THERMAL INFRARED DETECTION USING ANTENNA-COUPLED METAL-OXIDE-METAL DIODES

A Dissertation

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by

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This project focuses upon devices that can be used for detection of thermal or long-wave infrared radiation, which is a frequency range for which developing detectors is of special interest. Objects near 300 K, such as humans and animals, emit radiation most strongly in this range, and absorption is relatively low in the LWIR atmospheric window between 8 and 14 µm. These facts provide motivation to develop detectors for use in this frequency range, which could be used for target detection, tracking, and navigation in autonomous vehicles. The devices discussed in this dissertation, referred to as dipole antenna-coupled metal-oxide-metal diodes (ACMOMDs), feature a half-wavelength antenna that couples electromagnetic radiation to a metal-oxide-metal diode, which acts as a nonlinear junction to rectify the signal. These detectors are patterned using electron beam lithography and fabricated with shadow evaporation metal deposition.
Along with offering CMOS compatible fabrication, these detectors provide high speed and frequency selective detection without biasing, a small pixel footprint, and full functionality at room temperature without cooling. The detection characteristics can be tailored to provide for multi-spectral imaging in specific applications by modifying device geometries.

In this dissertation, a brief introduction to currently available infrared detectors is given, thereby providing a motivation for why ACMOMDs were chosen for this project. An overview of the metal-oxide metal diode is provided, detailing principles of operation and detection. The fabrication of ACMOMDs is described in detail, from bonding pad through device processes. Direct-current current-voltage characteristics of symmetrical and asymmetrical antenna diodes are presented. An experimental infrared test bench used for determining the detection characteristics of these detectors is detailed, along with the figures of merit which have been measured and calculated. The measured performance of fabricated ACMOMDs is presented, including responsivity, noise performance, signal-to-noise ratio, noise-equivalent power, and normalized detectivity. The response as a function of infrared input power, polarization dependence, and antenna-length dependence of these devices is also presented.
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CHAPTER 1
INTRODUCTION

The purpose of this research project is to develop prototype CMOS compatible devices capable of high speed detection in the thermal, or long-wave infrared (LWIR), band between 8 and 14 μm at room temperature without cooling. Developing detectors capable of functioning in the LWIR is of special interest for two reasons: the peak radiation of an object with a temperature around 300 K, such as a human or animal, is centered in this range and atmospheric absorption is relatively low between 8 and 14 μm [1].

Figure 1.1 shows a comparison of two images, one taken in the visible band and one taken in the thermal infrared.

Figure 1.1: Comparison of a human imaged in the: (A) visible band and (B) LWIR. In (A), facial features, shirt, plastic bag, and the surroundings are visible, while in (B), the man’s thermal signature, including his arm, is visible.
In the visible image, a man can be seen wearing a shirt with his hand inside a black plastic bag. His facial features and the surroundings in the room are visible. However, in the thermal infrared band the man’s shirt and the plastic bag are transparent, allowing the thermal radiation from his body to be imaged. While some details apparent in the visible image are lost, it is clear that the thermal IR image contains other valuable information not available in the visible image. This type of imaging is useful for detecting humans, animals, or any heat source (e.g. engines, machinery, etc.) in a scene where recognition may be difficult in the visible band. Employing multi-spectral imaging would clearly provide for powerful and robust information gathering.

The transmission of the earth’s atmosphere for wavelengths between 200 nm and 28 μm [1] is shown in Figure 1.2. The absorbing gas species are noted on the plot above valleys in transmission. There is a very large ‘window’ between 8 and 14 μm, where there is little absorption, noted by the shaded blue area. The fact that peak thermal radiation of objects near 300K is centered in the LWIR and also that this radiation corresponds to a band where there is little absorption not only make the LWIR an interesting frequency range, but also one that can be efficiently utilized. Possible applications for this type of detector include target detection and tracking, navigation in autonomous vehicles, and on-chip radio frequency (RF) interconnects.
Figure 1.2: Transmission of the earth’s atmosphere for wavelengths between 200 nm and 28 µm. The species of absorbing gases at various wavelengths is noted. The wavelength range of interest for this work is between 8 and 14 µm, where there is little absorption, denoted by the blue shaded area.

The ultimate goal of this research is to develop, fabricate, and characterize detectors that could be integrated with prefabricated CMOS imaging or Cellular Nonlinear/Neural Network (CNN) chips. In this chapter, the guidelines for this project will be outlined along with a short introduction to the CNN paradigm. In addition, infrared detectors from technologies that are currently available will be discussed, including the type which will be utilized for this project and the motivation behind this selection.
1.1 Project Overview

The primary goal of this project involves the development of high speed infrared detection devices capable of functioning in the LWIR at room temperature without cooling. These devices could then be integrated with CMOS imaging chips. One such example of an imaging chip would be the CNN variety, which are inherently parallel computing devices due to their architecture and offer high speed image processing [2-4]. A CNN array consists of $M \times N$ identical cells which each individually contain processing and sensing elements [4]. Each cell is a multiple-input, single-output processor, meaning that multiple sensors could be connected to each processor. Each cell is connected to neighboring cells [4], which provides an interface between cells so the images may be captured and processed in various ways. Figure 1.3 illustrates the CNN architecture for a single cell and the connection scheme of neighboring cells utilized in the CNN chip to be used for the project.

Figure 1.3: CNN Cell Architecture and Neighboring Connections. In the single cell, the dark blue region represents the computational area and the light yellow region represents the sensor integration area. This single cell is replicated and connected to neighboring cells to form a CNN array.
The dark blue area of each cell denotes where processing, memory, and control elements while the light yellow areas indicate areas for sensors and detectors.

Due to the parallel processing architecture of the CNN paradigm, these chips are known for their high speed image processing capabilities [5]. Commonly implemented detection arrays, such as charge-coupled devices (CCDs), are comprised of an array of sensors whose outputs are read and processed serially by a single computing element. However, with a CNN chip, each sensor is integrated into a cell containing its own processing architecture, so all pixels are read and processed in parallel [5]. This parallel processing allows image processing capability of 10,000 frames per second or more.

The requirement to integrate these detectors leads to certain device constraints, related to both fabrication and operation, which must all be met for a successful integration. In order to fully utilize the image processing capability of a CNN chip, sensing devices capable of detection at 10,000 frames per second or greater must be exploited in the design. Since the detectors developed in this project will be integrated onto a prefabricated CNN chip, the processes used to fabricate them must be compatible with standard complementary metal-oxide-semiconductor (CMOS) fabrication procedures. In addition, the chip area available for these detectors within each cell dictates that the detectors fit within a 10 µm × 10 µm pixel area. Lastly, the detectors must offer full functionality at room temperature without cooling.
1.2 Infrared Detectors

There are numerous types of devices available that can be employed to detect infrared radiation. These devices can be divided into three broad categories: thermal detectors, photon (quantum) detectors, and radiation-field detectors [6]. Each type is capable of detecting incident infrared radiation and converting it into some measurable signal. However, depending on the way in which the detector functions, each type has characteristics that suit it for use in specific applications.

The three infrared detector types are grouped depending on the physical mechanisms that give rise to their operation. When subjected to infrared radiation, the response of a thermal detector is based upon its material properties, which are dependent upon temperature. Photon detectors respond to infrared radiation by creating free carriers from the interactions between incident photons and electrons bound within the sensing material. Radiation-field detectors feature an antenna element that detects incident electromagnetic waves at a designed frequency.

1.2.1 Thermal Infrared Detectors

Thermopiles, bolometers, microcantilevers, ferroelectric, and pyroelectric detectors are types of thermal detectors, meaning that some material property changes in response to a temperature change, in this case thermal infrared radiation. Thermal devices are generally operational over a wide range of wavelengths and can offer uncooled functionality. However, these detectors have low detectivity relative to photon detectors. The sensitivity of thermal detectors can be increased by thermally
insulating them from their surroundings. However, the trade-off for this increased sensitivity is an increased response time.

A thermopile is a series combination of multiple thermocouples. A thermocouple is composed of a junction of two dissimilar thermoelectric materials, commonly metals or semiconductors [7]. A temperature difference present between the dissimilar materials produces a voltage potential, known as the Seebeck Effect [7, 8]. For a thermocouple used as a detector, one side of the junction is generally connected to a heat sink or cooling source. The other side of the junction, the ‘sensing’ side, is subjected to the incident radiation. The comprising materials of a thermocouple determine the voltage derived from a temperature difference between the two sides of the junction. The output of a thermopile detector is proportional to the incident radiation energy and can simply be monitored by reading the potential across the junction. Responsivity of a thermocouple can be increased by connecting more thermocouples in series and/or by thermally insulating the junction pairs from their surroundings [9]. However, there is a tradeoff between sensitivity and response time; the more sensitive the device, the slower it will respond to incident radiation.

Bolometers and microbolometers are detectors which utilize materials whose resistance varies as a function of temperature. The material chosen for the active element determines the magnitude and sign of the resistance change in response to a temperature change. When the detector is subjected to infrared radiation, the detector’s temperature changes and, consequently, so does the resistance of the active element [10, 11]. Detection of incident infrared radiation can be determined by using
a constant voltage supply and monitoring current through the bolometer, or by using a constant current supply and monitoring the voltage developed across the bolometer’s sensing element. The sensitivity of a bolometer can be increased by thermally insulating the device from detector substrate. Sensitivity is also controlled by the material chosen for the resistive element in the detector [12]. Metals have low temperature coefficients of resistivity, but exhibit low noise figures [13]. On the other hand, semiconductors have a much higher temperature coefficient of resistivity, but have higher associated device noise [14]. The main drawback to this type of device is the tradeoff between response time and detector sensitivity.

Bolometers can also be coupled with an antenna to provide added responsivity and frequency selectivity [15]. These detectors operate by utilizing a planar antenna, commonly the bow-tie variety, to couple electromagnetic radiation to the bolometer. The induced antenna current heats the bolometer and causes a change in the resistance of the detector element, just as in the case of the conventional bolometer.

Microcantilever detectors are microelectromechanical systems (MEMS) devices which feature a cantilever structure composed of layers of two different materials of dissimilar thermal expansion coefficients. As the temperature of the detector changes due to incident infrared radiation, the lengths of the layers within the structure change by different amounts, causing a deflection or bending of the cantilever [16]. This deflection due to the resulting stress is known as the bimaterial effect [17]. The deflection can be measured by numerous techniques including optical, capacitive, piezoresistive, and electron tunneling, each with extremely high
precision. One drawback to this type of detector is that physical vibrations of the
detector also cause cantilever deflections and sensor excitation unrelated to incident
radiation. Therefore, this type of device cannot be used in remote or portable sensing
applications where vibration isolation is not possible, such as an autonomous vehicle.

