a direct impact on the surface leakage current and detector performance.

2.5 Guard Diode Effects and Diffusion Volume Reduction

Diffusion current can be thought of as originating from a volume within a minority carrier diffusion length of the depletion region on the n- and p-sides of a junction (see Figure 8-a). If a photodiode is dominated by electron diffusion current on the p-side (as suggested in section 2.4.1) and the electron diffusion length is long, then reducing the volume of the p-region base layer should reduce the amount of diffusion current originating from this volume [1]. Two significant ways of decreasing diffusion volume by a guard diode and by physically eliminating a specified amount of material from the diode's back surface, e.g. thinning.

A guard diode is a second diode that surrounds the photodiode (see Figure 8-b). When the guard diode is reversed-biased, some minority carrier electrons that would have diffused toward the photodiode junction diffuse instead toward the guard diode junction.
Photodiode

Current originating from p-region diffusion volume

Guard Diode

Diagram of guard diode surrounding a photodiode

Figure 8

(a) Cross-section of thick diode with NO guard diode present

(b) Cross-section of thick diode with guard diode present
Hence, the diffusion volume surrounding the photodiode and lateral diffusion current are reduced (see Figure 9-a). Through the use of a guard diode, dark current can decrease considerably, depending on the minority carrier diffusion length and the distance between the photodiode and guard diode.

Similarly, if the thickness of the p-region directly underneath the n-region is less than a diffusion length from the photodiode ($L_{P-thickness} < L_n$), the bulk diffusion current can be reduced (see Figure 9-b) [19-20]. However, if the back surface of a thin photodiode has a large surface recombination velocity (possibly due to fast surface states [14]), the dark current can actually increase due to generation of minority carriers at the back surface. For this reason, it is critical that the back surface of a thin detector be passivated like the front surface.

In a thin photodiode surrounded by an operational guard diode, the lateral and bulk diffusion volume in the p-type base layer is reduced (see figure 9-c). Thus, the total electron diffusion current originating from the p-region base layer can theoretically decrease, lending to increased detector performance.

2.6 Minority Carrier Lifetime Model

The minority carrier lifetime in $p$-type Hg$_{0.8}$Cd$_{0.2}$Te is a material property that has a direct impact on dark current and, hence, infrared detector performance. Several techniques have been developed to measure and quantify minority carrier lifetimes. One such
(a) Cross-section of thick diode with guard diode "ON"

(b) Cross-section of thin diode with guard diode not present

(c) Cross-section of thin diode with guard diode "ON"

Figure 9
This technique involves using microwave radiation to detect transient changes in conductivity due to optically-generated excess carriers. Another method involves deducing lifetimes from measured dark current [16], [26]. However, to obtain reasonable values, an accurate model depicting the currents in a photodiode must be used. This study presents lifetime data based on both the contactless microwave reflection technique and measured dark current density.

To accurately calculate lifetimes from measured dark current, the traditional one-dimensional diode model needs to be extended to accommodate three dimensions. This adds complexity, but some simplifications can be made. If a photodiode operates in reverse-bias and the hole diffusion current is assumed to be negligible compared to electron diffusion current, the electron lifetime becomes inversely proportional to the diffusion current by the equation

$$ J_{\text{diff}} = -n_i^2 \frac{q}{N_a} \left[ \frac{L_n}{\tau_n} \right]. $$

Furthermore, if current-voltage measurements are taken at relatively high temperatures and low bias ($V_a < +100 \text{ mV}$), where generation-recombination and tunnel currents become negligible compared to diffusion current, the dark current is predominantly diffusion-limited.

Referring to Figure 10-a, it is easiest to think of diffusion current originating from three separate regions. For example, region 1 can be considered a one-dimensional source of bulk current defined by

$$ J_{\text{diff}}^1 = -n_i^2 \frac{q}{N_a} \left[ \frac{L_n}{\tau_n} \right] \tanh \left( \frac{L_{p-thickness}}{L_n} \right). $$
Diagram of diffusion current originating from three separate regions within the p-type base layer.

Top view of photodiode with NO guard diode present.

Top view of photodiode with guard diode "ON".

