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Silicon Based Metal-Semiconductor-Metal Photodetectors

By
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A thesis submitted to the
Faculty of Graduate Studies and Research
In partial fulfillment of the requirements
For the degree of
Master of Engineering
In Electrical Engineering

Ottawa-Carleton Institute of Electrical Engineering
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acceptance of the thesis

Silicon Based Metal-Semiconductor-Metal Photodetectors

submitted by

Amanda DeVries, B.A.Sc.

In partial fulfillment of

The requirements of the degree of

Master of Engineering

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ABSTRACT

With the possibility of fully optical telecommunication networks now within industry's grasp, optical designers face numerous challenges as they attempt to integrate optical and electronic functions together while continually increasing capacity and speed.

This thesis is comprised of two novel projects. An attempt was made to fabricate, test, and characterize a polysilicon-germanium metal-semiconductor-metal (MSM) 1550nm detector for long-haul optical communications. It was eventually determined that the high-quality germanium film required could not be fabricated given the limited resources at the Carleton University laboratory. Subsequently, a polysilicon MSM detector was fabricated, tested, and characterized at 850nm light for use in short-haul fiber communications and high bandwidth optical interconnects. Electron beam lithography, used for the first time in the Carleton Fabrication Lab, allowed the possibility of submicron dimensions, resulting in very small, fast devices. The detectors exhibited fast responses (1.5GHz), but large dark currents ($\sim 40\text{nA}$ over $750\text{ }\mu\text{m}^2$).

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1. INTRODUCTION

The use of light for telecommunications is a rapidly changing, very profitable industry. With more data now sent along communication networks than telephone conversations, the telecommunications industry has been hard pressed to meet consumers' bandwidth and processing speed demands. It is expected that the 'holy grail' of the telecommunications industry – the all-optical global network – will be a reality by the year 2015, with speeds in the terahertz range and transmission distances over 10,000 km.¹

In order to realize this exponential growth and satisfy the increasing demand, focus must be turned to the system components that comprise a communications network. The most promising advances to date involve the impressive evolution of optical amplifiers, optical cross-connects, and integrated optical components.

Integrating the various stages of optical transmitters and receivers on electronic chips eliminates many speed limitations inherent in metal interconnect networks. Monolithic integration also promises higher sensitivity, compact devices and reliable performance². New functions can be realized and the cost per component drops dramatically when several discrete devices are brought together on a single substrate. The ultimate goal of optical integration is expected to achieve the kind of success that electronic VLSI technology has enjoyed over the last 20 years.³

Integration also introduces new design challenges since the optical layers typically require very high quality, controlled composition films while the electronic devices and

interconnects introduce impedance matching issues. The problem is to reconcile these concerns into a solution that remains cost effective.

This thesis attempts to reconcile one of the many issues faced by the telecommunications industry by introducing a photodetector that is highly integrable and economical to produce.

Modern Optical Fiber Communications

Current data rates transmitted over fiber optic systems are in the range of OC-3 (155.52 Mbps), OC-12 (622.08 Mbps), and OC-48 (2488.32 Mbps) data rates. The next generation of optical network components at OC-192 (9953.28 Mbps) is already commercially available, with OC-768 in the foreseeable future^{4,5}. Thus the lightwave telecommunications industry is gaining momentum at breakneck speed.

The digital modulation schemes used for data transport currently involve a conversion from optical to electrical - or microwave - formats (and vice versa) at the transmitter and receiver ends. The fully optical networks envisioned for the near future must perform the modulation, guiding, amplification, and demodulation at the optical level. Optical networking technology has been pushed even further with the birth of WDM (or wavelength division multiplexing). By sending multiple channels (i.e. wavelengths) simultaneously over the same fiber, the total fiber capacity has dramatically increased over a very short period of time.

In WDM, each access node in the network is assigned a specific wavelength value. In order to establish a connection to a node, the transmitter selects the appropriate receiver

node wavelength to send its optical signal. Several optical signals, each transmitting using a different wavelength of light, can be multiplexed together and sent over the optical network. Thus dynamic WDM systems require wavelength-tunable transmitters and receivers, which are currently in the early stages of development.

Using WDM with wavelengths in the band of 1.3-1.6 μm (that is, the band of lowest loss in fiber optic glass) and assuming the selected node can support gigabit per second electrical processing, the theoretical aggregate data rate of an optical communication link could thus approach the terahertz range⁶.

The Role of MSM detectors in Modern Fiber Optic Systems

The integration of optical devices with electronic structures has presented many challenges to the telecommunications industry. Optical devices are normally vertical structures, while field effect transistors, often used in the amplification stage of optical receivers, are planar. Many techniques have been surveyed in order to successfully integrate the two inherently incompatible devices, including bridge interconnection and surface polishing for planarization⁷.

Lateral MSM detectors have been proven to be fast, reliable detectors that are extremely easy to fabricate and are intrinsically compatible with planar FETs. For these reasons, there have been many reports of MSM detectors integrated into photoreceiver systems. For example, Harder *et al* published the performance of a monolithic MSM, a transimpedance amplifier, and an output buffer using a GaAs MESFET process⁸. The fabrication process used the same buffer layer of the FET for the detector's active layer

and the electrodes from its gate metal.

The greatest disadvantage in employing MSMs in photoreceivers is their large dark current. As discussed in this report, the magnitude of dark current has a large dependence on the Schottky barrier height and it is often necessary to take steps to reduce this effect^{7,30}.

Problem Definition

This study begins by identifying the trends in data communications and attempting to determine the needs of future communication networks. Once these needs have been recognized, it will be demonstrated that the two optical detectors presented in this paper are highly feasible, economical solutions.

1.55 μm Detection

Fiber optic cable, normally constructed from fused germano-silicate glass, is demonstrated to have its lowest dispersion when propagating light at 1.3 μm and lowest losses at 1.55 μm , as will be discussed further. For this reason, 1.55 μm is the wavelength of choice in long distance fiber optic communication systems⁹.

An ideal, fully optical network would run entirely at this wavelength, however, current technology presents some limitations. At the receiver end, semiconductor detectors use the principle of light absorption and subsequent generation of electron-hole pairs to convert the optical energy signal into an electrical one that can be amplified and interpreted as data¹⁰. The energy bandgap of the material is inversely proportional to the

minimum wavelength that can be detected. Silicon, because of its relatively large bandgap, can at most detect light at around $1\ \mu\text{m}$ ¹⁰, rendering it unsuitable for the detection of long haul signals. The absorption coefficient of silicon and other common semiconductors is shown in Figure 1. As a result, present day detectors that have the correct bandgap are made from alloys of Indium Gallium Arsenide (InGaAs). On an integrated receiver, the detectors interface with the pre-amplifier and interconnect stages, which are made with silicon technologies almost 99% of the time¹⁰. Thus there are compatibility issues between the two material systems when integrating complex circuitry. Also, processes that use these materials are not as mature as silicon technologies, do not have a high quality native oxide like silicon, and are thus costly¹¹.

Figure 1: Absorption Coefficients¹⁰

Some of the work in this area has focussed on devices made with various strained alloys of silicon and germanium (SiGe). By varying the fraction of germanium in a silicon layer, one can tune the range of wavelength detection from that of pure silicon ($1\ \mu\text{m}$) to pure germanium ($>2\ \mu\text{m}$)¹⁰. Thus with the appropriate fraction of germanium, it is possible to target the desired $1.55\ \mu\text{m}$ mark. Germanium has been shown to be integrable with existing silicon processes, and to introduce dramatic improvement to the performance of semiconductor devices. For example, its incorporation into the base of bipolar transistors increased the device's speed¹². More recently, SiGe detectors have been demonstrated in integrated optical transmitter and receivers for $1550\ \text{nm}$ transmission operating at $20\ \text{Gb/s}$ ¹³.

Given these issues and constraints, the initial aim of this thesis was to design, fabricate, and test a novel, cost-effective, VLSI compatible SiGe device with good detection behaviour at $1550\ \text{nm}$.

Optoelectronic Integration

Another problem faced by the optical communications industry is that of integration. As outlined earlier, there are numerous benefits in combining both electrical and optical functions onto a single chip. Until communication networks are fully optical at all levels, there will always exist the drive to integrate the optical and electronic functions as much as possible. Specifically in the case of photoreceiver circuits, integrating the detector with the amplifier's electronics both reduces packaging costs and eliminates the parasitic inductance of the bond wire. Accompanied by these benefits are several difficulties that

arise when attempting to integrate very different material systems and structures. Often when developing a satisfactory process for integrating optical waveguides, filters and detectors, for example, the individual performance of each component is compromised. Thus the search for simple structures and common materials remains in the foreground in the task of optoelectronic integration.