Ferroelectric and pyroelectric detectors comprise a category of detectors
which contain an element composed of a material that changes polarization when
subjected to temperature changes [18, 19]. Pyroelectric detectors are composed of a
material which generates an electric potential or surface charge when exposed to
infrared radiation. When the intensity of irradiation changes, so does the surface
charge. Ferroelectric detectors function in a similar manner: when subjected to
infrared radiation, the active material exhibits a spontaneous electrical polarization.
This polarization is dependent upon the intensity of the infrared radiation. Due to the
sensing nature of these detectors, they must operate in a chopped system to facilitate
spontaneous polarization changes [20]. A chopped system employs a mechanical
wheel that spins, similar to a fan blade. The chopper is placed between the
illumination source and the detector, and alternatively either blocks the irradiation or
allows it through to the detector. When radiation is incident on the detector, the
periodic modulation due to the chopper creates an alternating signal which can be
monitored with external circuitry.
1.2.2 Quantum Infrared Detectors

Quantum, or photon, long-wavelength infrared detectors consist of photovoltaic, photoconductive, and quantum well detectors; each of these technologies exploit semiconductors for sensing infrared radiation. When subjected to infrared radiation, photons interact with electrons within the semiconductor to create mobile charge carriers. Responsivity of each type of detector is wavelength dependent, and is determined by the energy band structure of the detector. The energy band gap can be varied in a ternary alloy by adjusting the compositions of the comprising elements, which gives rise to the ability to tune the wavelength of desired peak responsivity within the range of the binary materials, and the use of quantum wells with well-defined intersubband transitions allows additional degrees of freedom for detection of long-wavelength infrared radiation. Although quantum detectors have fast response time, they generally must be cooled to cryogenic temperatures to minimize background noise, or dark currents, when detecting 3 μm or longer wavelengths [6]. In the context of this project, cryogenic temperatures cannot be supported since the detectors will be integrated with a CNN chip. In addition, cryogenic cooling imposes severe constraints on functionality in remote or portable applications, which would likely be the conditions for use in autonomous vehicles for the purposes described above.

Photovoltaic (PV) are semiconductor-based devices, comprised of a nonlinear junction, where photo-induced currents are created when subjected to infrared radiation [21, 22]. This occurs when incident photons create an electron-hole pair
either near to or within a potential barrier [22, 23]. Two barrier types commonly chosen are reverse-biased p-n junctions or Schottky barrier types. The built-in field created by the potential barrier separates the photo-generated electron-hole pair to create the photo-induced current. An intrinsic PV detector must have incident photon energies of at least the band gap of the semiconductor, or the Schottky barrier height, respective of the junction. For high speed operation, a bias is applied to a PV detector and the photocurrent is measured. The photocurrent of a PV detector is proportional to the absorption rate of incident photons, not by the incident photon energy, given that the incident photon energy is greater than the potential barrier height.

Photoconductive (PC) detectors are similar to PV detectors and function by the photo-generation of charge carriers in the semiconductor due to incident electromagnetic radiation. When incident upon the structure, electromagnetic radiation is absorbed and the conductivity of the detecting material changes [22]. This change in conductivity, or resistivity, can be monitored similar to that in the case of the thermal bolometric detector.

Quantum well infrared photodetectors (QWIPs) are composed of superlattice structures, typically grown by molecular beam epitaxy (MBE) or metal organic chemical vapor deposition (MOCVD) [23-25]. Alternating layers of doped or undoped compound semiconductors create quantum wells in which infrared radiation is absorbed [26]. When incident photons are absorbed, intersubband transitions within the valence or conduction band, take place and the excited carriers induce a current. QWIPs are generally cryogenically cooled since thermionic emission from
one quantum well to the next produces large dark currents. However, room-
temperature operation is possible with the sacrifice of response time and sensitivity
[26].

1.2.3 Radiation-Field Infrared Detectors

The least-developed and smallest class of infrared detectors studied to date
and the subject of this work, are those of the radiation-field variety, which directly
detect a radiation field similar to radio or television receivers [27]. These devices
feature an element that couples an incident electromagnetic wave at a specific
frequency to sensing circuitry. Responsivity of these types of devices is generally
frequency dependent, with the characteristics dependent upon the element that
couples radiation to the sensing element. Depending on the frequency of the detected
wave, a nonlinear junction, such as a diode, may be used as the sensing element to
provide rectification of the AC signal.

One type of a rectifying sensor that can be used to detect electromagnetic
radiation is an antenna-coupled diode [28]. Antennas are commonly used to collect
radio and television signals, but can be tailored to detect infrared radiation by scaling
the antenna dimensions. Radiation from an electromagnetic wave is coupled to a
nonlinear rectifying junction by the antenna. Various antenna types have been
coupled to diodes, including dipole antennas [29], bowtie antennas [30], log-periodic
antennas [30], spiral antennas [31], microstrip patch [32], and microstrip dipole [11,
33] antennas. Various diodes are available such as semiconductor p-n, Schottky, and
metal-oxide-metal varieties. Which of these diode types is most appropriate for a
given detection application depends on the desired operating characteristics. These
diodes provide for rectification of the coupled signal. Semiconductor-based diodes
are generally suitable for rectifying signals of frequency up to approximately 1 THz,
while MOM types must be used for signals with frequencies of greater than 1 THz.

Antenna-coupled diodes are frequency selective, have a small pixel
‘footprint,’ and operate with full functionality without cooling. Depending on the
type of diode chosen, antenna-coupled diodes can also have fast response times.
Therefore, based on these characteristics, these detectors are an excellent candidate
for infrared radiation detection.

1.3 Detector Characterization

There are four main figures of merit which are used to characterize infrared
detectors: responsivity, signal-to-noise ratio, noise-equivalent power, and normalized
detectivity. These characteristics will be used to compare the detectors fabricated in
this research to infrared detectors currently available on the market. This section will
describe the definitions of the figures of merit, an explanation of device noise used in
calculating the figures of merit, and a comparison of detectors which are currently
available. The types of noise which may impact the performance of ACMOMDS will
must be determined so that figures of merit can accurately calculated.
1.3.1 Figures of Merit

Responsivity relates the output of the infrared detector, as a current or voltage, to the intensity of the incident radiation. Responsivity can either be defined as spectral responsivity or blackbody responsivity, depending upon the type of illumination. Spectral responsivity is defined as the detector output per watt of monochromatic radiation [34]. Blackbody responsivity is defined as the detector output per watt of broadband incident radiation [34]. For blackbody responsivity, the radiant power on the detector contains all wavelengths of the radiation, independent of the spectral response characteristics of the detector [34]. Responsivity, both monochromatic and broadband, can be defined as:

\[
\mathcal{R}_v = \frac{V_s}{E_e A_d \phi_e} = \frac{V_s}{E_e A_d} \quad \text{or} \quad \mathcal{R}_i = \frac{I_S}{E_e A_d} = \frac{I_s}{\phi_e}
\]

where \( \mathcal{R}_v \) and \( \mathcal{R}_i \) are the voltage and current responsivities, respectively, \( V_s \) and \( I_s \) are the signal voltage and current, respectively, \( E_e \) is the irradiance in watts/cm\(^2\), \( A_d \) is the detector area in cm\(^2\), and \( \phi_e \) is the radiant flux in watts. Although responsivity is a figure of merit that can be used to describe the sensitivity of a detector in terms of its output for a given input, it is often difficult to compare detectors using this figure of merit alone. For example, depending on measurement conditions and device technologies, larger detectors may have higher responsivities than those of a smaller variety. In addition, responsivity is a function of frequency, or wavelength, making it more difficult to compare detectors with this measure.
The minimum level of radiant power that a detector can detect is dependent upon the noise level. The signal output must be above the noise level to be easily detected [34]. Signal-to-noise ratio (S/N or SNR) relates the output of a detector to the internal detector noise. This is expressed as:

$$\frac{S}{N} = \frac{V_S}{V_N} = \frac{I_S}{I_N}$$

where $S/N$ is a dimensionless ratio and $V_N$ and $I_N$ are the noise voltage and current, respectively. Like responsivity, it is difficult to compare detectors on SNR alone. In many cases, the SNR of a detector can be increased by increasing the infrared input power. As such, reported SNR values should always be accompanied by the irradiance.

Noise-equivalent power (NEP) relates the radiant flux incident on a detector to its SNR [34]. NEP is defined as the radiant power incident on a detector, not the absorbed power, which yields a SNR=1. This can be expressed as:

$$\text{NEP} = \frac{\phi_e}{V_S/V_N} = \frac{V_N}{\mathcal{R}_V} = \frac{I_N}{\mathcal{R}_I}$$

where NEP is in watts. Just as in the case of responsivity, NEP can be either blackbody or spectral, depending on if the incident radiation is monochromatic or broadband. Unlike responsivity, however, a small NEP is desired. [34]. Like responsivity, it is difficult to compare detectors based solely on NEP, since it is typically dependent on the square root of the detector area and the square root of the electrical bandwidth of the measurement. Other factors, such as chopping frequency, biasing conditions, and operating temperature can affect NEP. However, general
comparisons of detector NEPs can be made if the value is accompanied by detector area and the bandwidth of the measurement [34].

Since it is difficult to compare detectors based on responsivity, SNR, and NEP, Jones defined a new term called normalized detectivity in 1953 [34]. Normalized detectivity, or $D^*$, normalizes NEP to a 1 cm$^2$ detector area and a 1 Hz bandwidth. $D^*$ is expressed as:

$$D^* = \frac{\sqrt{A_D \Delta f}}{NEP}$$

where $D^*$ is in cm· Hz$^{1/2}$· watt$^{-1}$, or Jones. The interpretation of $D^*$ is that it yields SNR, given a detector with 1 W of radiant power incident on it, and are of 1 cm$^2$, and a noise-equivalent bandwidth of 1 Hz. Depending on whether the NEP was calculated using monochromatic or broadband radiation, the associated $D^*$ will also observe that form. Assumptions in this calculation are that the noise has a flat, white-noise spectrum, that noise is proportional to the square root of the bandwidth and detector area, that the detector is operating at optimum biasing and operating temperature, and that the spectral response is flat [34].