Figure 10
where $J^1_{\text{diff}}$ is the standard equation for diffusion current with an added hyperbolic tangent quantity which incorporates the probability that an electron will diffuse toward the diode junction. Similarly, lateral dark current from region 2 in Figure 10-a can be characterized by the equation

$$J^3_{\text{diff}} = \frac{n_i^2 q}{d^2 N_a} \left[ \frac{\text{vol}_{\text{diff}}}{\tau_n} \right],$$

(13)

where $\text{vol}_{\text{diff}}$ is a volume defined as $(L_{N-\text{thickness}})\left[\left(d + 2L_n \tanh\left(\frac{G_1}{\tau_n}\right)\right)^2 - d^2\right]$ based on the dimensions in Figure 10-b & c ($L_{N-\text{thickness}}$ is the depth of the n-region - See Figure 1-b, $d$ is length of the diode, and $G_1$ is some intermediate distance between the guard diode and photodiode [16], [26]). Like equation 12, a hyperbolic tangent function is included in the $\text{vol}_{\text{diff}}$ term of equation 13 to calculate the probability that an electron will "laterally" diffuse toward the photodiode junction. Dark current out of region 3 may be modeled as

$$J^3_{\text{diff}} = \frac{n_i^2 q}{d^2 N_a} \left[ L_n \left( \left(d + 2L_n \tanh\left(\frac{G_1}{\tau_n}\right)\right)^2 - d^2 \right) \right] \tanh\left(\frac{L_{P-\text{Thickness}}}{L_n}\right).$$

(14)

By using appropriate parameter constants $n_i$, $E_g$, and $u_a$ for the Hg$_{1-x}$Cd$_x$Te material system and by choosing a certain electron lifetime, a theoretical dark current density can be calculated and compared to an experimentally measured dark current density (See appendix for the assumptions made in the three dimensional current model and a discussion of material parameters). By varying $\tau_n$ until the theoretical and experimental values coincide, a minority carrier lifetime can be estimated.
Chapter 3

Experimental Approach

3.1 Introduction

The first half of this Chapter highlights the $PN$ homojunction formation process for the vacancy- and gold-doped photodiodes. Device structure geometry are also presented. In the latter half of Chapter 3, the measurement techniques for infrared detector characterization will be summarized.

3.2 Device Structures (PN junction formation)

The photodiodes in this study are fabricated on narrow bandgap material ($E_g \approx 0.125$ eV at 77 K) and are formed by ion implantation into $p$-Hg$_{0.8}$Cd$_{0.2}$Te grown by liquid phase epitaxy (LPE). Acceptor concentration is determined by a Hall effect measurement with a Van der Pauw four-point geometry. After the growth stage is completed, the wafer is "thinned down" to a predetermined thickness by a process known as diamond point turning. Next, the Hg$_{0.8}$Cd$_{0.2}$Te wafer undergoes an initial polish in preparation for surface passivation. In extrinsic-doped device structures, the Hg$_{0.8}$Cd$_{0.2}$Te film undergoes a
proprietary surface treatment and a layer of Zinc Sulfide is deposited on the surface by the MOCVD method. For vacancy-doped test samples, Cadmium-Telluride is used as the surface passivation. It is imperative that the Hg0.8Cd0.2Te be passivated at the surface to terminate the lattice bonds and hence reduce surface leakage currents.

The Hg0.8Cd0.2Te material is now ready for diode formation by ion implantation. Ion implantation is a popular technique used to form n-on-p junctions. Type conversion of ion-implanted p-Hg1-xCdxTe is primarily due to ion-irradiation damage rather than implanted species [1], [17-18]. Research conducted on low carrier concentration n-type wafers by Margalit, et al. shows that the sheet electron concentration in n+ layers which forms during implantation is not sensitive to either implant species or implant doses ranging from 5x10^{11} to 1x10^{15} cm^{-2}. Margalit concludes that the n+ implanted layers are due to implant damage rather than substitutional doping [1]. The ion implantation process uses boron as the preferred implanted species because of the element's small mass [1]. The junction formation was done at room temperature using implant doses ranging from 10^{14} to 10^{15} cm^{-2} at energies of 100 KeV.

After ion implantation, the vacancy-doped device structures undergo a controlled anneal. Mercury interstitials from the implantation damage act as a limited Hg in-diffusion source during post-implant anneals. The Hg interstitials fill the excess Hg vacancies in the as-grown p-type wafer, causing the region around the implanted area of Hg0.8Cd0.2Te to convert to n-type, completing the formation of an n-on-p junction. The extrinsic gold-doped
device structures do not undergo a post-implant anneal. Unless otherwise stated, the device structures used for experimentation have photodiode parameters listed in Table 1.
## Photodiode Parameters of Test Structures

### Gold-doped Devices

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Gold) acceptor concentration $N_A$</td>
<td>$10^{15}$ to $10^{16}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$p$-side thickness</td>
<td>10 - 50 microns</td>
</tr>
<tr>
<td>temperature $T$</td>
<td>77 K</td>
</tr>
<tr>
<td>band gap $E_g$</td>
<td>0.125 eV</td>
</tr>
<tr>
<td>insulator</td>
<td>ZnS, 2000 Angstroms</td>
</tr>
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</table>