An immediate application that would benefit from optical-electronic integration is optical interconnection at chip-to-chip or board-to-board levels. The potential bandwidth of optical interconnects far exceeds that of current electrical connections. With the rapid improvements made to processor speeds, computing networks now find their bottleneck at the interconnect level, where the metallic connections made between VLSI chips suffer from power consumption delays, crosstalk, and are limited in density by the total capacitance which affects propagation speed. Optical interconnects eliminate these fundamental problems, but introduce other factors including alignment issues, low conversion efficiency of transmitters and receivers, and lower switching speeds. However, these problems are not fundamental limitations and can eventually be overcome as optical technologies mature¹⁴.

The concept of optical interconnects as applied to both parallel-processing in digital computing systems and optical backplanes in telecommunication switches are currently areas of active research^{15,16}.

At the optical interconnect level, the distances involved are very short and thus issues such as loss and dispersion are not as significant as in the case of long haul

telecommunications. Instead, cost and ease of fabrication become important measures with which to determine the suitability of a particular detector. An economical, reliable choice is to use wavelengths corresponding to the strong absorption region of silicon. It is logical to employ silicon as the photoactive material in an integrated photoreceiver since the receiver electronics will already be silicon based.

Given the issues introduced by integration, the secondary aim of this thesis was to design, fabricate, and test a silicon device with good detection behaviour at 850 nm to be used in optical interconnect applications. It was expected that the photodetector would operate at higher speeds when compared to earlier devices made with similar structural and material characteristics.

Thesis Contributions

PolyGermanium Photodiode

This section documents the attempt to fabricate a SiGe-based photodiode with good responsivity at 1550 nm that can be easily introduced into current processing technologies. It begins with an analysis into appropriate detector structure and material composition and is followed by a description of the fabrication process and test procedures. Conclusions about the feasibility of producing such devices are drawn.

To the author's knowledge, this is the first use of polygermanium as the material in the active layer of an MSM photodetector. The ability of silicon-germanium alloys to absorb 1550 nm light holds promise for highly integrable, manufacturable devices. As will be

discussed in detail later in this report, using a polycrystalline material offers a high absorption coefficient, a thin active layer, and therefore a fast device.

Optimization of an Existing PolySilicon Photodiode

This section reports the optimization of an existing polysilicon detector whose successful performance at larger dimensions has already been reported¹⁷. The original device demonstrated good performance at 800-860 nm wavelengths for use in short haul communication links and high bandwidth optical interconnects.

The optimization of the device involves attempts to reduce its dimensions, thereby increasing response speed (smaller distance for carriers to travel between electrodes). The process to redesign, fabricate, and measure the detector's performance is presented. A submicron lithographic process novel to Carleton University's Fabrication Lab is also outlined. Final results include recommendations for further optimization.

Recent Work in Silicon-Based 1.55 μm Photodetection

To the author's knowledge, an MSM photodetector made from relaxed polygermanium has not been reported to date. However, there have been a number of similar structures made and the results of these endeavours are summarized here.

Jager and Kosak performed the earliest experiments with Schottky barrier contacts to germanium. Their work included metal evaporation on germanium heated to 300 °C. Those who continued their work (Thanailakis and Northrop; Turner and Rhoderick) tended to have conflicting data with regards to final barrier heights¹⁸. This observation has been confirmed in more recent studies²⁰. One observation made by Turner and

Rhoderick suggested that contacts to aluminium age sooner than other metals, possibly because aluminium oxidizes easily with the GeO_2 interfacial film.

In April of 1993, Xiao *et al* reported the fabrication of Schottky barrier diodes for infrared detection using Pt and Pd silicides and strained SiGe layers¹⁹. In order to combat problems with misfit dislocations created by growing SiGe films on Si substrates, the SiGe was graded. Thus, the Ge fraction was gradually increased over a region before depositing the desired Ge content. The entire film was grown in an RTCVD system between 600-700 °C. From earlier work, Xiao and his colleagues had considered the fact that platinum reacts preferentially to the silicon in a SiGe film, leading to Ge segregation. The isolated Ge tends to form three-dimensional islands, leading to surface roughness. To combat this, a silicon-capping layer (~40-100 Å) was deposited on the surface of the film that is ideally completely consumed during the silicidation step. The desired effect is to leave the SiGe film intact. The Schottky barrier detector was able to detect wavelengths greater than 8 µm, with maximum responsivity of 0.1 A/W at 2.5 µm. In May 1994, the same group reported successful work on Schottky barrier diodes using SiGe films for the purpose of decreasing barrier heights and extending the wavelength detection range²⁰.

Work by Jiang *et al* in February of 1996 confirmed the need for a silicon-capping layer for aluminium/SiGe Schottky diodes²¹. The film was deposited using RTCVD at 600 °C. Fermi level pinning was also observed, whereby the barrier height is not determined by the work function difference of the two materials, but rather by interface traps present at the junction and/or by any interfacial oxide. This effect generally leads to increased barrier heights¹⁰.

Chu *et al* investigated the effects of a sacrificial silicon-capping layer that does not completely react with the metal to form a silicide²². The unconsumed silicon tends to inhibit the barrier height's reduction, however it was concluded that the effect is minimal because carriers will tunnel through the layer, which is extremely thin (~0.1-10 nm).

In March 1997 Nur *et al* concluded that it was difficult to accurately determine the barrier heights of diodes made by thermally reacted Pt on SiGe due to the Fermi level pinning²³. To overcome this, a novel technique was devised whereby an SiGe strained layer was deposited using molecular beam epitaxy (MBE) at 550 ° C and was followed by a co-sputtering process of Pt and Si together to form the silicide. From this work, it was found that the value of the barrier height followed the expected pattern with increasing germanium content, unlike devices made with thermally reacted silicide films.

In order to inhibit the Ge segregation, Colace *et al* fabricated a Schottky barrier SiGe diode using a two step deposition process²⁴. Using LPCVD, an initially relaxed film ~50 nm thick was grown at 330 ° C. The islanding of the Ge was inhibited at the low temperature, and thus a second film (at 500 ° C) was grown without dislocations. The detectors exhibited a maximum responsivity of 0.12 A/W at 1330 nm, and a dark current density of 1 nA/μm².

In 1999, other novel structures using SiGe films for 1550 nm photodetection were studied by Janz *et al*.²⁵ A quantum-well device was fabricated using a combination of ultra high vacuum CVD (UHV-CVD) and MBE to get a strained superlattice without dislocations. A responsivity of 0.16 A/W at 1550 nm was achieved with this structure.

In summary, the deposition temperatures surveyed in the reported research literature range from 50-700 °C and depend on the method used. Titanium appears to be the Schottky barrier metal of choice for several groups. Many reports include efforts to eliminate Fermi level pinning, and a silicon-capping layer was favoured as the manner to do this.

Upon consideration of these papers, it was found that no progress has been made in the use of fully relaxed SiGe films for 1.55 μm photodetection. This may be due to the possibility that the dark current of a device made with this material may be large due to the number of dislocations, but it has not yet been shown to be beyond acceptable limits. It was also interesting to note that while much of the work reviewed here was based on Schottky barriers for 1.55 μm photodetection, very little research has been conducted in the area of MSMs, which hold much promise in integrated optoelectronic circuits. Thus this study will provide much insight into the possibility of silicon-based MSMs for future optical detector schemes.

2. DETECTOR DESIGN

This section deals with the various criteria that require consideration when designing a photodetector for fiber optic communications. These factors include the optical wavelength of interest, detector structure, semiconductor material composition, and electrode metal composition.

Wavelength

As mentioned earlier, fiber optic cable is made from fused silica glass. Glasses other than fused silica tend to exhibit higher signal attenuation⁹. The outer layer, or cladding, is doped to have a lower refractive index than the inner layer, or core. There are two mechanisms which cause the propagating signal to deviate from its original power level and original optical frequency band respectively: attenuation and dispersion.

Attenuation

Attenuation is caused by two factors: intrinsic properties of the glass, such as UV or IR absorption, and extrinsic qualities such as imperfect glass structure. Attenuation in fiber optic glass is at a minimum around 1.55 μm , as shown by Figure 2¹⁰.

Figure 2: Loss Spectrum of Fiber Optic Glass¹⁰

Dispersion

Because individual frequencies of light have different propagation constants, they travel at different velocities in the fiber. This ultimately affects the maximum bit rate of the optical signal. Two types of dispersion are found in fiber optic cable: chromatic and intermodal. Intermodal dispersion is only found in multi-mode fiber, and is due to the inherent differences in travelling velocities between modes. Chromatic dispersion is material related and due to the dependence of the refractive index of fiber on the wavelength of propagating light. In the latter case, a significant portion of light travels in the cladding layer (which has different propagation characteristics than the core), giving rise to dispersion. Optical fiber has a dispersion minimum around 1.27 μm , as show in Figure 3⁶.