1.3.2 Electrical Noise Considerations

Electrical noise is defined as the random current or voltage fluctuations in electrical circuits [34]. Since the electrical noise of devices impacts various metrics used to compare different detector technologies, the associated noise of a device must be examined. There are various entities which can impact measurements of an
electrical device and can be classified as either interferences or noise sources. Interference can be of the man-made variety, which can be generated by transformers, motors, radio signals, and other electrical equipment, or the natural variety, which from phenomena of nature, such as lightning, earthquakes, or sunspots. However, the noise sources associated with the operation of the infrared detector impact the calculation of figures of merit and must be accurately determined.

The intrinsic noise associated with infrared detection can classified as external or internal. External sources of noise include noise in the interface or operation of the measurement electronics, such as that from the preamplifier and lock-in amplifier. The low-noise current preamplifier and lock-in amplifier that are used for the measurements are specifically designed for low-noise detection of signals, but there is still noise which impacts the measurements. A detailed analysis of the preamplifier noise will be presented in Section 4.2.1.2.

There are several types of internal noise which may impact infrared detectors. However, the sources that may impact the performance of the antenna-coupled MOM diodes fabricated for this research that will be discussed include Johnson, shot, and 1/f noise.

Johnson, or Nyquist, noise is the fluctuation caused by the thermal motion of charge carriers in a resistive element [34]. Even though charge neutrality is maintained for the overall device or structure, local random thermal motion of carriers can cause charge gradients. The rms Johnson noise voltage across the resistor, \( R \), at an absolute temperature, \( T \), can be shown to be:
\[ v_J = \sqrt{4kTR_D\Delta f} \]

where \( k \) is Boltzmann’s constant, \( T \) is the absolute temperature of the detector in Kelvin, \( R_D \) is the diode resistance, and \( \Delta f \) is the electrical bandwidth of the measurement in Hz. The Norton equivalent rms Johnson noise current can be expressed as:

\[ i_J = \frac{4kT\Delta f}{R_D}. \]

Shot noise is associated with a dc current \( i \) flowing across a potential barrier [34]. This is related to thermionic emission of electrons over the barrier in a MOM diode. Since the charge carriers, in this case electrons in the metal, cross a potential barrier when the incident radiation heats the structure and increases the energy of the electrons, the current through the diode possesses this type of noise. The current fluctuations associated with shot noise are given by:

\[ i_S = \sqrt{2qi\Delta f} \]

where \( i_S \) is the shot current-noise, \( q \) is the charge of an electron, and \( i \) is the average device current.

1/f noise is a noise source that is a strong function of the frequency of operation. The current noise is inversely proportional to the square root of the frequency, expressed by the relation:

\[ i_f \propto \sqrt{\frac{k_B^2 df}{f^{-1}}} \]
where \( i_{dc} \) is the dc bias current, and \( f \) is the frequency of the operation of the device. Although the causes for this type of noise are not fully understood, hence the expression in terms of a proportionality, potential causes include carrier fluctuations, trap occupancy variations in the oxide barrier, and the associated variations in trapping time constants [34]. Assuming that the antenna-coupled MOM diode devices have ohmic contacts to the electrical leads, which in turn have ohmic contacts to the bonding wires and the LCC and socket, 1/f noise is always zero for unbiased detection of a device in equilibrium. However, if a dc bias is applied to the device, 1/f noise will be encountered and must be taken into account.

These three types of noise will be experimentally addressed in Section 4.2.1.2. The noise study will include those internal to the device as well as external, such as the preamplifier and lock-in amplifier.

1.3.2 Detector Comparison

Table 1.1 compares infrared detectors currently available in the market along with those currently being researched. The highest \( D^* \) is desired, but in most application contexts \( D^* \) is compared in light of the following parameters: detector area, operating temperature, and response time. Although some detector types may be functional in spectral ranges outside of the LWIR, each detector’s \( D^* \) is reported for LWIR detection to provide comparison in the spectrum of interest.
HgCdTe, or MCT, detectors are the best thermal IR detectors available on the market today. The detectivity value is an order of magnitude greater than any other technology and the response time is very short. However, there are several factors that make them impractical for use in some applications. The largest issue is that MCT detectors require cryogenic cooling, which would be not only impractical for portable applications, but does not allow for direct integration with commercial integrated circuits without major modifications. In addition, the detector area is quite large, also presenting a road-block to integration in high pixel-count imager applications. Bolometers suffer the same disadvantages; while offering a reasonable
D* with fast response times, large detector areas and the requirement of cryogenic cooling prevent bolometers from being usable for many applications.

Pyroelectric detectors offer a high D*, comparable to MCT detectors, offer full functionality at room temperature without cooling, and have fast response times. The barrier issues lie in the fact that the detector area is large and that most pyroelectric materials are not CMOS compatible. Thermistors and thermopiles offer reasonable D* values and full functionality at room temperature. The response times are relatively slow, however, and again detector area prevents this type of detector from being integrated into large-format imagers.

Antenna-coupled bolometers offer a small detector area, room-temperature operation, and a fast response time. D* is relatively low, though. Higher D* values of 2.89 × 10^7 and 1.08 × 10^8 cm·Hz^{1/2}·W^{-1} have been reported [35], but these values were obtained by thermally isolating the devices on a membrane and measuring the values in air and under vacuum, respectively. The need for a fabrication process that includes membrane formation is problematic for integration with CMOS, and placing the detector in a vacuum to improve performance is not viable for many potential applications.

Antenna-coupled MOM diodes, like antenna-couple bolometers, offer small detector areas, room temperature operation, and fast response. However, previous research has reported lower than desired D* values at 1× 10^6 cm·Hz^{1/2}·W^{-1} [36]. In order for a detector to be commercially viable, D* values in the 10^8 range are
required. This research focuses on antenna-coupled metal-oxide-metal diode fabrication, their detection characteristics, and viability for commercial applications.
CHAPTER 2

ANTENNA-COUPL ED METAL-OXIDE-METAL DIODES

For high-performance imaging applications, a high speed, frequency selective
detector is desired which offers full functionality at room temperature without
cooling, fits within approximately a 10 × 10 μm area (in order to supply high pixel
counts in a practical imager size), and offers CMOS compatible fabrication. Of the
technologies discussed in the previous chapter, the only category of infrared detector
capable of meeting all of these stipulations is the radiation-field type.

The infrared radiation-field detectors fabricated in this research are composed
of two parts: an antenna and a nonlinear junction. The antenna is a half-wavelength
dipole formed by two quarter wavelength metal lines, separated by an oxide barrier
that forms a metal-oxide-metal tunnel diode. This diode rectifies radiation-induced
terahertz antenna currents.

In this chapter, an introduction to dipole antennas is given, along with design
considerations and parameters for this project. An overview of MOM diodes is
presented next, including a discussion of the various types, such as the point-contact
and thin-film varieties, and energy band diagrams of these structures. Then, the
device fabricated for this project, the dipole antenna-coupled metal-oxide-metal
diode, is discussed. Principles of operation for these devices in response to incident radiation are provided, including an explanation of the functionality behind their operation.

2.1 Dipole Antenna

A dipole antenna is a common type of antenna with a center-fed element which can either transmit or receive electromagnetic radiation. The usable frequency range of dipole antennas is vast; NASA has studied the dynamics of the magnetosphere using a 1647 foot long dipole antenna with a center frequency of 300 kHz, and capable of operating between 3 kHz and 3MHz [37]. This project focuses on frequencies eight orders of magnitude higher, using dipole antennas with a length of 3.1 μm for detecting 28.3 THz radiation. Although the former case utilizes a dipole antenna in space and the latter antenna functions on a silicon substrate, the operating principle behind each remains the same.

When electromagnetic radiation is incident upon a thin antenna, electromagnetic waves propagate along the length of the antenna. Waves traveling in opposite directions form standing waves on the antenna. In the case of a half-wavelength dipole, a voltage node forms at the center and antinodes form at each end of the antenna; conversely, a current antinode forms at the center and nodes form at each end [38]. A half-wavelength dipole is shown in Figure 2.1. Below the antenna, an approximation of the voltage distribution along the antenna is shown as a function
of time. In addition, the corresponding approximation of the current distribution is also shown.

Figure 2.1: Dipole antenna with corresponding voltage and current distributions. Each line indicating the voltage distribution along the antenna corresponds to the current distribution with the same line type, showing one half of a wave cycle in total.
In this research, the dipole antenna serves as a means of coupling 28.3 THz (10.6 μm wavelength) infrared radiation to a rectifying junction. A rectifying junction, in this case a metal-oxide-metal diode, is used instead of the more conventional transistor-based received architectures common in radio-frequency applications is that no conventional circuit technologies currently operate fast enough. However, a metal-oxide-metal diode is capable of rectifying the terahertz antenna currents so that a DC current may be measured across the junction.

The dipole full-length $L$ is 3.1 μm, which corresponds to the equivalent substrate half-wavelength in silicon dioxide of the incident radiation. Since the detector is positioned at the interface of two different materials, the effective dielectric constant $\varepsilon_{\text{eff}}$ [39] is approximately:

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_{\text{SiO}_2} + \varepsilon_{\text{air}}}{2}$$

The dielectric constant of SiO$_2$ $\varepsilon_{\text{SiO}_2}$ at 28.3 THz is 4.84 [40], which gives an effective dielectric constant of 2.92. The effective wavelength of an electromagnetic wave in a substrate $\lambda_{\text{eff}}$ [38] is given by:

$$\lambda_{\text{eff}} = \frac{\lambda_o}{\sqrt{\varepsilon_{\text{eff}}}}$$

where $\lambda_o$ is the wavelength of interest in air. For an electromagnetic wave with wavelength 10.6 μm propagating in SiO$_2$, $\lambda_{\text{eff}}$ equals 6.2 μm. In addition, Rakos simulated the design to calculate the radiation resistance and reactance of the antenna [41]. For an incident wavelength of 10.6 μm, the reactance of the antenna goes to
zero at a dipole length of 3.1 μm, which denotes the first resonance of the antenna. The radiation resistance of the 3.1 μm antenna at 28.3 THz is approximately 80 Ω from simulations [41, 42].