### Vacancy-doped Devices

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Vac.) acceptor concentration $N_A$</td>
<td>$10^{17}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$p$-side thickness</td>
<td>10 - 50 microns</td>
</tr>
<tr>
<td>temperature $T$</td>
<td>77 K</td>
</tr>
<tr>
<td>band gap $E_g$</td>
<td>0.125 eV</td>
</tr>
<tr>
<td>insulator</td>
<td>CdTe, 2000 Angstroms</td>
</tr>
</tbody>
</table>

Table 1 - Photodiode Parameters of Test Structures
3.3 Test Samples

After the PN junction formation process, the field plates and bonding pads are deposited onto the wafer. Next, the samples are sawed into test bars and mounted into standard 62-pin packages. Each photodiode is bonded to a connector in the 62-pin package. Testing is conducted on diode cells composed of four Hg_{0.8}Cd_{0.2}Te diodes sharing a common field plate and substrate contact (see Figure 11-a). During fabrication, two separate diode cell configurations are created; one diode cell configuration contains only four photodiodes while a second cell configuration is constructed to have an additional guard diode that surrounds the four photodiodes.

All test diodes within each cell are designed to have different perimeters and areas. Referring to Figure 11, bond pad number one is connected to a 1.2 mil by 1.2 mil photodiode while a 5 mil by 6 mil diode is connected to bond pad number two. The number three and four bond pads have contact to a 2x2 mil^2 and a 3x3 mil^2 diode, respectively. The table in Figure 11-b includes the implanted perimeter and implanted area of each diode in mils and centimeters. In diode cells with a guard diode, experiments were conducted on photodiodes spaced 15 microns away from the surrounding guard diode. The design of the cells is expressly created to understand where the excess dark currents are originating within the test diodes.

Photodiodes were fabricated on thick and thin p-region base layers. This is done to evaluate the theoretical decrease in dark current when the bulk diffusion volume is thinned
(a) Diagram of diode cell structure containing four photodiodes (guard diode not shown)

**Table of Photodiode Dimensions**

<table>
<thead>
<tr>
<th>Bond Pad</th>
<th>Pixel size of Photodiode</th>
<th>Photodiode Implant Area (mils^2)</th>
<th>Photodiode Implant Area (cm^2)</th>
<th>Photodiode Perimeter (mils)</th>
<th>Photodiode Perimeter (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2x1.2</td>
<td>2.7</td>
<td>1.76 E-5</td>
<td>4.8</td>
<td>1.2 E-2</td>
</tr>
<tr>
<td>2</td>
<td>5x6</td>
<td>29.92</td>
<td>1.93 E-4</td>
<td>21.88</td>
<td>5.6 E-2</td>
</tr>
<tr>
<td>3</td>
<td>2x2</td>
<td>3.92</td>
<td>2.58 E-5</td>
<td>7.92</td>
<td>2.5 E-2</td>
</tr>
<tr>
<td>4</td>
<td>3x3</td>
<td>8.92</td>
<td>5.81 E-5</td>
<td>11.95</td>
<td>3.0 E-2</td>
</tr>
</tbody>
</table>

(b) Table of each photodiode's perimeter and area

Figure 11: Physical layout of diode cell.
Thick photodiodes have a p-region base layer thickness that is much greater than the minority carrier diffusion length on the p-side \((L_{p\text{-thickness}} \gg L_n)\). On the other hand, thin photodiodes are approximately 10 microns thick, which in many cases, is shorter than the diffusion length \((L_{p\text{-thickness}} < L_n)\).

### 3.4 Current-Voltage Measurement Technique

Current, as a function of voltage, was measured on diode cells cooled to 77 degrees Kelvin by immersion in liquid nitrogen. This was done in order to minimize the flow of dark current in the devices, provide a thermally stable environment, and mimic the actual operating temperature of an infrared detector array. To obtain measurements, the 62-pin package is placed in a fixture having electrical connections to the bond pad of each photodiode, field plate, and substrate contact; contact is also made to the guard diode in cells configured with one. The field plate voltages in each cell are then optimized to obtain the minimum dark current per diode at a fixed reverse-bias (100 mV).