Figure 3: Dispersive Behaviour of Fiber Optic Glass

In consideration of these two minima, it would be desirable to operate long-distance lightwave communication systems at these particular wavelengths. WDM systems have thus been designed such that the wavelength bands allocated for communication channels fall in the 1.3-1.6 μm range. The challenge presented to optoelectronic device designers is to design reliable, high-powered lasers and detectors that operate in this waveband.

One motivation of this thesis is to meet this challenge and construct a photodetector that targets this wavelength range, specifically the 1.55 μm mark.

Structure

There are many common photodetector structures, each with their relative merits and disadvantages. These will be discussed below, beginning with the simplest *PN* photodiode.

PN Junction

A large reverse bias is applied to a *PN* junction diode, heavily doped on one side. Light incident on the detector with energy equal to or greater than the semiconductor's bandgap will generate electron-hole pairs within the space charge layer. Any excess energy is dissipated as heat. If the carriers are generated outside the depletion region, they slowly diffuse either to the electrodes or to the depletion region. Those carriers either generated in or diffused to the depletion layer are swept by the high electric field there toward the electrodes, contributing to the reverse current¹⁰.

The *PN* junction is easy to fabricate and analyze. Its detected wavelength, operating bias, capacitance, and bandwidth are all highly tuneable by simply varying fabrication parameters. However, due to its small depletion width (hence narrow high-field area), the *PN* photodiode has a lot of carrier generation outside this region, limiting its frequency response to the kilohertz range.

PIN Diode

An enhancement to the basic *PN* structure is the introduction of an intrinsic layer in between the *n* and *p* layers, creating a *PIN* diode. Under sufficient bias the entire intrinsic region is depleted, thereby widening the high field region and dramatically increasing the device's response speed.

The *PIN*s process parameters are easily tunable, as in the *PN* junction diode, and it is relatively robust in terms of sensitivity to temperature, shock and vibration. The *PIN* diode exhibits a high frequency response and is a common detector structure in telecommunication receivers.

Avalanche Diode

The Avalanche photodiode (APD) uses carrier multiplication and impact ionization to create a current gain under high reverse bias. Its structure is similar to a *PIN* diode, however instead of an intrinsic region, the middle layer is commonly lightly doped as either *n* or *p* type material¹⁰.

The multiplication effect produces a higher responsivity in APDs versus other detectors. However, it also has higher noise due to the same avalanche process, and is highly temperature sensitive, too much so for reliable optical receivers⁹.

Schottky Barrier/Heterojunction Diode

Instead of complementary *n* and *p* layers brought together as in the *PN* junction, one layer of the structure is either a metal (Schottky barrier) or another semiconductor material altogether (heterojunction). The resulting energy-band diagram is similar for both cases, and both operate using electron-hole pair generation under strong reverse bias as in the *PIN* diode. The physical mechanism behind the Schottky barrier is of particular importance to this thesis thus a detailed description of its operation will be treated in Chapter 3.

MSM Diode

The MSM Diode is essentially two Schottky barrier diodes back-to-back. The entire semiconductor layer between two metal electrodes becomes fully depleted under sufficient bias. In order to maximize responsivity and speed, the electrodes of the diode are typically patterned as interdigitated fingers. This pattern is illustrated in Figure 4.

Figure 4: An MSM Photodiode³

Current lightwave receivers do not use MSM detectors, but they are an appealing solution for optoelectronic integrated circuit (OEIC) receivers because they integrate easily with the MESFET and HEMT circuitry that normally make up the pre-amplifier stage of optical receivers². MSM structures make for a very simple, cost-effective photodetector design. They exhibit low capacitance and can have very high bandwidths. The small capacitance permits large area devices, which enable improved coupling to optical fibers. Their main limitations include relatively high dark current (thermionic emission current over the Schottky barrier) and relatively poor external quantum efficiency (due to electrode shadowing).

In keeping with the objectives of the thesis as outlined earlier, the goal of this project was to manufacture and test a novel MSM photodetector. Detailed theory behind the MSM is given in Chapter 3.

Material

The initial thrust of this study was to fabricate a good working photodetector able to absorb light at $1.55\ \mu\text{m}$ and be compatible with current CMOS processes. As mentioned earlier, a silicon-germanium alloy is suited for this purpose. However, there were several factors to consider before using this material.

Germanium Content

Figure 5 illustrates the bandgap of $\text{Si}_x\text{Ge}_{1-x}$ alloys with increasing Ge content for strained and unstrained films. The required energy bandgap to absorb $1.55\ \mu\text{m}$ light is $\sim 0.8\ \text{eV}$, corresponding to a Ge fraction of 0.5 in strained layers and >0.9 in relaxed layers.

Figure 5: Energy Bandgap versus Germanium content¹²

Strained versus Relaxed

Depositing a high quality $\text{Si}_x\text{Ge}_{1-x}$ layer presents some challenges. The large lattice mismatch (about 4.17% at room temperature) between silicon and germanium results in strained (or pseudomorphic) growth up to a certain critical film thickness¹². Beyond this point, the misfit between lattice constants induces dislocations rather than strain²⁶. This minimum thickness decreases as the fraction of germanium is increased, as shown by Figure 6. Layers grown beyond this critical film thickness are considered 'relaxed' or 'unstrained' material.

Figure 6: Critical film thickness versus Germanium content¹²

It can be seen from Figure 6 that the critical film thickness of a strained film with a large Ge content is a very small value, too small to be an adequate active region in a photodetector. Given these considerations, a SiGe photodetector can be made in two ways:

-
- 1) Increase the critical film thickness by introducing a graded germanium region between the silicon substrate and the active region, as per Sturm *et al*¹⁹ and Colace *et al*²⁴, or
 - 2) Grow relaxed layers of whatever thickness is required to provide the optimum responsivity and speed in a detector.

Successful detectors have been demonstrated using the first concept²⁷, which allows a large bandgap reduction with relatively little Ge. However only very thin layers can be grown in order to remain dislocation free. In the second case, the relaxed layer can be as thick as necessary but this solution requires a larger fraction of Ge to shrink the bandgap.

Monocrystalline versus Polycrystalline Material

Another consideration is the choice of depositing crystalline or polycrystalline material.

Polycrystalline material was chosen for three reasons:

- 1) So that device processing could take place in house. The Carleton University Fabrication Laboratory has a Rapid Thermal Chemical Vapour Deposition (RTCVD) machine, currently capable of depositing doped or intrinsic polycrystalline silicon, germanium material, or alloys of the two. To take advantage of this asset, the material used for the photodetector will be polycrystalline. In industry, depositing a polycrystalline layer is a standard, mature process used for gates, resistors, and capacitors in well-established CMOS processes¹⁰.
 - 2) As shown by Figure 7, the absorption coefficient of amorphous germanium is greater than that of the corresponding monocrystalline material. Thus a smaller film thickness
-

is required in the polycrystalline case. The thinner the film, the faster the device will respond since the carriers have a shorter distance to travel to the electrodes.

- 3) A successful MSM photodetector was fabricated at the Carleton lab using LPCVD (low-pressure chemical vapour deposition)¹⁷ polysilicon, so the extension to polygermanium seemed logical.

Figure 7: Absorption Coefficient of Amorphous versus Crystalline Ge, Si²⁸

Metal Electrodes

Two factors were considered when selecting the Schottky barrier metal:

- 1) The resultant Schottky barrier height, and
- 2) The adhesion properties of the metal

Table 1 lists reported Schottky barrier heights of common metals used in device processing. Titanium, because of its good adhesion and Schottky barrier height to silicon, was chosen as the electrode metal.

Table 1: Schottky barrier height of metal/monocrystalline silicon contacts¹⁰

	n-Si (eV)	p-Si (eV)
Al	0.62	0.7
Au	0.74	0.34
Ni	0.57	0.51
Pd	0.75	0.38
Pt	0.87	0.25
Ti	0.50	0.6
W	0.67	0.45

The photolithographic mask made in a previous study was reused here¹⁷, whereby the widths and spacings of the electrodes were both set to 2.5 μm .

Conclusions

InP or InGaAs based detectors, although proven material for absorbing 1.55 μm light, are expensive and difficult to fabricate on a large scale. A preferable detector would be able to detect light at this frequency and yet still be readily integrable with conventional silicon processes. As such, an MSM diode made from relaxed polycrystalline SiGe and titanium was designed, fabricated and tested.

3. SCHOTTKY/MSM THEORY

Schottky Barrier Diodes

A Schottky diode is formed when a semiconductor is brought into contact with a metal to form a metal-semiconductor (M-S) junction. A potential barrier arises due to the mismatch between work functions of the two materials. If the Fermi level of the metal is greater than that of the semiconductor (in the case of an n-type semiconductor, for example), then electrons in the semiconductor, having greater energy, will leave the semiconductor and flow towards the metal until the Fermi levels are aligned. This state of equilibrium is illustrated in Figure 8.