The width of the dipole antenna must also be considered in the design process. Transverse currents, those perpendicular to the length of the dipole, cannot be neglected if the width of the antenna is too large compared with the free-space wavelength of radiation $\lambda_0$ [43]. Simulation results at 10 and 46 GHz show that the antenna width must be less than $\lambda_0/35$ can suppress transverse currents so that longitudinal currents, those along the antenna axis, can be dominant as desired [43]. Therefore, for radiation at 10.6 μm, the dipole antenna width must be less than 303 nm. The width of the dipole antennas fabricated in this research is 50 nm, and therefore longitudinal currents are able to propagate along the antenna length.

### 2.2 Metal-Oxide-Metal Diodes

A metal-oxide-metal diode (MOM) diode, also commonly referred to as metal-insulator-metal (MIM) and metal-barrier-metal (MBM) diodes, is schematically illustrated in Figure 2.2. It consists of a thin (~20 Å) insulator, denoted by the white area, sandwiched between two parallel conductors. There have been numerous types of MOM diodes studied over the past half century. These consist of both point-contact and thin-film MOM diodes.
Figure 2.2: Simplified schematic illustration of a MOM diode, which is a thin insulator of tunneling thickness sandwiched by two parallel metal electrodes.

An energy band diagram of a MOM diode under no applied bias is shown in Figure 2.3. The structure in this figure features dissimilar metals of work functions $\phi_1$ and $\phi_2$, interface barrier heights $\phi_{b1}$ and $\phi_{b2}$, and an oxide barrier of thickness $d$. The work function of a metal is defined as the minimum energy required to move an electron from the Fermi level into vacuum [44]. The barrier height of a metal-insulator interface is defined as the potential difference between the Fermi level of the metal and the band edge of the insulator. Although the figure shows a diode formed with dissimilar metal electrodes, referred to as an asymmetric diode, the same metal can be used for each electrode to form a symmetric diode. In an unbiased structure, such as Figure 2.3, the Fermi levels of the metals in the unbiased structure align to reach equilibrium and the energy bands bend within the oxide layer, resulting in a built-in field. This built-in field is equal to the difference in the work functions of the metals divided by the thickness of the barrier.
In theory, there is no field present in the oxide for symmetrical MOM diodes, i.e. with the same metal used in each electrode, since the work functions are the same. However, in practice, even MOM diodes fabricated with the same metals can exhibit behavior that gives rise to an asymmetrical barrier. Any impurities or charges trapped at the metal-oxide interface or within the oxide can cause asymmetries in the potential barrier shape [45]. However, for the purposes of illustration and explanation, a simplified trapezoidal barrier will be assumed throughout this analysis.

The band diagram of a MOM diode when a small DC voltage bias $V_{DCapp}$ is applied is shown in Figure 2.4.
Figure 2.4: Energy band diagram of MOM diode under small applied bias. The difference between the two metal’s Fermi levels is equal to the applied bias.

The positively-biased electrode moves down in energy, causing a difference in the Fermi levels equal to the applied bias $V_{DCapp}$. The electric field across the oxide layer of the structure changes by an amount equal to the applied bias divided by the thickness of the layer and adds to any field already present in the barrier.

For an MOM diode with an oxide barrier thickness on the order of 20 Å, even small biases of approximately one volt can cause extremely high fields (5 MV/cm), and exceed the breakdown field of the oxide. Depending on the growth or deposition method, this can be vary from 1.4 MV/cm for deposited films [46] to over 500 MV/cm for ultra-thin (5 Å) native oxide barriers grown in oxygen [47]. K. Gloos et al. found that the breakdown field increases for decreasing barrier thickness [47].
the breakdown field of the insulator in the MOM diode is exceeded, the device may be destroyed.

When a small bias, much less than the barrier height $\phi_b$, is applied between the two conductors, electrons can traverse a sufficiently thin barrier by quantum mechanical tunneling [48-50]. For a finite potential barrier, as in the case for MOM diodes, the wave function of an electron on one side of the barrier penetrates the barrier and yields a finite probability of the electron being on the opposite side of the barrier [11, 48]. The probability for electrons to tunnel through a potential barrier decreases exponentially with increasing barrier thickness [51]. For tunneling to take place in an MOM structure, the oxide thickness must less than approximately 50 Å.

For the case of a MOM diode with dissimilar metal electrodes, as shown in Figure 2.4, electrons on the left side of the barrier have a higher probability of tunneling through the potential barrier to the right side than in the reverse direction, because electrons on the left have available states of which to tunnel, whereas those on the right have no available states of which to tunnel on the left. The nonlinear current voltage (I-V) characteristic of a MOM diode arises from this quantum mechanical process. The nonlinearity depends on the work functions of each metal as well as the oxide type and thickness [45, 52-54]. Further detail on the antenna-coupled MOM diodes fabricated for this project can be found in Chapter 3.
2.2.1 MOM Diode Design

There are many varieties of MOM diodes which can be utilized as nonlinear junctions. However, the desired diode characteristics must first be analyzed with respect to the desired frequency of operation. Since MOM diodes are tunneling devices, if the tunneling transit time is slower than one wave cycle of the 28.3 THz incoming wave, then the device will fail to respond and will not rectify the incoming signal efficiently. The overlap area of the MOM diode must be small enough so that the RC time constant is less than one infrared wave cycle [29].

An equivalent circuit of an antenna-coupled metal-oxide-metal diode under incident infrared radiation can be modeled as an antenna and diode connected in series [49, 55], as shown in Figure 2.5.

Figure 2.5: Equivalent-circuit model of an antenna-coupled MOM diode. As a receiver, the antenna is represented by a voltage source with series impedance. The diode is represented by a parallel combination of a capacitor and voltage controlled current source in series with the lead impedance.
The MOM diode can be described by a junction capacitance $C_D$ in parallel with a nonlinear voltage-dependent resistance $R_D(V)$. This parallel combination is in series with the resistance $r$, which represents metal lead and/or spreading resistance [55].

An antenna functioning as a receiver can be represented by an alternating current source $V_{ir}\cos(\omega t)$ with induced voltage $V_{ir}$ at angular frequency $\omega$, operating at the frequency of the incident electromagnetic radiation. This is connected in series with impedance $R_A + jX_A$, where $R_A$ is the real impedance of the source. For this circuit, the RC time constant is the product of the diode capacitance and the equivalent resistance, which is $R_D$ in parallel with the series combination of $R_A$ and $r$. This leads to a cut-off frequency $f_c$ of:

$$f_c = \frac{R_A + r + R_D(v)}{2\pi(R_A + r)R_D(v)C_D}.$$

While rectification and mixing are still observed above this frequency, it is with diminished efficiency. Although there is some disagreement on this issue, the signal amplitude has been theoretically calculated to decrease as $\omega^{-1}$ [50, 56], $\omega^{-3/2}$ [49], and $\omega^{-2}$ [57].

To minimize the response time of the diode and attain a high cut-off frequency, the diode capacitance must be small. If the capacitor is considered a small parallel plate capacitor, the diode capacitance $C_D$ is:

$$C_D = \varepsilon_{ox}\varepsilon_o \frac{A}{D}$$

where $\varepsilon_{ox}$ is the relative permittivity of the oxide in the MOM diode, $\varepsilon_o$ is the permittivity of free space, $A$ is the junction area, and $D$ is the thickness of the oxide.
dielectric. The dielectric constant of Al$_2$O$_3$ at 28.3 THz is approximately 1 [58]. For a diode with a 25 Å barrier composed of Al$_2$O$_3$, a 50 x 50 nm overlap area, and an antenna resistance of 1 kΩ, the cut-off frequency is 180 THz. The exact composition of the oxide barrier is not known, so it will be written as AlO$_x$, where $x$ is not necessarily an integer. The cut-off frequency will change depending on the dielectric constant of the AlO$_x$.

### 2.2.2 Point Contact MOM Diodes

The first MOM diode structures fabricated in the laboratory were of the point-contact, or cat-whisker, variety and were introduced in the early 1960s [57, 59]. These diodes consisted of a thin, sharp tipped tungsten wire with a thin (~35 Å) oxide covering that mechanically contacted a polished metal, commonly nickel, post. An illustration of a point-contact MOM diode can be seen in Figure 2.6, where the dark color denotes the tungsten wire and metal post while the light color surrounding the wire indicates the native oxide coating on the tungsten wire.
When a small DC bias was applied between the thin wire and the post, electrons tunneled from one metal electrode to the other through the insulating oxide barrier [57]. The contact area was controlled by both the shape of the whisker and its contact pressure on the polished post [59]. This contact area also has an effect on diode resistance, so this parameter can be modulated if desired with a point-contact MOM diode. A nonlinear current-voltage characteristic arises from electrons tunneling through this oxide barrier.

The metallic wire also functioned as a receiving antenna when subjected to incident optical or infrared radiation. It has been shown that these structures are capable of coupling incident radiation into an optically induced voltage across the diode [48, 55]. The drawback to this type of device lies in its size and mechanical
instability. Physical vibrations can cause the contact pressure and area of the wire to change. In extreme cases, the wire may lose contact with the post and produce unstable current-voltage and detection characteristics. While very small contact areas can be achieved and the whisker can act as an in-air receiving antenna, this type of MOM diode and antenna structure would not be suitable for many imaging applications due to its mechanical instabilities and non-CMOS compatible processing.

2.2.3 Thin-film MOM Diodes

With the aid of higher resolution lithography and new fabrication techniques, MOM diodes were able to take a thin-film form in the late 1970s as ‘edge’ MOM diodes [60, 61]. Thin-film diodes are fabricated on the surface of a semiconductor wafer. Since they do not rely on contact pressure between separate components, as in the case of point-contact MOM diodes, they do not suffer from mechanical instabilities.

Edge MOM diode structures were fabricated using an optical lithographically-defined sandwich structure of a metal layer between two layers of insulating material. The edge of the thin sandwich structure was then coated with an oxide layer thin enough to allow tunneling behavior. Then, an overlying metal was laid over the original structure. An edge MOM diode is illustrated in Figure 2.7. The medium gray metal is sandwiched between the light gray insulators. An oxide of tunneling thickness covers this sandwiched metal layer and is shown as the light gray material. The MOM diode is formed between the sandwiched metal layer, the thin oxide
coating layer (which is cut away at the left end to indicate the presence of the oxide), and the overlying dark gray metal structure, which provide a small contact area for tunneling.

Figure 2.7: Illustration of an edge MOM diode structure. In this structure, a metal layer is sandwiched by two insulators. A thin oxide is grown or deposited on the sandwiched metal layer (which is cut away at the left to indicate its presence) and the overlapping metal is patterned to complete the MOM structure.