Three separate current-voltage measurements are taken in this study. First, measurements are collected on photodiodes without a surrounding guard diode. In diode cells configured with a guard diode, two separate current-voltage measurements are taken while the guard diode is reversed-bias to 100 mV and while the guard diode is electrically floating; this study will refer to a reversed-biased guard diode as "ON" and a floating guard diode as "OFF". A Hewlett Packard Semiconductor Parameter Analyzer (HP 4145A),
controlled by a PC-compatible computer, is used to measure the diode's current-voltage curve. Next, current and current density versus voltage plots are generated on a semi-log plot (see Figure 12 for a typical current-voltage curve). Current density will be defined in this study as current divided by the photodiode's implant area, which is listed in Figure 11-b. Current-Voltage measurements were also taken as a function of temperature by this same method except that a Variable Temperature Hansen Dewar was used to contain and cool the test devices using liquid Helium.
Figure 12: A typical experimentally measured current-voltage plot for a 1.2x1.2 mil$^2$ HgCdTe photodiode at 77 K. (semi-log plot)
Chapter 4

Results and Discussion

4.1 Introduction

This chapter presents measurements collected on extrinsic gold-doped photodiodes. The data will be compared to typical electrical characteristics found in vacancy-doped photodiodes. In Section 4.2, dark current measurements on thick and thin gold-doped diodes will be discussed. Additionally, dark current in gold-doped photodiodes will be compared as the detector is operated with and without a guard diode. Variable temperature current data will be analyzed in Section 4.3 to determine the current components in thick and thin gold-doped devices. In Section 4.4, electron lifetimes for gold- and vacancy-doped detectors will be extracted from dark current measurements using a model developed by Dr. M. Kinch at Texas Instruments, which was described previously in Section 2.6.

4.2 Current-Voltage Measurements

Current-Voltage (also called I-V) characteristics were measured on four sizes of test diodes having areas of 2.7 mils$^2$, 4 mils$^2$, 9 mils$^2$, and 30 mils$^2$ respectively (see figure 11 in
Section 3.4, p. 44). I-V measurements were collected on photodiodes in cells that both did and did not have guard diodes. In diode cells with guard diodes, separate current-voltage measurements were taken with the guard diode "ON" and "OFF" to determine how much dark current decreases when a guard diode surrounds a photodiode.

4.2.1 Thick versus Thin Gold-Doped Photodiodes

Thick Photodiodes

Current density was measured at 77K on photodiodes fabricated in thick material ($N_a \approx 2 \times 10^{16}$ to $3 \times 10^{16}$ cm$^{-3}$) with a 10.3 micron cutoff wavelength. Figure 13 shows that at +50 mV, the current densities in photodiodes without guard diodes ranged between 0.25 mA/cm$^2$ to 0.5 mA/cm$^2$. For each area, the diodes are ranked according to increasing current density. The current density values vary with the diode implant area.

Data was also collected on diode cells configured with a guard diode. Referring to Figure 14, when the guard diode is "OFF" (electrically floating), current density averaged around 0.4 mA/cm$^2$. In comparison, the dark current density with the guard diode "ON" decreased to approximately 0.25 mA/cm$^2$ with nearly no dependence on diode implant area. This demonstrates that the lateral dark current may have decreased with the guard diode reversed-biased, which is expected since the lateral diffusion volume is reduced when a guard diode is "ON" (see section 2.5 for further discussion).
Figure 13: Distribution plot of measured dark current density for four implant areas of thick gold-doped photodiodes without guard diodes. (+50 mV at 77 K)
Figure 14: Distribution plot of measured dark current density for four implant areas of thick gold-doped photodiodes with guard diodes "ON" versus "OFF".

(+50 mV at 77 K with 15 micron spacing between guard diode and photodiode)
It is possible to determine whether bulk or lateral currents dominate the dark current by plotting dark current density as a function of diode perimeter to area ratio (P/A). This type of analysis determines the quality of the Hg$_{0.8}$Cd$_{0.2}$Te surface since poor surface passivation often modulates excess surface leakage current (see Section 2.4.4 for further discussion). Figure 15 plots current density for photodiodes without a guard diode as a function of diode perimeter to area ratio (diode cells without guard diodes were chosen so that any distortions caused by the presence of a guard diode would be removed). The data in Figure 15 suggests that dark current follows a linear perimeter dependence. The observed dark current dependence on diode geometry implies that surface and/or lateral currents become dominant for small geometry devices in thick gold-doped photodiodes.

**Thin Photodiodes**

Dark current in thin photodiodes ($N_d \approx 2 \times 10^{16}$ to $3 \times 10^{16}$ cm$^{-3}$) with a 10.3 micron cutoff wavelength behaved similarly to their thick counterparts. As seen in Figure 16, dark current density in photodiodes without guard diodes averaged approximately 0.2 to 0.5 mA/cm$^2$. These measurements are in the same range of current density values for thick photodiodes. Further analysis indicates that for the 2x2 mils$^2$, 3x3 mils$^2$, and 5x6 mils$^2$ photodiodes, dark current density for thin photodiodes decreased by 25 to 45 percent compared to equivalent thick photodiodes. However, dark current densities for the 1.2x1.2 mils$^2$ thin and thick photodiodes were approximately the same.
Figure 15: Measured dark current density as a function of perimeter to area ratio (P/A) for thick gold-doped photodiodes without guard diodes. (+50 mV at 77 K)
Figure 16: Distribution plot of measured dark current density for four implant areas of thin gold-doped photodiodes without guard diodes. (+50 mV at 77 K)
For thin photodiodes surrounded by a guard diode, the current density when the guard diode is "OFF" averaged 0.4 mA/cm² while dark current density decreased by a factor of two to 0.15 mA/cm² with the guard diode reversed-biased (see Figure 17). Similar to thick detectors, the use of a guard diode reduces lateral dark current and improves performance.