Figure 8: Energy Band Diagram of an M-S junction in Equilibrium¹⁰

Here, ϕ_m is the work function of the metal, ϕ_s is the work function of the semiconductor, and χ_s is the electron affinity of the semiconductor. The electrons that migrate across the interface to the metal leave behind fixed positive ions in the semiconductor, creating a depletion layer with a built-in potential across it. The energy band diagram illustrates this behaviour with band bending near the interface. The built-in voltage is the difference between the original Fermi levels, i.e.

EQ. 1 $V_{bi} = \phi_m - \phi_s$ ⁽¹⁰⁾

Thus V_{bi} gives the value of the energy required for electrons to move from the semiconductor to the metal. Carriers in the metal see a barrier given by the Schottky barrier height ϕ_b :

EQ. 2 $\phi_b = \phi_m - \chi_s$ ⁽¹⁰⁾

Both ϕ_m and χ_s are illustrated in Figure 8.

A positive voltage V_A applied at the metal lowers the barrier from the semiconductor to the metal by $-V_A$. In this forward bias condition the barrier encountered by electrons in the metal is unaffected. The Richardson-Dushman equation describes this emission current under an applied bias V :

EQ. 3 $J = A^{**} T^2 \exp\left(\frac{-q(\phi_b - V)}{kT}\right)$ ⁽¹⁰⁾

Where V is the applied voltage, k is Boltzmann's constant (1.38×10^{-23} J/K), and T is the temperature in Kelvin. A^{**} is the effective Richardson constant using the effective mass of the electron, and is given by:

EQ. 4 $A^{**} = \left(\frac{4\pi q m_e k}{h^3}\right)$ ⁽¹⁰⁾

Where m_e is the effective mass of an electron, q is the electronic charge (1.602×10^{-19} J), and h is Planck's constant (6.625×10^{-34} Js).

Applying a reverse bias (or negative voltage on the metal $-V_A$) increases the barrier height on the semiconductor side but again the barrier height seen by electrons on the metal side is constant. Thus in forward bias, electrons in the semiconductor may flow freely towards the metal, but in reverse bias they are blocked by a large barrier. The reverse saturation current of a Schottky diode is the small leakage carrier flow from the metal to the semiconductor and is given by:

$$\text{EQ. 5} \quad J_0 = A^* T^2 \exp\left(\frac{-q\phi_b}{kT}\right) \quad (10)$$

The current-voltage relationship of a Schottky diode in both forward and reverse bias can be expressed as:

$$\text{EQ. 6} \quad I = I_0 (\exp(V / n\phi_T) - 1) \quad (10)$$

Where n is the ideality factor used to account for nonlinear effects and ϕ_T is the thermal voltage kT/q .

Image Force Effect

In reality, equation 6 does not accurately describe the current-voltage relationship observed experimentally. The non-ideal behaviour can be accounted for by considering the image force of an electron. The electric field lines emanating from an electron with a charge $-q$ at a distance x from the interface act as if an image charge $+q$ were situated on the other side of the interface at the same distance x . A new relationship can be derived for the energy versus distance into the semiconductor using Coulomb's force of attraction $F=qE$. Thus the band bending at the M-S interface is not as abrupt as was shown

previously in Figure 8, and the work function of the metal is lowered by an amount $\Delta\phi$.

The M-S current-voltage relationship becomes:

$$\text{EQ. 7} \quad J = A^{**} T^2 \exp\left(\frac{-q(\phi_b - \Delta\phi - V)}{kT}\right) \quad (10)$$

where:

$$\text{EQ. 8} \quad \Delta\phi = \sqrt{\frac{qE_{ext}}{4\pi\epsilon_s}}$$

where E_{ext} is the externally applied electric field, and ϵ_s is the semiconductor permittivity.

Equation 7 is a more accurate description of the I-V characteristics of a Schottky barrier diode.

Schottky Barrier Diodes as Photodetectors

A Schottky barrier diode made for photodetection is typically constructed with a substrate layer, an absorbing semiconductor layer, and a thin semi-transparent metal layer deposited on top. If light energy is incident on the diode, one of two processes occurs. If the photon energy E_{ph} is less than the energy gap E_g of the semiconductor but greater than the Schottky barrier height ϕ_b , electrons excited in the metal may overcome the barrier height, giving rise to current flow. In the second process, the photon energy E_{ph} is greater than the bandgap E_g and the incident photons generate electron-hole pairs in the semiconductor, which are swept away by the electric field force in the depletion region toward their respective contacts. If the absorption region is fully depleted, the device is very fast, as both carriers move at their saturation velocities.

MSM Operation

Under sufficient applied bias, the two depletion regions at each interface of the MSM electrodes become wide enough such that they will meet and the semiconductor layer will be fully depleted. The voltage at which the meeting occurs is called the reach-through voltage, or V_{RT} . Applying a bias across the two electrodes in this way creates a reverse-biased M-S junction at one electrode and a forward-biased junction at the other. If the applied voltage is increased further, the flat part of the energy band and the zero electric field point will shift to the point $x=w$. This is called the MSM flat-band condition.

Figure 9 illustrates the energy-band diagram of a symmetrical n-type MSM with no applied bias.

Figure 9: Energy Band Diagram of an MSM Detector in Equilibrium²⁹

Figure 10 shows the energy bands and electric fields in (a) reach through and (b) flat-band conditions. Here, w is the width of the depletion region, ϕ_{n1} is the Schottky barrier height on the reverse-biased side (where electron injection takes place) and governs the electron current there. ϕ_{p2} is the Schottky barrier height on the forward-biased side (where hole

injection takes place) and governs the hole current. V_{bi1} , V_{bi2} are the built-in potentials for contacts 1 and 2 respectively.

(a)

Figure 10: Energy Bands and Electric Field Distribution at (a) $V=V_{RT}$ and (b) $V=V_{FB}$

For good responsivity, the MSM is normally biased at a voltage greater than the flat-band voltage (V_{FB}). The value of V_{FB} can be derived from Gauss' Law, and is given by:

$$\text{EQ. 9} \quad V_{fb} = q \frac{N_d}{2\epsilon_s} s^2 \quad (2)$$

where N_D is the effective carrier concentration, and s is the electrode spacing.

Dark Current

The dark current of a photodetector is the current present even when there is no light incident on the device.

In the case of an MSM, the fundamental dark current mechanism is thermionic emission, and results from carriers able to overcome the Schottky barrier at the contacts when an intermediate bias (and no incident light) is applied. Thus the dark current is significantly influenced by the barrier height and the quality of the metal-semiconductor interface, which implies a need for tighter tolerances in device fabrication.

As shown by equation 10, the electron and hole injection associated with the dark current are exponentially related to the Schottky barrier heights ϕ_n and $\phi_p = E_g - \phi_n$, respectively³.

$$\text{EQ. 10} \quad J_{dark} = A_n^{**} T^2 \exp\{-q(\phi_n - \Delta\phi_n)/kT\} + A_p^{**} T^2 \exp\{-q(\phi_p - \Delta\phi_p)/kT\} \quad (3)$$

Where A_n^{**} , A_p^{**} are the effective Richardson constants for electrons and holes respectively, T is the operating temperature, and the image force effect has been taken into account. At low bias the dark current is negligible, whereas at high bias, tunnelling

current becomes significant and the thermionic emission model breaks down³. It has been suggested that a minimum dark current value exists if the Schottky barrier height is chosen to be one half of the energy gap of the semiconductor E_g .³ Normally, the noise generated by dark current is ignored due to the much larger magnitude of the noise in the amplifier stages of optical receivers.

In one study, placing the electrode tips and pads on top of a silicon nitride layer successfully reduced the dark current in GaAs MSM detectors. The insulating layer eliminated parasitic leakage paths and the high electric field regions at the electrode tips.³⁰

Noise

The noise of an MSM is similar to that of a *PIN* diode. Thermal noise due to the series resistance can be neglected, however shot noise due to the dark current and the random arrival of incident photons must be considered. It is also possible that MSMs exhibit $1/f$ noise because the current flow is lateral, similar to field effect devices³¹. It is thought that the origin of the $1/f$ noise is due to traps³, and thus may be a significant factor in the polycrystalline devices fabricated in this study.

Quantum Efficiency

The quantum efficiency of a detector is the ratio of the number of generated electron-hole pairs to the number of photons required. The internal quantum efficiency η_i in equation 11 is solely dependent on the absorption process and the collection of photo-generated electron-hole pairs.

EQ. 11 $\eta_i = 1 - \exp(-\alpha l)^{(3)}$

where α is the absorption coefficient of the material and l is the thickness of the absorption region.

External quantum efficiency η_e takes into account the dependency of efficiency on the overall detector structure. Thus it varies widely between the various detector schemes. MSMs in particular suffer from low external quantum efficiency due to the shadowing of the electrodes on the surface of the device. The quantum efficiency can be increased dramatically if very thin electrodes and wide active regions are used, however this would decrease the speed of the device and increase electrode resistance. This relation is given by equation 12.