These structures can also function as a rectifying antenna; the leads of the overlying metal can be structured to serve as an antenna and the edge MOM forms the nonlinear junction. The overlap areas of edge-MOM diodes are commonly too large for optical-frequency detection, however, since they are defined using optical lithography. However, another similar type of thin-film MOM diodes can be made with even smaller overlap areas. Overlap diodes fabricated using electron beam lithography simply consist of a metal line with an oxide covering that is overlapped
by another metal line. These can function as rectifying antennas as well, with the metal leads forming the antenna and the diode serving as the nonlinear junction.

2.3 Conduction Mechanisms

There are many possible mechanisms that can describe the flow of electrons in an antenna-coupled MOM diode. In every case, current flows from one metal electrode to the other. However, this electrical conduction can arise from various mechanisms which can be either classical or quantum mechanical. The specific properties and times for each mechanism can be used to determine which mechanism is predominant, but several conduction mechanisms often occur simultaneously in a device. Each operation will be described in this section, and the detection mechanisms which give rise to the signals in the structures fabricated for this project are indicated.

When photons of energy $h\nu$ are incident upon a MOM diode structure, they can interact with electrons within the metal. Electrons resident at the Fermi level near the barrier can gain energy and tunnel across the barrier to the other metal with increased probability [48, 49, 62]. The energy associated with electromagnetic radiation comes in indivisible packets called quanta, each associated with a single photon. This can be defined by:

$$E = h\nu = \frac{hc}{\lambda}$$
where $E$ is the energy associated with electromagnetic radiation in joules, $h$ is Planck’s constant, $\nu$ is the photon’s frequency in hertz, $c$ is the speed of light in vacuum in meters per second, and $\lambda$ is the wavelength in meters.

Figure 2.8 illustrates an incident photon of energy $h\nu$ interacting with electrons near the barrier in a MOM structure. Excited electrons gain energy from the incident photon, which increases the probability of tunneling through the oxide to the other metal electrode. Those electrons which do tunnel due to energy gained from incident photons give rise to photon-assisted tunneling current in the MOM diode [62].

![Figure 2.8: Photon-assisted tunneling in MOM diode structure. Electrons near the barrier in Metal 1 can gain energy from incident photons, which increases their probability of tunneling through the barrier to Metal 2.](image)
The electrons which tunnel through the oxide without photon excitation lead to an associated dark current for the device [48]. However, since the incident photon energy of infrared photons is relatively low, ~0.1 eV for 10μm wavelength, this is not the detection mechanism for the devices presented in this work.

If the incident photon energy $h\nu$ is greater than that of the barrier height, electrons can move to the other metal electrode without tunneling by surmounting the barrier. Incident photons excite electrons into states above the barrier and cross the barrier with a probability close to unity [63]. The interaction of a photon of energy $h\nu$ with an electron near the barrier is shown in Figure 2.9.

Figure 2.9: Electrons surmounting barrier in MOM diode structure. Electrons in Metal 1 can gain enough energy from incident photons to surmount the barrier in order to get to Metal 2.
The associated dark current of the structure is still present, shown by the electrons tunneling through the barrier without excitation. Again, since infrared photon energies are much less than the metal-oxide barrier height in the MOM diode, this is not typically observed for infrared detection.

There exists another conduction mechanism that is a combination of the cases of photon-assisted tunneling and electrons surmounting the barrier. In this case, photon-excited electrons with energy well above the Fermi level but still below the top of the tunnel barrier can tunnel from one metal to the other [63], as shown in Figure 2.10. This can substantially contribute to the tunneling current because the effective barrier height is reduced for these electrons [64].

![Figure 2.10: Excited electrons tunnel across the barrier in MOM diode structure. Electrons in Metal 1 can gain energy from incident photons and tunnel to Metal 2 near the top of the tunnel barrier.](image)
When optical or infrared radiation is incident upon a structure, photons can interact with the material, causing lattice vibrations also known as phonons. These vibrations can cause heating within the metal in a metal-oxide-metal diode. Electrons close to the barrier gain energy as $k\Delta T$ [11] where $k$ is Boltzman’s constant. According to the density of states of electrons in a metal and the temperature dependent Fermi distribution function, a carrier distribution can be determined. As temperature increases, the Fermi function becomes less sharp, and an increasing portion of the electron distribution have probabilities of energies above the Fermi level, hence increasing the tunneling current [65]. When electrons tunnel through the barrier due to the extra energy gained by heating of the structure, it is known as thermally-assisted tunneling, shown in Figure 2.11. If a temperature difference between the metals is present, an even greater contribution of thermally-assisted tunneling can be expected. However, due to the poor absorptivity of metals in the LWIR [66] and the fact that the entire structure is illuminated, it is not believed that a temperature difference is developed. Thermally-assisted tunneling increases monotonically with heating due to photon absorption in the substrate and also with the applied DC bias [57]. Thermally-assisted tunneling does not contribute to the rectification at infrared frequencies because it is too slow [48, 67]. While thermally assisted tunneling may give rise to electrons tunneling through the barrier in the devices, it is not a detection mechanism which would produce a polarization-dependent response in response to infrared photons.
Figure 2.11: Thermally-assisted tunneling in MOM diode structure. Electrons with increased energy from heating of the structure have an increased probability of tunneling from one metal to the other through the barrier.

Wilke et al. determined that the heating of the structure due to incident radiation can cause spreading resistance nonlinearity and thermal currents that are as strong as electron tunneling currents, even at room temperature [45, 67]. As heat is generated in the vicinity of the MOM structure on a Si/SiO$_2$ substrate, thermionic emission of electrons over the barrier occurs. Joule heating due to the dissipation of laser-induced ac current in the antenna structure can also contribute to this effect [68].

The last principle of operation for antenna-coupled MOM diodes is Fermi level modulation or field-assisted tunneling. When infrared radiation is incident upon the structure, an optical or infrared voltage is induced [48, 69]. This oscillating perturbation of the barrier can lead to multiple types of conduction mechanisms [64].
This is shown in Figure 2.12, where the radiation is incident upon the structure, causing an alternating current bias that is in summation with the bias voltage.

This time-dependent bias $V(t)$ can be expressed as:

$$V(t) = V_{DCapp} + V_{IR} \cos(\omega t)$$

where $V_{IR}$ is the amplitude of the induced voltage and $\omega$ is the angular frequency of the incident radiation [48, 55]. The oscillation of the tunnel barrier leads to a degeneracy of electronic states that are separated by multiples of the photon energy [64].
When the induced alternating current infrared voltage has the same polarity as the applied DC bias, the separation between the Fermi levels of the two metal electrodes is increased. The initial state on the left side of the barrier is directly coupled to final states on the right side that are separated by the incident photon energy [64]. Therefore, the probability of an electron to tunnel through the potential barrier from left to right increases, as does the tunneling current in the structure. On the other hand, when the induced infrared voltage is of opposite polarity to the DC applied bias, the Fermi levels come closer together and the tunneling probability of an electron through the potential barrier decreases. The increased probability of tunneling when the overall bias is largest is greater in magnitude than the decreased probability of tunneling when the overall bias is smaller. This nonlinear tunneling behavior allows the MOM diode to act as a rectifier. Since tunneling is an inherently fast process [70], $10^{-15}$ s to traverse a barrier on the order of 10 Å, MOM diodes are capable of rectifying high frequency signals. This applies in the LWIR [66, 71, 72], mid-IR [73, 74], and even up to optical frequencies [75, 76].

Any number of the aforementioned conduction mechanisms can occur simultaneously in an MOM diode [63]. In addition, trap states in the tunnel barrier can impact the conduction mechanisms as well, since electrons can occupy vacant trap states and tunnel from one metal to the other in multiple steps [77]. However, the wavelength of the incident radiation impacts which conduction mechanisms are expected to occur. Photon assisted tunneling is expected to dominate for photon
energies that are on the order of the barrier height [63]. For infrared radiation in the LWIR, tunneling due to Fermi-level modulation is likely to dominate.

2.4 Substrate and Antenna Effects

The radiation pattern of a dipole antenna is significantly influenced by the dielectric environment surrounding it. Since the antennas in this research will be placed at an air/SiO₂ interface, the radiation pattern with respect to the antenna axis will be strongly asymmetrical [68]. As a result of this asymmetry, the dipole antenna is more sensitive to radiation from the half-space with the higher dielectric constant. The power received by the antenna from each half-space can be approximated by:

\[ \eta_{rel} = \frac{P_2}{P_1} \approx \frac{\varepsilon_2^{3/2}}{\varepsilon_1^{3/2}} \]

where \( \eta_{rel} \) describes the relative efficiency of coupling of an antenna at an interface of materials 1 and 2, \( P_1 \) and \( P_2 \) is the power coupled to, or received by, the antenna from material 1 and 2, respectively, and \( \varepsilon_1 \) and \( \varepsilon_2 \) are the dielectric constants of materials 1 and 2, respectively [68].

Given the dielectric constant of silicon, and the relatively small thickness of the silicon dioxide matching layer in terms of the wavelength of the incident radiation, simulations indicate that the coupling of the radiation to the antenna will be approximately 40 times more efficient for illumination from the substrate side as compared to the air-side [78]. Although substrate-side illumination is theoretically much more efficient than air-side illumination, it presents some difficulty from a
practical point of view. For example, a standard leadless chip carrier cannot be used, necessitating the use of a flip-chip arrangement, and in an imaging system this would preclude placing circuitry below the antenna.

However, a strong antenna response that is on the same order as for substrate-side illumination, can still be observed when utilizing air-side illumination [67, 78] if a well-designed SiO$_2$ surface layer is used. The relevant mechanism of the antenna response is the coupling of the incident energy from within the top SiO$_2$ layer. J. Alda et al. reported that the ratio of antenna responses between the air-side and substrate-side illumination $\Delta V_{air} / \Delta V_{substrate} = 0.84$ for 10.6 $\mu$m wavelength illumination [78]. Therefore, it can be concluded that air-side illumination can be made to be nearly as efficient depending on the material properties and thickness of the SiO$_2$ layer. This verifies that the integration of the antenna-coupled MOM diodes fabricated in this research with a prefabricated CMOS chip is possible.

The material properties and thickness of the SiO$_2$ play an important role in the antenna signal. The spectral dependence of the complex part of the refractive index combined with the role of reflections within the SiO$_2$ layer impact the spectral dependence of the antenna [78]. It should be noted that reflections from the back side of the wafer have been found to be of negligible importance [78]. For this research project this is certainly the case, since the roughness of the backside of the wafers is on the order of the wavelength of incident radiation.