Thin photodiodes should exhibit less dark current than thick photodiodes (see Section 2.5). If the diffusion volume is reduced in diodes where the electron diffusion length is longer than the p-region thickness ($L_n > L_{p-thickness}$), bulk electron diffusion current should also decrease. To verify this theory, dark current in thin photodiodes should be less than thick photodiodes. As mentioned above, dark current densities for three out of the four thin (without a guard diode) photodiodes of varied dimensions decreased compared to thick photodiodes. In the case between thick and thin detectors with operational guard diodes, thin photodiodes exhibited roughly 15 to 30 percent less dark current density than thick photodiodes. Thus, as theory suggests, thin photodiodes, on average, display less dark current density than thick detectors.

Figure 18 plots dark current density as a function of diode perimeter to area ratio (P/A) for thin gold-doped photodiodes without a guard diode. These particular photodiodes displayed excessive lateral (perimeter) dependent dark current, especially for the 1.2x1.2 mils² diodes. The dark current seems to be dependent exponentially on the perimeter as compared to a linear perimeter dependence for thick photodiodes. This strong perimeter
Figure 17: Distribution plot of measured dark current density for four implant areas of thin gold-doped photodiodes with a guard diode "ON" versus "OFF". (+50 mV at 77 K with 15 microns spacing between guard diode and photodiode)
Figure 18: Measured dark current density as a function of perimeter to area ratio (P/A) for thin gold-doped photodiodes without guard diodes. (+50 mV at 77 K)
effect suggests a surface leakage problem, possibly due to fast surface states (see Section 2.4.4 for further discussion on surface states). Improving the material/device surface passivation process should help reduce this current source.

4.2.2 Gold-doped versus Vacancy-doped Photodiodes

To determine if gold-doped detectors perform better than vacancy-doped devices, dark currents comparisons between thin photodiodes are made. Analysis of diode data shows that thin gold-doped photodiodes with guard diodes outperformed vacancy-doped [high $N_a$ ($\approx 1\times 10^{17}$ cm$^{-3}$)] photodiodes. Dark currents in the vacancy-doped detectors are 2 to 3 times larger than those in gold-doped devices. It is believed that vacancy-doped photodiodes are limited by a short minority carrier lifetime associated with the high acceptor concentration starting material. Figure 19 shows representative values of dark current density versus cutoff wavelength for gold- and vacancy-doped photodiodes. This plot suggests that gold-doped photodiodes have consistently lower dark current as a function of cutoff wavelength.

4.3 Variable Temperature Measurements

As discussed in Section 2.4, the total dark current in a photodiode is made up of separate current mechanisms with each component having a unique temperature behavior. In an ideal diode, diffusion current is the dominant current component. However, it is important to understand if other current mechanisms, such as tunneling, dominate under normal
Figure 19: Measured dark current density as a function of cutoff wavelength at 77K for thin gold-doped photodiodes versus thin vacancy-doped photodiodes. (+50 mV with guard diode "ON")
operating conditions. If the dominant current mechanisms can be determined, changes in photodiode fabrication can be implemented to reduce dark currents and, thus, improve infrared detector performance.

Various techniques are used to separate dark current into its various components. For example, Figure 20-a illustrates differences in voltage dependencies for theoretic diffusion current, generation-recombination current and tunnel current. Separating the current mechanisms is done by simply examining a photodiode's current-voltage plot (see Figure 20-b, which shows a typical experimentally measured current-voltage plot for a 1.2 x 1.2 mil² Hg0.8Cd0.2Te photodiode at 77K).

Another technique used to separate dark current components is an analysis of current-voltage measurements over a range of temperatures. Diffusion current can be identified by its $n_i^2$ temperature dependence (see Section 2.4.1 for further explanation). Since g-r current varies mainly as $n_i$ with temperature, it may be uniquely determined by a slope of $E_g/2kT$ on a semilog plot of dark current versus 1/Temperature (see Section 2.4.2). Tunnel current is recognized by its temperature insensitivity.