EQ. 12 $\eta_e = \eta_i(1 - R)(S / A)^{(3)}$

where R is the reflectivity, and S/A is the fraction of device surface that is exposed to light. In the case of the MSM detector:

EQ. 13 $\frac{S}{A} = \frac{s}{s + w}$

where s is the spacing between the electrodes of width w .

Transparent electrodes have been used to increase quantum efficiency but have yet to be demonstrated to work reliably³¹.

Responsivity

Instead of using the quantum efficiency as a measure of device performance, it is more common to use the responsivity $\mathfrak{R}$ of the detector. The responsivity is given as the ratio of the generated photocurrent I_{ph} to the incident optical power P_{inc} , with units of amps per watt.

$$\text{EQ. 14} \quad \mathfrak{R} = \frac{I_{ph}}{P_{inc}} = \frac{\eta_e q}{h\nu} \text{ (3)}$$

where ν is the frequency of light in Hertz.

Bandwidth

The frequency response of the MSM detector is determined by the transit time of the carriers and its RC time constant.

Transit Time

Both the electrode spacing and the applied bias determine carrier transit time. The electrode spacing determines the distance carriers must travel, and the correct applied bias ensures complete depletion of the active region. Under sufficient bias, all carrier generation takes place within the high field region and the carriers travel at saturation velocity.

RC Time Constant

The total resistance of the device is made up of the contact and load resistances. The capacitance of an interdigitated MSM device is given by:

EQ. 15 $C = (N - 1)C_0l^{(3)}$

Here, N is the number of fingers with width w , spacing s , and length l . C_0 is the gap capacitance of the contacts per unit length. The value of C_0 is given as follows²:

EQ. 16 $C_0 = \epsilon_0(1 + \epsilon_s) \frac{K(\pi/2, k)}{K(\pi/2, k')}^{(2)}$

where ϵ_0 and ϵ_s are the dielectric constants of free space and the semiconductor respectively, and $K(k)$, $K'=K(k')$ are complete elliptic integrals of the first kind⁷:

EQ. 17 $K(\varphi, k) = \int_0^{\varphi} \frac{1}{\sqrt{1 - k^2 \sin^2 \theta}} d\theta^{(3)}$

and k , k' are given by:

EQ. 18 $k = \tan^2\left(\frac{\pi w}{4(s + w)}\right), k' = \sqrt{1 - k^2}^{(2)}$

The capacitance of an MSM diode is normally much smaller than that of an equal area *PIN* diode and correspondingly the MSM has a higher frequency response². For the same reason, the RC time constant is fairly small and therefore carrier transit time is frequently the speed limitation in MSM structures³¹. The low capacitance is particularly appealing because it allows the device area to be very large for coupling to fiber optic cable. As well, its contribution to the total front-end of the receiver capacitance is negligible.

4. EXPERIMENT: POLYGERMANIUM MSM PHOTODETECTOR

To simplify the processing and to insure adequate detection of 1550 nm light, initial experiments used pure germanium material instead of a SiGe alloy. According to Z-Q Li *et al*, a silicon buffer layer must first be deposited in order to provide nucleation sites on the oxide when using SiH₄ and GeH₄ as source gases.³² A silicon capping layer between the germanium and metal electrode may also be necessary to reduce the dark current inherent over a small Schottky barrier but may also limit the device speed.

The wafer substrate was p-type, with resistivities typically between 4-18 Ω -cm. A 1000 Å silicon dioxide layer was thermally grown before the active layer so that the active layer was isolated from the bulk silicon. The deposited films were annealed with hydrogen to passivate the dangling bonds between grain boundaries. In polysilicon films, this has shown to be effective in reducing the potential barrier that exists at the boundaries by reducing the number of trap states there, thereby increasing carrier mobility.³³ The electrodes were patterned using a metal lift-off procedure, since the limited metal etching facilities available in the fabrication lab are not capable of providing good definition at these dimensions. The lift-off process consists of the following steps:

1. Deposit polysilicon/polygermanium film on 1000 Å SiO₂ in a coldwall AET Rx Series RTCVD chamber. For details on process conditions, please see Appendix A.
 2. Hydrogen anneal for 100 minutes at 420 °C and atmospheric pressure.
 3. Spin coat wafers at 4000 rpm for 30 seconds with HPR504 photoresist.
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4. Expose and develop windows into the photoresist using a Karl Suss alignment system.
 5. Plasma etch (Technics PE-II A) in an O₂ plasma for 30 seconds at 100 Watts and 0.3 Torr any residual photoresist from electrode windows.
 6. Blanket sputter metal for 15 minutes at 100 Watts, with 60 sccm argon using a Materials Research Corp. sputtering system.
 7. Dissolve remaining photoresist using an acetone bath in an Ultrasonic agitator for ~20 minutes.
 8. Rinse with isopropanol alcohol and blow dry with a nitrogen gun.

Figure 11 outlines the metal liftoff process.

Figure 11: Typical Metal Liftoff Process

Initial deposition attempts included a ~ 100 Å silicon buffer layer to permit nucleation, followed in the same cycle by the polygermanium layer. Three metals (aluminium, platinum, and titanium) were used for the electrodes for the sake of comparison. The result for each metal was an ohmic contact instead of a Schottky barrier. The next experiment included the ~ 100 Å silicon capping layer, which was expected to increase

the Schottky barrier height. It was thought that perhaps the metal would adhere to silicon better than to germanium, however the result was again an ohmic contact. The device still exhibited light-detecting behaviour, but a detector with ohmic contacts does not satisfy the purpose of this project.

The samples were examined through a JEOL JSM-840 scanning electron microscope (SEM) and were shown to have very rough surfaces. The germanium appeared to have deposited in clumps (or 'islands') across the wafer instead of as a smooth, uniform layer. Although the processing conditions were different, other groups made the same observation about their germanium films¹⁹. When compared to the polysilicon depositions made in an LPCVD chamber in the same laboratory¹⁷, the difference in surface quality was quite apparent. Figure 12 compares the two samples. To confirm that it was the use of germanium, and not the equipment that was the problem, a polysilicon film was grown in the RTCVD chamber. As shown in Figure 13, a Schottky barrier was formed between the polysilicon and metal contacts.

Figure 12: Images of (a) PolySilicon and (b) PolyGermanium samples ($\text{bar}=1\ \mu\text{m}$)

Figure 13: Schottky characteristic using RTCVD polysilicon

Further research into germanium deposition processes revealed that most successful high quality germanium films are deposited using lower temperatures than that used in the present study^{32,34}. This holds true even for films deposited in RTCVD chambers³⁵. For example, Kobayashi *et al* performed studies to compare the grain size and surface roughness of several germanium films deposited at different temperatures³⁶. As shown by Figure 14, their results indicate that the temperature used in this thesis study was too high if minimum surface roughness is required. The value of T_a in the figure is the temperature of a post-deposition heat treatment which was performed on some of the films.

Figure 14: Surface Roughness versus Substrate Temperature³⁶

Steps were taken to reduce the deposition temperature as much as possible. However, the Modline4 pyrometer used by the RTCVD was limited in its operation to temperatures above ~640 °C. Attempts to operate the RTCVD below the rated temperature of the pyrometer led to little or no deposition on the wafer surface.

At this point the original idea of a SiGe alloy film seemed as if it could resolve the surface roughness problem, or at least minimize its effects. The deposited film would still include the silicon buffer layer to encourage nucleation. Various compositions of gas flows in the RTCVD chamber were tried. Each time however, the surface was too rough and the contacts were ohmic.

The results of these endeavours are summarized in Appendix A.

A thicker silicon capping layer may have alleviated the problem, however the resulting structure would likely have had a slow response due to carriers piling up at the silicon-germanium interface.

It was finally concluded that given the limited resources at the Carleton University Lab and in the interests of time, a successful working polygermanium or polySiGe detector could not be made. Certainly with more flexible equipment and a better understanding of germanium processing, a polygermanium MSM detector would be possible, but in lieu of exploring this idea further, the focus of the thesis shifted to a related topic.

5. EXPERIMENT: POLYSILICON MSM PHOTODETECTOR

A successful polysilicon detector made for short-haul applications such as optical LANs, or optical interconnects between boards and/or VLSI chips has already been made at the Carleton University fabrication lab. Therefore, a seemingly logical step would be to take advantage of the advanced lithography equipment available in the lab and optimize the detector's performance.

The JEOL JSM-840 scanning electron microscope can be adapted to create minimum 0.1 μm patterns using polymethyl methacrylate (PMMA) as a positive resist and the electron beam as the exposure source. The SEM uses the information contained in a digital schematic (as opposed to a glass or chrome plate in a UV lithographic process) to direct the electron beam and expose the PMMA. The sample is subsequently developed in a 3:1 methyl isobutyl ketone:isopropanol alcohol (MIBK:IPA) solution to reveal the desired pattern. A picture of the final detector is illustrated in Figure 15.