Surface impedance has an influence on the current distribution $I$ along an antenna. When subjected to a specific wavelength of irradiation, antenna currents
will propagate along an antenna. There is an exponential attenuation of these antenna currents due to the surface resistance of metals at infrared frequencies, which is related to the skin effect [68]. The surface attenuation constant $\Gamma_{sr}$ is given by:

\[
\Gamma_{sr} = -\frac{1}{2} \ln \frac{I(L)}{I(0)} = \frac{2\pi}{\lambda_0} \kappa
\]

where $L$ is the antenna length, $\lambda_0$ is the illumination wavelength, and $\kappa$ is the imaginary part of the complex refractive index of the antenna metal.

There is further attenuation of the antenna currents due to the placement of the dipole between two materials of different dielectric constants $\varepsilon_1$ and $\varepsilon_2$. The phase velocity of the electromagnetic waves, in this case antenna currents propagating along the length of the metal dipole antenna, can be described by:

\[
v_p = c \left( \frac{\varepsilon_1 + \varepsilon_2}{2} \right)^{-1}
\]

where $v_p$ is the phase velocity and $c$ is the speed of light in free space. The phase velocity of the antenna currents is intermediate between the phase velocities of the two surrounding dielectrics [79]. Therefore, the antenna currents are exponentially attenuated as a function of the length, with the attenuation constant due to the dielectric difference $\Gamma_C$ expressed as:

\[
\Gamma_C = -\frac{1}{L} \ln \frac{I(L)}{I(0)} = \frac{2\pi}{\lambda_0} \sqrt{\frac{\varepsilon_1 + \varepsilon_2}{2}},
\]

which is known as the Coleman effect. The effect of this attenuation can be determined by studying its influence on dipole antennas of different lengths $L$ [68]. This will be experimentally addressed in Section 4.2.3.
CHAPTER 3
FABRICATION

The fabrication of these antenna-coupled metal-oxide-metal diodes (ACMOMDs) is performed in the Notre Dame Nanofabrication Facility (NDNF). The processes utilized in the fabrication of the devices include thermal oxidation of silicon wafers, optical and electron beam lithography (EBL), metal deposition, and multiple developing and etching steps. Optical lithography is used to create bonding pads for the devices, while EBL is used to pattern the ACMOMD devices. In this chapter, the fabrication processes for both the bonding pads and the ACMOMDs are discussed in detail.

3.1  Substrate

The substrate for the ACMOMDs fabricated in this research is a 625 μm thick, single-side polished p-type silicon wafer of 13-16 Ω-cm resistivity. A thermal oxide of 1.5 μm is grown on both sides of the wafer to provide an insulating substrate for the device and to also serve as a quarter wave matching layer for 10.6 μm irradiation. This layer is grown using an oxidation furnace with a 5/265/5 minute dry/wet/dry process at 1200°C. Since the roughness on the back side of the wafer is on the order
of the wavelength of the irradiation, it is not expected that any backside reflections will reach the top surface.

Surface roughness of the substrate must be minimized since these devices are composed of very thin metal lines on the order of 30 nm. If the surface roughness of the substrate is too great, the antenna, leads, or both could be broken and cause an open circuit. Thermal oxidation of silicon was chosen because of its convenience, ability to provide consistently smooth films, and offer low optical loss. The transmission through a 625 μm single-side polished silicon wafer, measured using a Bruker IFS-66v/S Vacuum Fourier Transform Infrared spectrometer, both with and without the thermally-grown silicon dioxide matching layers is shown in Figure 3.1. This shows that approximately 25% more of the incident radiation is coupled into the wafer at 10.6 μm with the SiO₂ layer than without. Since it has been shown that radiation coupled to the antenna from within the SiO₂ layer is greater than that coupled to antenna from the air side [78], these SiO₂ layers are important to the device response.
Figure 3.1: Infrared transmission spectra through Si and Si/SiO₂ wafer between 8 and 14 μm. The wavelength of interest is 10.6 μm, where the transmission is about 25% greater with the SiO₂ layer than without, meaning that more light is coupled into the wafer and can be coupled to the device from within the SiO₂ layer.

3.2 Bonding Pad Fabrication

In order for the characteristics of completed nano-scale devices to be determined, a means for electrically contacting them must be provided. In the case of both electrical and infrared measurements for this project, bonding pads serve as a way to provide a larger contact area than the nano-scale ACMOMDs. The bonding pads are defined using optical lithography and can be fabricated by utilizing either a lift-off or etching process, as shown in Figure 3.2.
Figure 3.2: Bonding pad fabrication by: (A) etching and (B) lift-off. Both methods provide the same patterned bonding pads, but the etching method is preferred.
The final bonding pad structures have the same pattern and metal thicknesses for both fabrication methods, but the fabrication processes differ.

The bonding pads for each device are composed of a two 4 μm × 10 μm metal leads, between which an ACMOMD will be placed. A tapered metal line connects these leads to two 120 μm × 120 μm metal bond pads which can be contacted with a probe station or wire bond. For each set of bonding pads, 22 devices can be selected; this number corresponds to the number of pins available on the leadless chip carrier to be used, which will be described in Section 3.2.4.

With the etching process, 50 Å of titanium and 200 Å of gold are first deposited on a clean silicon/silicon dioxide substrate using an electron beam evaporator, in this case an Airco Temescal FC1800 evaporator. The titanium serves as an adhesion layer for the gold to the substrate. Shipley Microposit 1813 positive photoresist is then applied to the wafer using a spin-coat process at 4000 rpm for 30 s, which provides a film layer of approximately 1.35 μm after a 90 ºC hotplate pre-bake for 90 s. The wafer is then exposed using a chrome plate mask on the Karl Suss contact aligner with a dose of 60 mJ/cm². The development is performed by submerging the wafer in Clariant AZ917 metal-ion-free (MIF) developer for approximately 25 s. The completion of the development, however, can be much more accurately determined by eye than by time because of variations in developing rate due to factors such as developer purity and temperature, pre-bake temperature, and resist film age. The developed resist structure covers the areas of the Ti/Au layer on the wafer which are to remain. The bonding pads are defined when the gold and
titanium layers are etched away by a 7 s Transene TFA gold etch to remove the Au layer, and a 30 s Piranha etch, which is a 3:1 mixture of sulfuric acid and 30% hydrogen peroxide, to remove the Ti underlayer. Due to the isotropic etching behavior of each etchant, the bonding pads do have sloped sidewalls, which is useful so that reliable electrical connections can be made from the thin metal of the ACMOMDs to the bonding pads. Since the edges of the bonding pads are sloped, the device leads will not be broken by traversing a step from the substrate to the gold pad. Therefore, a reliable and repeatable electrical connection of the devices to the bonding pads is made.

The lift-off process for fabricating bonding pads begins by spin-coating the wafer with Clariant AZ 5214-E negative photoresist at 4000 rpm for 30 s. After a 90 °C hotplate pre-bake for 60 s, a photoresist layer of approximately 1.40 μm thick remains. The bonding pads are defined with a 30 mJ/cm² g-line UV exposure on the Karl Suss contact aligner. This is followed by an image reversal procedure: a 60 s, 110 °C image reversal hotplate bake followed by a 200 mJ/cm² Cobilt CA-800 broadband UV flood exposure. The wafer is then developed in AZ917 MIF developer, just as in the case of the etching process, and 50 Å of titanium and 200 Å of gold are deposited using a Airco Temescal FC1800 electron beam evaporator. By using a lift-off solvent, in this case acetone, the photoresist and overlying metal is removed and the bonding pads remain on the substrate. The lift-off process can leave sharp edges if the resist profile is not undercut, which could cause a break between the bonding pad and ACMOMDs. Although either method can be utilized for
fabricating suitable bonding pads, the etching process is preferred due to its consistency in terms of providing a reliable electrical connection to the devices.

The bonding pad design was chosen to allow for easy integration with a 44-pin leadless chip carrier (LCC), which is used in the infrared testing setup. Figure 3.3 is an optical micrograph of one set of titanium-gold bonding pads fabricated on a silicon wafer with 1.5 µm thermally-grown silicon dioxide layer.

Figure 3.3: Titanium-gold bonding pads on Si/SiO₂ substrate. These bonding pads provide electrical contacts to the ACMOMDs so that they may be characterized. Note: leprechaun in the upper left, Golden Dome in the upper right, interlocking ND Nano logo in the lower left, and gold helmet of the Fighting Irish in the lower right.
The design was created using L-Edit and exported to the Mann 3000 pattern generator, where an emulsion plate was exposed with a 10× larger replica of the pattern. Then the pattern on the emulsion plate was reduced by 10× and stepped in 4 × 4 mm increments across a 4” chrome plate using the Mann/GCA 3696 step and repeat camera.

3.3 ACMOMD Fabrication

The ACMOMD fabrication process utilizes electron beam lithography to create the antenna-coupled MOM diode pattern in a positive radiation resist. The pattern in the resist serves to define the device when metal is deposited on the sample. Each step performed during the fabrication of the ACMOMD is explained in detail, including EBL, development, metal deposition, and lift-off.

3.3.1 Electron Beam Lithography

Electron beam resist is a material that is sensitive to high energy electrons and most commonly used as a high-resolution resist for direct-write EBL. The resist is composed of long molecular chains suspended in a solvent. This liquid solution can be applied to a wafer using spin coating, just as in the case for optical lithography. The spin speed determines the thickness of the resist on the sample.

For this project, two types of electron beam lithography resist are utilized: polymethyl methacrylate and copolymer methyl methacrylate. Polymethyl methacrylate (PMMA) is a high contrast, high resolution resist, while copolymer
methyl methacrylate – methacrylic acid (MMA-MAA) is a lower resolution mixture of methyl methacrylate and 8.5% polymethyl methacrylate.

For the experiments in this research, MicroChem Corporation’s MMA(8.5)MAA EL11 is used as the bottom layer of resist that lies upon the sample substrate. This resist has an 8.5% MMA concentration and is prepared as an 11% solids concentration in ethyl lactate. The copolymer layer is then covered by a layer of MicroChem 950K PMMA A2. The molecular weight of this resist is 950,000 and is a 2% solids concentration in anisole.