This thesis focuses on the latter technique: current-voltage measurements taken as a function of temperature. Analysis of the extrinsic gold-doped photodiodes was performed by generating Arrhenius-style plots of dark current at +50 mV versus inverse temperature for temperatures between 40K and 150K, as will be discussed next.
Figure 20: (a) Diffusion current, G-R current, and Tunnel current as a function of photodiode reverse-bias
(b) Dark current density separated into current components for a 1.2x1.2 mil\(^2\) HgCdTe photodiode at 77 K. (semi-log scale)
4.3.1 Thick Gold-Doped Photodiodes

Extrinsic gold-doped photodiodes fabricated on thick Hg$_{0.8}$Cd$_{0.2}$Te material having an $N_a$ of $2.3 \times 10^{16}$ cm$^{-3}$ were tested in a Variable Temperature Hansen Dewar. I-V measurements were taken on test diodes configured both with and without a guard diode. On photodiodes surrounded by a guard diode, separate measurements were taken with the guard diode both biased and floating. Figures 21 and 22 show two separate Arrhenius plots for the cases when a guard diode surrounding the detector is "ON" and "OFF". Similarly, an Arrhenius-style plot in Figure 23 was generated for the case when a guard diode is not present in the diode cell. These three graphs appear to be similar in shape; each plot has a change in slope near 66K ($1000/T=15$). Below 66K, the lack of a temperature dependence suggests the current is tunnel-limited. The high-temperature (above 66K) regime has an activation energy $E_a$ of 104 meV or roughly $0.90E_g$. This implies that diffusion current appears to dominate above 66K. Generation-Recombination current in gold-doped photodiodes does not seem to dominate between 40K and 150K at the biases measured.

4.3.2 Thin Gold-Doped Photodiodes

Variable temperature I-V measurements were also collected on thin gold-doped photodiodes with guard diodes and having hole carrier concentrations of $2.4 \times 10^{15}$ cm$^{-3}$ (data on photodiodes without guard diodes was not available). Like their thick counterparts, the thin gold-doped devices have an identifiable change in slope when dark current density is
Figure 21: Measured dark current density versus inverse temperature for thick gold-doped photodiodes with guard diode "ON". (+50 mV)
Figure 22: Measured dark current density versus inverse Temperature for thick gold-doped photodiodes with guard diode "OFF". (+50 mV)
Figure 23: Measured dark current density versus inverse Temperature for thick gold-doped photodiodes with guard diode NOT present. (+50 mV)
plotted on an Arrhenius style plot (see Figure 24). However, the change in slope occurs at 55K (1000/T=18) rather than 66K, as seen in thick diodes. The small slope in Figure 24 below 55K suggests that the tunnel current dominates. For temperatures above 55K, the slope of the semi-log plot for data taken with the guard diode "OFF" is 104 meV, or equivalent to those on thick gold-doped diodes. This suggests that diffusion current dominates above 55K on thin detectors with guard diodes floating. However, the slope appears to be slightly less when the guard diode is "ON" (see Figure 24). Fitting the high-temperature portion of the dark current data yields an activation energy $E_a$ of 80 meV, or roughly $0.66E_g$.

The discrepancy in activation energies between the cases when the guard diode is "ON" and when the guard diode is "OFF" may be attributed to differences in lateral diffusion current. When a photodiode is operated without a guard diode, the lateral dark currents are limited by the minority carrier diffusion length and are proportional to $\sqrt{\tau}$, similarly to the bulk diffusion current for a thick diode (see equation 5 in Section 2.4.1). However, when a photodiode is surrounded by a reverse-biased guard diode, the lateral diffusion current is limited by the distance between the guard diode and photodiode (represented as $G_1$ in Figure 10-c in Section 2.6, p. 37). The lateral diffusion current now becomes proportional to $\sqrt{\tau}$ rather than $\sqrt{\tau}$. If the minority carrier lifetime is limited by Shockley-Read recombination with an activation energy $E_R$ (see Kinch et al.) then the difference in measured activation energies for the guard diode "ON" versus "OFF" cases will be $E_R/2$. Thus, these variable
Figure 24: Measured dark current density versus inverse Temperature for thin gold-doped photodiodes with guard diode "ON" versus "OFF". (+50 mV with 15 microns spacing between guard diode and photodiode)
temperature measurements can be used to estimate the position of recombination centers relative to the valence and conduction bands.

The variable temperature data collected on both thick and thin gold-doped photodiodes is similar to the results measured on vacancy-doped photodiodes. The generation-recombination current component in gold-doped photodiodes is not observed between temperatures of 5 K and 100K, in agreement with research done on vacancy-doped detectors by DeWames et al. [10].

4.4 Minority Carrier Lifetime Data

By using an extrinsic dopant such as gold in place of Hg-vacancies, it is believed that the minority carrier lifetime on the p-side of the junction will increase and, thus, reduce the electron diffusion current (see equation 5 in Section 2.4.1). As discussed in Section 2.6, the minority carrier lifetime can be estimated by different techniques. The data in this section compares calculated electron lifetimes based on a three dimensional current model to lifetime data obtained by Chen et al. using their microwave reflection technique [15-16], [26].