Figure 15: 0.5 μm MSM pattern

Ebeam lithography is not expected to replace photolithography in high-volume manufacturing facilities, however it is an inexpensive way to do submicron lithography in

a research environment. The fabrication of a 0.5 μm MSM device in actual manufacturing conditions would likely use state-of-the-art submicron photolithographic equipment.

It is expected that the speed of the 0.5 μm detector will be dramatically improved over the 2.5 μm device previously made; specifically, with thinner electrode widths and spacings, the carriers have a smaller distance to travel. Many groups have attempted to increase the speed of silicon detectors in other ways. For instance, Chen *et al* used a very thin active layer to reduce the distance travelled by the carriers. The corresponding loss of efficiency was overcome using a scattering reflector to trap light in the active layer³⁷. Using a costly SOI substrate to block photocarriers generated deep in the bulk silicon allowed Honkanen *et al* to achieve speeds of 5 GHz from doped silicon MSMs³⁸.

Some groups have also achieved fast speeds in the same manner employed in this report. Using electron beam lithography, Alexandrou *et al* reported success in fabricating crystalline silicon MSMs in 1993 that worked at 38 GHz under 725 nm light. The diode used 0.3 μm finger widths and spacings³⁹. Similarly, Chou and Liu fabricated crystalline silicon MSMs with 0.1 μm widths and spacings, and achieved speeds of 41 GHz.⁴⁰

Employing a new lithographic process involves some parameter tuning and optimization. Specifically, the metal liftoff process described earlier does not work well at submicron dimensions. A more complex process was used, whereby a two-level stack of PMMA with different molecular weights (i.e. 495K and 950K) creates a 'lip' in the resist stack that allows for easier liftoff. Without this lip, the metal coverage would likely prevent the

solvent from getting to the resist in order to dissolve it. This process is shown in Figure

16.

Figure 16: Enhanced Metal Lift-off Process

For the most part the remaining process parameters were the same as for the original polysilicon detector. An initial 1000 Å oxide layer was grown to isolate the devices from the bulk silicon. The polysilicon film was deposited in the LPCVD chamber (rate: ~150 Å per minute), with its thickness scaled down to be the same order of magnitude as the electrode dimensions. For comparison studies, devices were also made with crystallized amorphous silicon. In this case, amorphous silicon was deposited at 560°C for 175 min., followed by a hydrogen anneal at 650°C for 1 hour to partially crystallize the material. The expected result is a polysilicon material with larger grain sizes, hence a lower density of trap states at the grain boundaries.

For the electrodes, a metal stack of Ti/Al was used since Ti provides the optimum Schottky barrier, while Al adheres well to gold bond wires. All of the process steps used employ standard, mature techniques used in typical CMOS processes. For instance, the deposition of the active layer could coincide with the definition of the polysilicon MESFET gate in a typical photoreceiver chip.

The enhanced liftoff process was performed in the fabrication lab at Carleton University for the first time for this study. Because of this, numerous problems presented themselves during the course of the work.

The thickness of the resist stack was optimized based on the minimum lithographic dimensions (i.e. 0.5 µm) used. The resist must be thick enough to provide an adequate barrier (with a 'lip' profile) to the substrate. However, it cannot be thicker than the electrode dimensions, otherwise it may be difficult to dissolve in the lift-off step. Thus

the resist thickness was tuned by diluting the commercial standard PMMA solutions using chlorobenzene. Attempts were also made to tune the spin speed, but it was found that increasing the spin speed to thin the resist led to problems with thickness uniformity across the wafer. This effect is acknowledged in other works⁴¹.

It was found that PMMA, although a stable compound, presents some difficulties in its handling and use. Over long storage times, the casting solvent (in this case chlorobenzene) tends to evaporate, leading to thicker resists when spun. Thus periodic measuring of the thickness of a particular resist solution is recommended. As well, caution must be taken when dispensing the resist onto the wafer in the spinner. Over a period of time, the PMMA tends to dry up around the rim of the bottle, and upon constant opening and closing of the lid the dried PMMA falls into the solution and appears as tiny spots on the wafer after spinning. Usually if care is taken to obtain the PMMA from the middle of the solution (that is, not at the bottom or on the sides), the amount of spotting can be kept to a minimum.

There exists a trade-off during e-beam exposure between a lengthy write time with a small beam current, and shorter exposure times with too large a current. The optimized exposure settings required tuning of the electron beam current, the charge dose (i.e. Coulombs per unit area), and various other settings on the scanning electron microscope.

It was also found that the exposed electron beam in the SEM is highly susceptible to outside electromagnetic effects. It is unknown what the particular source of interference was in this case, but it appeared that the recent construction on the floors above the

fabrication lab included the installation of new EM sources. As a result, the manner in which the beam sweeps the sample had to be adjusted, because the resulting noise caused by the EM interference manifested itself quite significantly. As shown in Figure 17, this leads to considerable noise problems.

Figure 17: Noise Effects from EM interference (6500x magnification)

For the purposes of this project, a few simple changes in parameters to the design file averted the noise problem, however it would be useful in the future to monitor the EM field in the fabrication lab and identify changes to the EM patterns and associated SEM behaviour. An associate at NRC also suggested that the potentiometers in some of the SEM functions (for example, X/Y shift dials, rotation dials, etc) may get noisy after years of use and require replacing. As well, field cancellation circuitry may be necessary if the problems introduced by noise become significant.

Files which require long write times can often be a problem because the electron beam current tends to drift over time. Currently, a SEM operator must monitor the beam current during the write time and make adjustments as necessary. However, the lithography system has an optional package which may be a good solution to this problem. An automated beam current reader takes current readings at regular intervals during the write time and automatically adjusts the dose to account for current drift.

A planar plasma etcher is used to etch residual resist in the electrode windows, however, this was found to be a difficult process to control. The PMMA is very soft and readily etches in the chamber, at a rate of approximately 50 Å per second in an oxygen plasma at 0.3 Torr and 100 Watts of power. The plasma etch was found to be necessary in order to completely open windows in the resist and enable good metal adhesion. However, the process presented a danger in that too heavy an etch would remove the resist's lip profile required for successful lift-off. As well, the plasma etcher in the Carleton fabrication lab is found to etch unevenly across even small areas, thus to maintain a consistent etch across the samples, the same spot in the chamber was used each time. After various experiments, it was found that approximately 200 Å of PMMA (most likely sufficient to remove any residual resist) could be etched using conditions of 50 W at 0.3 Torr for 15 seconds.

To maintain the clean surface of the open windows in the resist, the samples must be immediately transferred to the evaporation chamber for the metal deposit following the plasma etch. The evaporation of 20 nm Ti/ 80 nm Al is a straightforward procedure, whereby the samples were positioned directly above the metal target so that resulting step

coverage was perpendicular to the wafer surface. This type of coverage is desirable in a lift-off process, since it is more difficult for the acetone to get under the metal if it is deposited at an angle. This concept is illustrated in Figure 18.

For this same reason, the evaporation system was chosen over the sputtering system because the sputtering platform is typically quite close to the metal target, creating a flux of metal ions that do not all travel perpendicular to the sample. In contrast, the evaporation chamber has a large distance between the crucible and sample holder, and it is a reasonable approximation to assume that the majority of the metal travels in a straight line toward the sample, producing a step coverage that facilitates easy lift-off of field metal.

Determining the required thickness of the metal stack introduced a trade-off between two factors. The metal needed to be as thin as possible to allow the lift-off process to work easily, however a very thin electrode may not be able to carry the generated photocurrent and may introduce a large resistance, thereby causing the device to become RC time-limited. Chou and Liu estimated that the actual resistance of nanoscale electrodes are at least 3.7 times greater than that predicted by bulk resistivities, due to the fact that collisions between electrons and the metal boundary become significant at this scale⁴⁰.

Figure 18: Step Coverage for Angled versus Perpendicular Evaporant Flux

Finally, the acetone lift-off process introduced a trade-off between too little agitation (whereby the metal did not always completely lift) and too much agitation (whereby the rough handling caused too much metal to lift-off). The technique eventually used began with 20 minutes in the ultrasonic followed by 10 minutes standing in clean acetone. The devices were then rinsed with alcohol and blown dry with a nitrogen gun.