The copolymer MMA layer is applied using a wafer spinner at 4000 rpm for 30 s. This approximately yields a 4500 Å layer after a 2 minute hotplate bake at 170 °C for 2 minutes. The sample is allowed to cool and then covered by a top layer of 950k PMMA A2 resist which is also spun on at 4000 rpm for 30 s. The sample is then baked for 3 minutes on a hotplate at 170 °C. The thickness of this layer is approximately 700 Å, totaling 5200 Å for the resist stack.

The reason the bi-layer resist stack was chosen can be explained with a profile image, shown in Figure 3.4, of the resist after electron beam lithography and development. The PMMA is a high-resolution, high-contrast resist that will be used to define the desired pattern for the device on the substrate. Incident electrons break the long molecular chains, which can be then removed using a developing solution. The copolymer MMA layer, which is a more sensitive resist, simply serves the purpose of a spacing layer. This layer of resist lifts the PMMA off of the substrate,
while providing an undercut beneath the PMMA opening to facilitate a double-angle metal deposition procedure.

![Diagram of bi-layer resist stack](image)

**Figure 3.4: Profile of developed bi-layer resist stack on sample substrate.** The copolymer layer is a lower resolution, higher sensitivity resist than the PMMA, which provides an undercut after development and forms the foundation for the fabrication method of the ACMOMDs.

This double-angle metal deposition has been utilized to fabricate nano-scale tunnel junctions [80] and single electron transistors [81-83]. The amount of undercut is directly dependent upon the thickness of the resist as well as the spread of the electron beam within the resist layer, a function of the accelerating voltage of the electron beam lithography system.

In this research, the EBL is performed using an Elionix ELS-7700 Electron Beam Lithography System. This system operates at 25, 50, and 75 kV, although for this project the EBL is performed exclusively at 75 kV, for which the system is optimized. This system is capable of high resolution lithography and provides for alignment of patterns to both electron beam and optical lithographically-defined patterns already on the wafer.
The pattern for the antenna-coupled MOM diode is created using the supplied Elionix software. Figure 3.5 shows a screenshot of the pattern array. The pattern is composed of 21 devices. For each device, there are two rectangles, one at each end, which contact the bonding pads that are detailed in Section 3.1. Leads from these rectangles provide the electrical connection to the two halves of a dipole antenna. There is a small gap between each half of the dipole antenna. The length of the dipole antenna was designed to correspond to the equivalent wavelength of the desired detection wavelength, in this case 10.6 \( \mu \)m radiation, in the silicon dioxide layer, upon which the antenna is located.

![Figure 3.5: Screenshot of EBL pattern using Elionix software. The devices shown are aligned and exposed into the resist over the bonding pads shown in Figure 3.3. The different colors represent different electron doses.](image)
With a beam accelerating voltage of 75 kV, the undercut for the aforementioned resist stack shown in Figure 3.4 is roughly 25 nm in each direction. That is, for a 50 nm line in the PMMA, the line width in the underlying copolymer MMA at the substrate level would be 100 nm. The gap between the dipole halves is 65 – 85 nm, as shown by the rectangle in the screenshot in Figure 3.6. Since the undercut of a 75 kV exposure is approximately 25 nm and the PMMA bridge width ranges from 65 – 85 nm, there is some residual copolymer left beneath the PMMA bridge after development. Therefore, a 50 µC/cm² areal dose is applied to this gap, represented by the rectangle between the two halves of the dipole antenna.

Figure 3.6: Screenshot of dipole antenna. This magnified view of a single device pattern shows the dipole antenna (oriented horizontally) and the lead structures (oriented vertically). A purple rectangle is shown in gap in the pattern of the dipole antenna, where the small areal dose is applied.
The exposed pattern is developed in a mixture of methyl isobutyl ketone (MIBK), isopropanol (IPA), and methyl ethyl ketone (MEK), of ratio 1:3:1.5\% MIBK:IPA:MEK [84], for 35 s. The sample is immediately rinsed in IPA for 30 s to stop the development and clean the sample. The areal dose applied to the gap is high enough to expose the underlying copolymer MMA layer but low enough to keep the PMMA bridge intact after development. Since the PMMA is left intact and the MMA is removed below, a shadow evaporation technique can be utilized that allows these antenna-coupled MOM diodes to be fabricated using a single EBL step. An illustration of the developed structure on the sample is shown in Figure 3.7.

Figure 3.7: Illustration of the EBL pattern on substrate after development. The largest rectangles on either end of the pattern represent where contact will be made with the bonding pads. The electrical leads lead to each half of the dipole antenna, which are separated by a small PMMA bridge.
There is a small PMMA ‘bridge’ between each half of the antenna, created by the gap in the EBL pattern. A cutaway view of the sample and resist profile, showing the PMMA bridge, is shown in Figure 3.8.

Figure 3.8: Cutaway view of EBL pattern on sample after development. This cross-section is taken along the antenna shown in Figure 3.9 and through the PMMA bridge. This bridge and undercut forms the basis for how the ACMOMDs presented in this work are formed.

The line widths of the antenna leads and antenna in the PMMA are 50 nm after development. The sample is placed in the Plasmatherm reactive ion etcher (RIE) for a 7 s O₂ de-scum procedure. The purpose of this step is to clean any residual resist from the substrate in the patterned areas to facilitate improved adhesion of the metal during deposition. An optical micrograph of the electrical leads and developed EBL pattern is shown in Figure 3.9.
3.3.2 Metal Deposition

All metal evaporations for devices fabricated in this project are performed with the Temescal FC1800 #1 electron beam evaporator. A schematic of the chamber is shown in Figure 3.10. It is important to note the location of the source relative to the sample. The source is at the center of the bottom of the chamber and the sample is held upside-down on a bar at the top of the chamber. Evaporated particles travel in a straight path as they leave the source, leading to a directional, non-conformal deposition that is essential to the fabrication of the devices. A turret containing six materials is located the bottom of the chamber, and the desired metal is chosen by selecting the proper turret location. A shutter shields the sample from undesired metal deposition. A quartz crystal is located at the top of the chamber, which is connected to a film deposition monitor which allows the operator to observe evaporation rate as well as total deposition thickness. A view port on the lid of the chamber allows the user to adjust the beam position on the source as well as the horizontal and vertical raster scans.
3.3.2.1 Air Oxidation Method

The sample stage is based upon a thin aluminum back plate that attaches to the existing U-bar with binder clips. A $\frac{1}{2}''$ diameter piece of aluminum bar is attached to the back plate by two $\frac{1}{2}''$ single screw conduit straps. The round bar has two drilled holes that were tapped to provide a means for mounting the sample holding plate.
This plate is then held to the round bar by two screws that go through the sample holding plate. This stage can be seen in Figure 3.11.

![Diagram](image)

**Figure 3.11**: Manual two-angle stage for fabricating MOM diodes with the air oxidation procedure. The sample holding plate pivots about an aluminum rod. The angle of the sample holding plate is set manually.

The sample is attached to the sample holding plate with adhesive tape. This provides for an easy and reliable way to both hold the sample on the plate and remove it after evaporations. The leads of the antenna are oriented parallel to the rotational axis of the sample holding stage. The U-bar, along with the attached stage, is placed into the chamber of the evaporator (refer to Figure 3.9) and the sample holding plate is manually placed in the -7° position, denoted by the red line in Figure 3.11.

The first metal is deposited on the sample at three to five Å/s until a final thickness of 300 Å is reached. The electron gun is turned off for fifteen minutes, allowing the gun, turret, chamber, and sample to cool down from the evaporation.
Then, the deposited layer of metal, which for this project is always aluminum, is oxidized. Aluminum quickly forms a native oxide in air that is 20-25 Å thick, depending on environmental conditions in the laboratory, such as temperature and humidity. A transmission electron micrograph of an aluminum native oxide formed in air is shown in Figure 3.12.

![Transmission electron micrograph of native oxide formed on aluminum in air. The native oxide was then covered with another layer of aluminum to protect the native oxide during specimen preparation. This oxide, formed with an air oxidation, is approximately 22 Å thick.](image)
It is important to make sure the sample returns to ambient temperature after the first evaporation to ensure that the oxidation conditions remain as consistent as possible from one experiment to the next. If the sample is still hot from the metal deposition, a thicker oxide could form on the deposited aluminum. When the chamber is vented, the sample is introduced to ambient laboratory conditions, and the aluminum forms a native oxide. This is referred to as an air oxidation, since the oxidation occurs at the ambient laboratory conditions.

After the aluminum layer is oxidized by opening the evaporator chamber, the angle of the stage is manually switched to the +7º position, denoted by the dashed blue line in Figure 3.11, and the second metal layer is then deposited, forming the metal-oxide-metal diode.

A cross-section of the sample, along the antenna arms and through the PMMA bridge, can be seen in Figure 3.13.

![Figure 3.13: Cross-section of sample after metal deposition. The dotted lines represent the angles at which the depositions occur. The first deposition, with aluminum, is performed at an angle of 7º from normal and is then oxidized. The second metal deposition, with platinum, is performed at an opposing 7º angle.](image-url)
The dashed lines represent the two angles of evaporation and the resulting locations of metal deposition for each angle. The darker metal represents the first deposition while the lighter metal represents the second deposition. The deposition portion of the fabrication is complete; however, the resist and overlying metal layers are still present on the sample.

Once the MOM diode has been formed, electro-static discharge (ESD) precautions are made any time the sample is handled. A grounding wrist strap is worn and is connected through a high impedance cord to ground. Static dissipative gloves are also worn to protect the devices. The sample is removed from the sample holding plate and placed in methylene chloride, which serves as the lift-off solvent. The PMMA and MMA dissolve, yielding the resultant structure on the substrate shown in Figure 3.14. The circled area shows where the metal-oxide-metal diode is formed. The overlap area of the two metal electrodes is roughly 50 × 50 nm.

Figure 3.14: Cross-section of device after lift-off. The PMMA bridge shown in Figure 3.13 causes a break in the aluminum and platinum layers, but the aluminum and platinum layers are electrically connected through the circled MOM diode.
The completed antenna-coupled diodes connected to the titanium-gold electrical leads are shown in the optical micrograph in Figure 3.15.

![Completed antenna-coupled MOM diodes connected to electrical leads. The titanium-gold leads provide electrical connection for I-V and IR characterization.](image)

Figure 3.15: Completed antenna-coupled MOM diodes connected to electrical leads. The titanium-gold leads provide electrical connection for I-V and IR characterization.