Chen et al. have conducted minority carrier lifetime measurements over a range of hole carrier concentrations for both vacancy- and extrinsic-doped p-type Hg_{0.8}Cd_{0.2}Te LPE films [22]. He has found that films doped with either copper or gold have lifetimes several times longer than vacancy-doped films and that these lifetimes are limited mostly by Auger 7 and radiative recombination processes [1], [22] (see Figure 25).
Figure 25: Measured minority carrier electron lifetimes for extrinsic-doped photodiodes compared to vacancy-doped photodiodes as a function of doping concentration at 77K.

The solid line through the data of extrinsic-doped films was calculated with Auger 7 and radiative recombination processes. The dashed line through the data of vacancy-doped films is the trend line. (lifetimes measured by microwave reflection technique [M.C. Chen, 1993])
Referring to Figure 26, electron lifetimes deduced from diffusion current model seem to support M. C. Chen's conclusion; lifetimes in gold-doped photodiodes are consistently two to four times longer than those in vacancy-doped detectors over a carrier concentration range from $4 \times 10^{15}$ to $4 \times 10^{16}$ cm$^{-3}$. Minority carrier lifetimes in gold-doped devices were estimated to be between approximately 3 nanoseconds for an $N_A = 3.4 \times 10^{16}$ cm$^{-3}$ to 40 nanoseconds for an $N_A = 4.4 \times 10^{15}$ cm$^{-3}$. The discrepancy in actual values between these deduced lifetimes and the microwave reflection lifetimes may be due to the use of unprocessed Hg$_{0.8}$Cd$_{0.2}$Te LPE films in the microwave reflection technique.

Dr. Chen goes a step further and calculates theoretic diffusion-limited RoA values based on lifetimes given in Figure 27 (RoA is often used as a figure of merit and is given as $R_oA = \frac{kTN_A}{q^2n^2d}$ [1]). While measured RoA values in the gold-doped photodiodes are not as high as those predicted by Chen et al., gold-doped detectors do exhibit larger RoA's than vacancy-doped devices.
Figure 26: Minority carrier electron lifetimes deduced from measured dark current density for gold-doped photodiodes compared to vacancy-doped photodiodes as a function of doping concentration.
Figure 27: Calculated diffusion limited $R_o A$ values, based on lifetimes in Fig. 25, for films with extrinsic and vacancy doping. The calculation assumes a device thickness of 6 microns. [M.C. Chen, 1993]
Chapter 5

Conclusion

5.1 Summary

In the present study, gold-doped Hg$_{0.8}$Cd$_{0.2}$Te photodiodes were electrically characterized. As part of the characterization process, current-voltage measurements at 77 K were conducted on both thick (> 50 microns) and thin (10 microns) photodiodes. Theory states that thin photodiodes should exhibit less dark current than equivalent thick photodiodes [19-20]. In dark current comparisons between thick and thin gold-doped photodiodes with similar cutoff wavelengths and acceptor concentrations, thin detectors exhibited an average of 25 to 35 percent less dark current than thick detectors.

Photodiodes can also be operated with a surrounding guard diode. The primary reason for a guard diode is to attract minority carriers that otherwise diffuse toward the photodiode. Theory states that operating a guard diode in the reverse-bias state should decrease the amount of dark current in a photodiode. In dark current comparisons between photodiodes with guard diodes "ON" versus "OFF", dark currents with a guard diode "ON" were 40 to 60 percent lower than in the case with the guard diode left electrically floating.
The quality of the surface passivation for Hg$_{0.8}$Cd$_{0.2}$Te epitaxial films can be determined by comparing whether lateral/surface or bulk dark currents dominate a detector. This study shows that both thin and thick gold-doped photodiodes display signs of perimeter-dependent current, likely due to surface leakage current.

Dark current comparisons were also made between thin gold-doped ($N_a \approx 3 \times 10^{16} \text{cm}^{-3}$) and vacancy-doped, ($N_a \approx 1 \times 10^{17} \text{cm}^{-3}$) photodiodes. Gold-doped detectors outperformed vacancy-doped photodiodes based on current-voltage measurements at 77 K. The measured current density for gold-doped photodiodes is two to three times less than that in vacancy-doped detectors.

In gold-doped detectors, efforts to separate dark current into its fundamental current components were also made by collecting current-voltage measurements over a range of temperatures between 40K and 150K. In thick photodiodes, measurements taken with the guard diode in three different configurations (guard diode "ON", guard diode "OFF", and no guard diode present) gave similar results. Variable temperature data suggests that the diffusion current dominates above 66K while the tunnel current component prevails at lower temperatures.