The bulk of the work in this project involved addressing the various issues outlined above. To summarize, the fabrication process of the polysilicon detector was as follows:

1. Deposit polysilicon 0.5 μm film in at LPCVD chamber at 627 °C and 0.25 Torr.
 2. Hydrogen anneal for 100 minutes at 420 °C and atmospheric pressure.
 3. Spin stacked 495K/950K PMMA resist layer.
 4. Expose electrode pattern using SEM.
 5. Develop in MIBK:IPA for 3 minutes.
 6. Light plasma etch in oxygen at 50 W for 20 s at 0.3 Torr to ensure clean windows for good metal adhesion.
 7. Blanket thermal evaporation 20 nm Ti/ 80 nm Al.
 8. Dissolve remaining PMMA using acetone in ultrasonic agitator for 20 minutes.
Continue dissolution outside of the ultrasonic for another 10 minutes.
 9. Rinse with isopropanol alcohol and blow dry with a nitrogen gun.
-

Performance Evaluation of the Polysilicon Detector

A series of measurements were made to characterize the detector's performance. These included I-V measurements to extract the actual barrier height of titanium to silicon, dark current measurements, DC photoresponse measurements using a continuous wave light source, and high frequency measurements using a pulsed source. In both photoresponse tests, an optical fiber was positioned directly above the detector with the incident light perpendicular to the detector plane. The fiber core was centred directly on the detector to maximize the amount of incident light, and was as physically close as possible to the samples.

Barrier Height

Using I-V data taken from a sample Schottky barrier, the barrier height can be extracted by plotting the forward bias curve on a logarithmic scale. Extrapolating the straight line to the zero bias point gives a value of the saturation current density, J_0 . From J_0 the

barrier height can be found using $J_0 = A^{**}T^2 \exp\left(\frac{-q\phi_b}{kT}\right)$:

$$\text{EQ. 19} \quad \phi_b = -\frac{kT}{q} \cdot \ln\left(\frac{J_0}{A^{**}T^2}\right) \quad (10)$$

This method assumes near-ideal Schottky behaviour at the metal-semiconductor junction.

In this case, an average of several I-V curves was taken and the barrier height was found to be 0.48 eV, very close to the expected value of 0.5 eV. However, the ideality factor of the contact was found to be ~ 3.3 , indicating that the barrier likely does not follow

Schottky theory very closely. Therefore there may be other unknown current mechanisms

at work in the detector, perhaps due to an interfacial oxide layer at the metal-semiconductor junction.

Dark Current

Because of the high trap density in polysilicon, it is expected that the dark current of the device will be high due to carrier recombination/generation at the trap centers. Assuming the current behaves according to a thermionic emission mechanism, we can estimate the expected dark current value using the calculated barrier height of 0.48 eV.

Dark current measurements were made with a Hewlett-Packard 4155 Semiconductor Parameter Analyser at Carleton University. To illustrate the dependence of grain size on the magnitude of dark current, the dark current of crystallized amorphous silicon detectors is shown with both the measured and theoretical dark current of the as-deposited polysilicon samples.

Figure 19: MSM Dark Current

The as-deposited polysilicon samples have a larger dark current value than expected; in addition, they appear to have a larger bias dependence than predicted by thermionic emission theory. As suggested earlier, it is possible that the metal-semiconductor contacts do not follow Schottky behaviour, and that the grain boundaries of the polysilicon material introduce other current mechanisms. For instance, carrier recombination/generation at trap states could contribute to the dark current. In addition, emission at the grain boundaries induced by the applied electric field may account for the large dependence on bias.

As expected, the crystallized amorphous silicon devices have a lower dark current due to the larger grains (hence lower density of traps) present in the material. This result may confirm the presence of field-induced emission at the grain boundaries, since the bias dependence is less apparent in this material. However, depositing amorphous silicon is a

costlier procedure and does not integrate as easily as polysilicon deposition into conventional CMOS processing.

Responsivity/External Quantum Efficiency

A quick calculation into the expected detector quantum efficiency and responsivity requires knowledge of the absorption coefficient of the active layer. According to an earlier study that used the same photoactive material, the absorption coefficient of the polysilicon is approximately $2.5 \times 10^3 \text{ cm}^{-1}$ at 980 nm.¹⁷ Using the equations detailed in chapter 3, and assuming a reflectivity R of 0.3 (air-silicon):

$$\text{EQ. 20} \quad \eta_e = [1 - \exp(-\alpha l)](1 - R) \frac{S}{A}$$

$$\eta_e = [1 - \exp(-(2.5 \times 10^3) \cdot (0.5 \times 10^{-4}))](1 - 0.3) \left(\frac{0.5 \times 10^{-4}}{2 \cdot 0.5 \times 10^{-4}} \right)$$

$$\eta_e = 4.11\%$$

$$\text{EQ. 21} \quad \mathcal{R} = \frac{\eta_e q}{h\nu} = \frac{\eta_e q \lambda}{hc} = \frac{0.0774 \cdot 1.602 \times 10^{-19} \cdot 980 \times 10^{-9}}{6.625 \times 10^{-34} \cdot 3 \times 10^8} = 0.0325 \frac{\text{A}}{\text{W}}$$

The actual polysilicon thickness was measured after deposition and found to be $\sim 0.42 \mu\text{m}$. This reduces the expected quantum efficiency to 3.5% and the responsivity to 27.6 mA/W.

Responsivity measurements were taken at the Institute for Microstructural Sciences at NRC in the manner illustrated in Figure 20. A 980 nm laser was chopped at 400 Hz and

the reference signal was split off and fed into a lock-in amplifier. A pre-amplifier supplied the bias and read the photodetector's signal, converting the output current into a voltage signal that was also fed into the lock-in. Figure 21 illustrates the generated photocurrent as a function of applied bias for three different laser input power levels.

Figure 20: Photoresponse Measurement Setup

Figure 21: MSM Responsivity

From the above curve, the device responsivity was measured to be 3 mA/W at 980 nm and 4 V applied bias. This value is much lower than the expected value of ~28 mA/W.

There are a number of minor practical differences between the calculated and actual responsivity. The measured value of incident light power was taken at a point that was not the same as the output facet which illuminated the device; therefore, there is some loss in the splice and connectors (typical SMA connector losses are ~1 dB, while most worst case splice losses are ~0.3 dB)⁶.

The spot size of the multimode fiber is about 50 μm , but the device's area is on the order of 50x15 μm ; therefore only about 30% of the light actually illuminated the detector. If the illumination power is to be considered constant over the fiber spot size (in actuality, the modes follow a more gaussian profile), then a recalculation of the responsivity given a smaller incident power level improves the value to about 8 mA/W.

It is suspected that these issues partially contribute to a much lower responsivity than initially calculated. Other theories, which may require a more detailed study, concern the resultant structure of the polysilicon layer. The thin layer deposited may not have the columnar profile of the material that was deposited earlier and was reported to have an absorption coefficient of $\alpha = 2.5 \times 10^3 \text{ cm}^{-1}$ at 980 nm¹⁷. Thus this value of α may be incorrect for this device. The potentially less-ordered structure in this case may also have a significant density of recombination centers, leading to a marked decrease in carrier collection at the electrodes. Experiments that could determine the amount of

photogeneration taking place and what fraction of the photogenerated carriers are actually collected may provide some information on this topic.

The polysilicon detector may be better suited for applications that operate at shorter wavelengths, where the response would likely be better since the absorption coefficient of silicon increases rapidly below 1 μm wavelength.

Responsivity measurements were attempted on the crystallized amorphous devices but they appeared to have no detectable photoresponse. It is thought that due to the smaller density of grain boundaries, the corresponding absorption coefficient is smaller than that of the as-deposited polysilicon and closer to that of monocrystalline (whose absorption length at 980 nm is $\sim 100 \mu\text{m}$). Therefore the 0.5 μm active layer is too thin to provide any measurable response.

Capacitance

Using the formulae given in chapter 3 and the values specific to this design, the following calculations present the expected value of capacitance at 0.5 μm finger widths and spacings:

$$\text{EQ. 22} \quad k = \tan^2\left(\frac{\pi \cdot 0.5\mu\text{m}}{4(0.5\mu\text{m} + 0.5\mu\text{m})}\right) = 0.1716, k' = \sqrt{1 - k^2} = 0.9852$$

Computing the complete ellipticals of the first kind is a standard function in MATLAB.

The results are presented in the next equation.

$$\text{EQ. 23} \quad K(\varphi, k) = \int_0^{\varphi} \frac{1}{\sqrt{1 - k^2 \sin^2 \theta}} d\theta = 1.5826$$

$$K(\varphi, k') = \int_0^{\varphi} \frac{1}{\sqrt{1 - k'^2 \sin^2 \theta}} d\theta = 3.1651$$

Finally, these values are used to compute the total capacitance from the gap capacitance per unit length:

$$\text{EQ. 24} \quad C_0 = \epsilon_0(1 + \epsilon_s) \frac{K(\pi/2, k)}{K(\pi/2, k')} = 8.854 \times 10^{-14} \frac{F}{cm} (1 + 11.8) \frac{1.5826}{3.1651} = 567 \text{ fF/cm}$$

$$\text{EQ. 25} \quad C = (N - 1)C_0 l = (20 - 1)(567 \times 10^{-15} \frac{F}{cm})(50 \times 10^{-4} \text{ cm}) = 53.8 \text{ fF}$$

In contrast, a *PN* diode with a 0.5 μm intrinsic layer and with equivalent area would have a capacitance of:

$$\text{EQ. 26} \quad C_{pin} = \text{Area} \frac{\epsilon}{w} = 181 \text{ fF}$$

As stated earlier, the capacitance of MSM photodetectors is smaller than that of comparable *PN* diodes. Therefore, capacitance does not play much of a role in the frequency response of the detector since an MSM detector is normally limited by the transit time of photogenerated carriers, and not the RC time constant.^{3,31}

Frequency Response

As a first order approximation, carrier transit times can be found by dividing the distance between electrodes by the saturation velocity (assuming full depletion of the active layer).