Diffusion current in thin photodiodes was observed at temperatures above 55K while tunnel current seemed to be the dominant current mechanism at temperatures below 55K. Gold-doped photodetectors do not exhibit any signs of generation-recombination current.
between temperatures of 40K to 150K at the bias tested. The diffusion and/or tunnel current components are likely overshadowing the g-r current.

The minority carrier (electron) lifetime was also estimated in both gold- and vacancy-doped photodiodes. Lifetime data deduced from measured dark current densities indicates that gold-doped devices have minority carrier lifetimes approximately three times longer than vacancy-doped diodes for equivalent acceptor concentrations. This qualitatively agrees with lifetime measurements taken by Dr. Chen using a microwave reflection technique [22].

In conclusion, this thesis presents a set of self-consistent experiments for characterizing gold-doped photodiodes. Minority carrier lifetime data based on two separate techniques suggests that gold-doped photodiodes exhibit longer lifetimes than vacancy-doped detectors. Consistent with this observation, dark currents in gold-doped photodiodes are lower than those in vacancy-doped devices.

5.2 Future Work

Additional experiments are necessary before gold-doped photodiodes replace the standard vacancy-doped infrared detector technology at Texas Instruments. Understanding the bake stability is critical. Furthermore, experiments on photodiodes with higher gold concentrations need to be conducted to understand any changes in current-voltage characteristics. Also, other extrinsic acceptor dopants such as copper could be examined to see if other dopants provide even longer minority carrier lifetimes than those exhibited in
gold-doped photodiodes.
Chapter 6

Appendix

6.1 Modeling Dark Current within a Photodiode

To reliably model the dark current within a photodiode and estimate a minority carrier lifetime, accurate material parameters have to be established; e.g., experimental constants and empirical expressions for $n_i$, $E_g$, and $\mu_a$ in the Hg$_{1-x}$Cd$_x$Te material system. In this thesis, "best estimates" of material parameters were found in literature.

In the mercury-cadmium-telluride material system (Hg$_{1-x}$Cd$_x$Te), the energy bandgap $E_g$ is related to the mole fraction of cadmium ($x$) and temperature ($T$). The model in this study uses the empirical expression

$$E_g = -0.302 + 1.93x + 5.35(10^{-4})T(1 - 2x) - 0.810x^2 + 0.832x^3$$

for this energy gap versus alloy composition derived by G. L. Hansen et al. [23].

G.L. Hansen and J.L. Schmit have also derived the following similar expression

$$n_i = [5.585 - 3.820x + 1.753(10^{-3})T - 1.364(10^{-3})xT] \frac{1}{(10^{-14})E_g^{3/2}T^{3/2} \exp\left(-\frac{E_g}{2kT}\right)}$$
for the intrinsic carrier concentration \((n_i)\) in \(\text{Hg}_1-x\text{Cd}_x\text{Te}\) as a function of temperature and composition by using the Kane nonparabolic approximation for band structure \([24]\). Electron mobility is another important material parameter needed to model electron diffusion current in a photodiode. The theory of Brooks-Herning provides a derivation for mobility based upon impurity scattering and screening of the Coulomb field by free electrons and holes \([25]\). Unpublished work by Dr. M. Kinch of Texas Instruments extends the Brooks-Herning theory on mobility to the mercury-cadmium-telluride material system and is the basis for the mobility used in the diffusion current model discussed in see Section 2.6 \([16]\).

6.2 Basic Assumptions in the Current Model

Several assumptions have been made in the model used to estimate the minority carrier lifetime from the dark current. First, to calculate the diffusion current, an accurate acceptor concentration \(N_A\) has to be known. In this thesis, \(N_A\) is based on Hall effect measurements using a Van der Pauw four-point geometry. Other "best guess" assumptions have to be made about the dimensions of the \(p\)-region diffusion volume and device structure geometry. The depth of the \(n\)-region (referred to as \(L_{N-thickness}\)) is one such dimension that is assumed. Based on characterization tests at Texas Instruments, \(L_{N-thickness}\) is approximately 2 to 5 microns. Similarly, \(L_{P-thickness}\), the thickness of the \(p\)-region base layer, is estimated by subtracting \(L_{N-thickness}\) from the total measured thickness of the
detector. When the guard diode is operated, the value for \( G_1 \) (see Figure 10-c) is estimated to be approximately half the distance between the guard diode and photodiode.
Bibliography


[22] M.C. Chen, L. Colombo, J. Dodge, and J. Tregilgas, "The Minority Carrier Lifetime in Doped and Undoped Hg_{0.78}Cd_{0.22}Te LPE Films," 1993 U.S. Workshop on the Physics and Chemistry of Mercury Cadmium Telluride and Other IR Material.