It is assumed that the saturation velocity of polycrystalline silicon is the same as that of monocrystalline silicon, because its value only depends on carrier effective mass and is independent of mobility⁴².

$$\text{EQ. 27} \quad \tau = \frac{w}{v_{sat}} = \frac{.5 \times 10^{-4} \text{ cm}}{10^7 \text{ cm/s}} = 5 \text{ ps}$$

Where w is the distance travelled by carriers between electrodes. Thus an ideal detector bandwidth can be found:

$$\text{EQ. 28} \quad B = \frac{1}{2\pi\tau} = \frac{1}{2\pi \cdot 5 \times 10^{-12}} = 31.8 \text{ GHz}$$

The actual frequency response of the detector was measured using a 850 nm Ti:sapphire laser. The laser, with a FWHM pulse width of 150 fs, was pulsed at a rate of 76 MHz. A bias-tee circuit was used to both provide the bias to the detector and carry the RF signal to a 50 GHz digital sampling oscilloscope. This setup is shown in Figure 22. The detector response at the oscilloscope at bias points of 1, 2, and 4 V is plotted in Figure 23.

Figure 22: Impulse Response Measurement Setup

Figure 23: Temporal Response

From this data, it can be seen that the response at the falling edge can be broken into two parts: a fast and a slow response. Thus there are multiple frequency components which will appear in the spectral response. This concept is shown in further detail in the following figure using the data collected at 4 V:

Figure 24: Temporal Response at 4 V

In order to study this result further, the data was plotted on a logarithmic scale and the two time constants were found by fitting the two sections of the graph to appropriate line equations. The slope of each line gives the time constant associated with that particular area of the graph. This result is plotted in Figure 25.

Figure 25: Exponential Fitting to Impulse Response Data

The time constants seen here are much larger than originally expected in the first order transit time approximation, for several possible reasons. The possibly large number of grain boundaries may serve as trap centers for photogenerated carriers, which hold the carriers for an indefinite time and then release them. Further study into the actual structure of the polysilicon material, for example, using deep-level transient spectroscopy (DLTS), may substantiate this theory. DLTS measurements can determine whether or not the time constants have a $\exp(-E_A/kT)$ temperature dependence (where E_A is the trap energy), perhaps leading to the conclusion that trap states play a significant role in the carrier transport within polysilicon.

The slow response may also be due to carriers generated in the outside edges of the detector, beyond the influence of the high electric field. These carriers have to rely on the

slow process of diffusion to travel to the electrodes. As mentioned earlier, the spot size of the fiber illuminating the detector was much larger than the total device area and indeed a significant fraction of the carriers may have been generated this way. A mesa etch of the active region around the detector would likely eliminate this problem.

The very end of the tail was found to be made up of several ripples, most likely reflections within the cable from the bias-tee circuit to the oscilloscope. This idea was confirmed when a shorter cable was inserted and caused the reflections to shift away from the pulse. Reflections such as these are acknowledged as a typical source of measurement error⁴³, as may be the case in this study.

The frequency response was found by feeding the impulse data into a Fast Fourier Transform (FFT) algorithm. The result is plotted as follows:

Figure 26: FFT of Temporal Response

The two different time constants are not obvious within the spectral response because the FFT algorithm finds an overall average system response. Thus the detector bandwidth was found to have a 3dB point at 1.5 GHz. It was expected that the frequency response of the 0.5 μm detector, as a first-order approximation, would scale linearly with the speed of 750 MHz reported from the 2.5 μm MSM made earlier, assuming that the both devices are transit-time limited. Thus in contrast to the measured response stated above, the expected bandwidth was about 3.75 GHz. This discrepancy is possibly due to the issues presented earlier in this discussion (increased trap density, wasted illumination outside detector area, etc...)

6. CONCLUSIONS AND RECOMMENDATIONS

The fabrication of a polygermanium MSM for 1550 nm detection using a metal lift-off process was attempted. The resultant germanium film deposited by the RTCVD system was too rough to produce the necessary rectifying Schottky contact. A lower temperature process may permit the growth of a smooth germanium surface, but this option is not available in the Carleton Fabrication Lab.

A fast but leaky polysilicon MSM detector was fabricated, tested, and characterized. The narrow widths and spacings allowed photogenerated carriers to be collected quickly, however the large trap density inherent in polycrystalline material caused the response to be much slower than expected. The detector has a responsivity of 3 mA/W at 980 nm, a dark current of 39 nA at 4 V, and a 3 dB bandwidth of 1.5 GHz.

There are several ways to optimize the device fabricated in this project. A number of published works recommend various methods to reduce dark current. As mentioned earlier, placing the electrode tips and contact pads on top of silicon nitride has been shown to eliminate leakage paths and high electric field regions³⁰. Reducing the dark current would certainly strengthen the signal to noise ratio and hence improve device performance.

The device total area can be increased in order to maximize the responsivity of the device by allowing all incident light from the fiber to be collected. This may further complicate the lift-off process and would result in increased device capacitance, but this trade-off

would likely be acceptable. Another way to boost responsivity is to deposit an anti-reflection coating such as silicon nitride.

The detector response can be greatly improved by finding methods to eliminate the slow component of the frequency response. A mesa etch (or even a light block) around the detector would eliminate the carriers which slowly diffuse to the electrodes. Increasing the total detector area would also suppress this effect, since the electric field would be present everywhere that the light is incident, allowing carriers to drift quickly to the electrodes.

Certainly there is much work involved in examining the polysilicon structure and the current mechanisms it uses. For instance, using the same material with different finger spacings may confirm whether or not the device is in fact transit-time limited. As mentioned earlier, deep-level transient spectroscopy may be able to provide more insight into the effect of trap states on detector speed.

This study has demonstrated the ability to manufacture submicron photodetectors with satisfactory performance, but has also opened many questions about carrier transport in polysilicon and its effects on photoresponse and speed.

7. APPENDIX A: SUMMARY OF ATTEMPTED SiGe EXPERIMENTS

Experiment Number	Film Composition*	Purpose	Results
1	Si B/ Ge AL	Initial attempts	Ohmic
2	Si B/ Ge AL/ Si C	Determine if silicon cap will give Schottky contact	Ohmic
3	Si	Determine if Schottky contact is possible in RTCVD	Schottky
4	Si B/ Ge AL/ Si C	Decrease temperature to reduce surface roughness	No film deposited
5	Si B/ Ge AL/ Si C	Decrease pressure to reduce surface roughness	Ohmic
6	Si B/ SiGe AL/ Si C	Change to SiGe alloy; Add H ₂ to reduce surface roughness	Ohmic

(table continued below)

Experiment Number	Deposition Temperature (°C)	Pressure (Torr)	Gas Flows			
			N ₂	SiH ₄	GeH ₄	H ₂
1	750	5	750	2.5	500	0
2	750	5	750	2.5	500	0
3	680	0.5	750	5	0	0
4	630-680	5	750	2.5	500	0
5	640	1.6	750	2.5	500	0
6	640	1.6	750	2.5	500	100

* Notes:

- The substrate was always an n-type wafer with 1000 Å gate oxide grown on top.
- Base pressure was usually 5×10^{-8} Torr or better.
- Abbreviations:
 - B: buffer layer (~100 Å)
 - AL: active layer (~2500-3000 Å)
 - C: capping layer (~100 Å)

8. APPENDIX B: LIST OF INSTRUMENTS USED FOR MEASUREMENTS

DC Measurements

ILX LightWave LDX-3412 Precision Current Source

Semiconductor GaAs Laser Diode

Newport 835 Optical Power Meter

Stanford Research Systems SR540 Chopper Controller

Stanford Research Systems SR530 Lock-In Amplifier

Stanford Research Systems SR570 Low Noise Current Pre-Amplifier

High Speed Measurements

Coherent Systems Miro 900 Ti:Sapphire Laser

50 GHz Hewlett-Packard Bias-Tee

Stanford Research Systems SR570 Low Noise Current Pre-Amplifier

Tektronix CSA 803C 50 GHz Communications Signal Analyzer

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