A completed antenna diode can be seen in the scanning electron micrograph (SEM) in Figure 3.16. The bonding pads of the device can be seen at the top right and bottom left of the image. The large rectangles ensure proper connection between the bonding pad and the antenna lead. The antenna arms are each 1.55 µm long, yielding an antenna full-length of 3.1 µm. The overlap between the two evaporations, which forms the MOM antenna-coupled diode, can be seen in the inset SEM in Figure 3.16. The double-angle evaporation is evident in this image, as parallel leads can be seen above and below the antenna structure.
Figure 3.16: Electron micrograph of completed ACMOMD. The connection of the EBL defined device to the titanium gold contacts can be seen at the lower left and upper right corners. The DC leads provide the electrical connection to the MOM diode at the center of the dipole antenna. Inset image: MOM diode overlap.

3.3.2.2 Controlled-Oxidation Method

The air-oxidation method provides a simple means for forming MOM-based devices with a single electron beam lithography step. However, the formation of the oxide barrier on the aluminum is not controlled. Changes in ambient conditions can affect the growth and quality of the barrier. With an air oxidation, the user has no control over the thickness of the layer besides the fact that the oxide thickness is self limiting at approximately 25 Å.
Given MOM diodes with the same material composition, a thinner barrier layer would provide a lower resistance. This can be accomplished by utilizing a controlled oxidation, one where the amount of oxygen introduced into the evaporator chamber to oxidize the first deposited metal can be controlled. This provides the ability to tailor the barrier layer depending on the desired thickness. Since temperature and humidity vary in the nanofabrication laboratory, diodes from one run to another can differ simply because of varying aluminum oxidation conditions. Provided that a sufficient cooling time is provided after each metal deposition, the sample temperature can be assumed to be the same from one run to the next. By controlling the temperature of the sample, the base chamber pressure, and the oxygen introduced into the chamber, a level of fabrication repeatability can be established between fabrication runs.

The obstacle with choosing a controlled oxidation procedure lies in the sample manipulation. Since these devices are fabricated with a one-lithography, two-angle metal deposition to create the MOM diode, a means for varying the angle must be provided without opening the chamber. In the case of the air oxidation, it was viable to change the stage angle manually when the chamber was opened to oxidize the sample. However, the chamber cannot be vented in the controlled oxidation case, as control of the alumina oxide layer growth conditions would be lost. Therefore, a stage was constructed which consists of a U-bar, sample holding plate, and a push-type solenoid to change the angle of the sample. This variable-angle sample manipulator is shown in Figure 3.17. The power supply is connected to wires that
connect to the solenoid inside the chamber through the use of an electrical feed-through. The dashed line denotes which equipment is inside and outside of the evaporator chamber.

Figure 3.17: Electronic two-angle stage for fabricating ACMOMDs with the controlled oxidation procedure. The stage is similar to the manual stage shown in Figure 3.11, except a solenoid drives the stage to allow for sample angle manipulation while maintaining vacuum.

The angle positions are determined by the position of set-screws that limit the travel of the sample holding plate. When the power supply is off, the solenoid is relaxed, and the spring pulls up the plate until the set screw limits further travel of the
plate. This sets the first angle of the sample angle manipulator, noted by the blue plate position. This angle is determined by a sensor that functions by changing resistance as a function of angle, which is accurate to within 0.1 degrees. The dashed blue line showing the angle of the sample plate is the same as for the manual sample angle stage which is shown in Figure 3.11. When the power supply is turned on, the solenoid extends, pushing the sample holding plate until the opposite set screw limits further motion. The red dashed line represents a comparable angle to the second position of the manual sample angle stage.

The controlled-oxidation fabrication procedure remains much the same as the air oxidation procedure. The first evaporation, including deposition rate and thickness, and cooling procedure remain unchanged. For the controlled oxidation, oxygen is bled into the chamber to a pressure of 50 mTorr. The total oxygen exposure of the sample is equal to the oxygen pressure in the chamber times the total time. When the desired oxygen exposure is reached, the cryostat isolation valve is opened to pump the oxygen out of the chamber. Before the second metal deposition, the solenoid power supply is turned on to switch the sample angle from the first deposition angle, -7º, to the second deposition angle, +7º. The second metal layer is then deposited the same as for the air-oxidation samples. The lift-off procedure also remains unchanged.
3.3.3 Packaging

Once the fabrication is complete, the ACMOMDs can be characterized. In this project, current-voltage characteristics for the diode are first obtained and then the samples are prepared for infrared testing. Each array of bonding pads is separated into single 44-pin chips. This sample is placed in a 44-pin leadless chip carrier (LCC) and held in place using an adhesive. Aluminum wire bonds then connect each 120 × 120 μm bonding pad to the corresponding pin on the 44-pin LCC. A set of ACMOMDs wirebonded within a 44-pin LCC is shown in Figure 3.18.

Figure 3.18: Set of completed ACMOMDs in a 44-pin LCC. This LCC fits into a socket for the infrared characterization of the device. This arrangement allows up to 20 devices to be measured on each sample.
CHAPTER 4
DETECTOR CHARACTERIZATION

In order to compare the ACMOMDs fabricated in this research to other infrared detector technologies, their response to infrared radiation must be characterized. First, the DC current-voltage characteristics are provided. Then, the layout of the experimental infrared testing arrangement is provided and the purpose of each component is explained. The figures of merit detailed in Section 1.3 will be calculated and compared to various types of infrared detectors available. Measurements that characterize the performance of ACMOMDs will then be presented, which determine polarization dependence, antenna-length dependence, and spatial response. Noise sources will be explained in detail and accompanied with an experimental noise analysis.

4.1 Current-Voltage Characteristics

The current-voltage characteristics of the MOM diodes are obtained using a Micromanipulator Co. 8065 probe station and a Keithley 236 Source Measure Unit. The nonlinear current-voltage characteristic of the MOM diode depends on metals used, oxide type, and oxide thickness, as described in Chapter 2. First, the I-V
characteristics will be shown for symmetric and asymmetric diodes fabricated with an air oxidation step. Asymmetrical diodes have also been explored with controlled oxidations to vary oxide thicknesses, and the I-V characteristics are shown.

Three entities have been examined and compared for each diode type: zero-bias diode resistance, zero-bias curvature, and peak curvature. From the measured device characteristics, the low-pressure oxygen alumina growth characteristics have been inferred, and the relationship between oxygen exposure, and hence oxide thickness, and diode resistance, zero-bias curvature, and peak curvature has been determined.

Zero-bias resistance is 1/(dI/dV) at zero-bias. Curvature, is found by dividing the second derivative of the current by the first derivative [85]:

\[
\gamma = \frac{\partial^2 I}{\partial V^2} \times \frac{\partial I}{\partial V}.
\]

Zero-bias curvature is the value of the curvature coefficient at zero-bias. Peak curvature is the value at which the maximum curvature of the diode is reached across the entire biasing voltage range.

Various metals have been utilized to create asymmetrical metal-oxide-metal diodes. The first metal for the diodes must always be one that readily forms a thin oxide in the presence of oxygen, whether at atmospheric partial pressure or lower pressures. The difference in work functions of the metals creates a built-in electric field in the oxide between the electrodes, since the Fermi levels of the materials align.
to reach an equilibrium state. Table 4.1 outlines work functions of metals used in the fabrication of the MOM diodes, as well as other metals of interest [44].

**TABLE 4.1**

**METAL WORK FUNCTIONS OF COMMONLY EVAPORATED MATERIALS USED IN MICROELECTRONICS FABRICATION**

<table>
<thead>
<tr>
<th>Metal</th>
<th>Work Function $\phi_b$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>4.28</td>
</tr>
<tr>
<td>Ti</td>
<td>4.33</td>
</tr>
<tr>
<td>W</td>
<td>4.50</td>
</tr>
<tr>
<td>Cr</td>
<td>4.50</td>
</tr>
<tr>
<td>Cu</td>
<td>4.65</td>
</tr>
<tr>
<td>Au</td>
<td>5.10</td>
</tr>
<tr>
<td>Ni</td>
<td>5.15</td>
</tr>
<tr>
<td>Pt</td>
<td>5.65</td>
</tr>
</tbody>
</table>

The metal combination of choice for the controlled-oxidation MOM fabrication was aluminum and platinum. The aluminum serves as the base metal, AlO$_x$ as the tunnel barrier, and platinum as the top metal. The energy band diagram for this structure is similar to Figure 2.2, where Metal 1 is the platinum electrode, with $\phi_{b1}$=5.65 eV, and Metal 2 is the aluminum electrode, with $\phi_{b2}$=4.28 eV. The reason for this choice of metals is because of the large separation of the work functions and more nonlinearity can be obtained in the I-V characteristic. This is the largest separation of work functions of materials that are commonly used for microelectronics fabrication.
Other combinations of materials in Table 4.1 were fabricated, such as Al/AlOₓ/Ti, Al/AlOₓ/Ni, and Ni/NiO/Pt. The aluminum-based devices were found to be the most repeatable, with yields of greater than 90%, but Al/AlOₓ/Ti and Al/AlOₓ/Ni devices were not pursued since their curvatures were not as large as Al/AlOₓ/Pt devices. While Ni readily forms a native oxide in the presence of oxygen, the growth is much less repeatable than that for aluminum oxide growth. Therefore, Ni/NiO/Pt devices were not pursued because the devices were inconsistent and the yield was poor. Tungsten also grows a native oxide in the presence of oxygen, but it was found that the integrity of the resist profile was compromised when utilizing tungsten as the first metal layer. This may be due to either the difference in coefficients of thermal expansion between the tungsten and resist or the high melting point of tungsten, which deforms the resist upon deposition. As a result of this deformation of the resist, a shadow evaporation process could not be utilized to make tungsten-based devices.

4.1.1 Air-Oxidation

Figure 4.1, upper left, shows an I-V characteristic for an Al/AlOₓ/Al symmetric ACMOMD, whose fabrication was discussed in Section 3.2.3.1. The acquired data points are plotted along with a fifth-order polynomial fit. The resistance, upper right, is calculated by taking the inverse of the first derivative of the current. The second derivative of the current represents the diode nonlinearity, lower
left, that is useful for detection. The curvature of a diode, lower right, is obtained by dividing the second derivative of the current by the first derivative of the current.

Figure 4.1: I-V characteristic (upper left), resistance (upper right), diode nonlinearity (lower left), and curvature (lower right) for an air oxidation Al/AlO\textsubscript{x}/Al ACMOMD. This I-V characteristic is fairly symmetric about zero bias since both metals in the MOM diode are aluminum.

The I-V characteristic of this Al/AlO\textsubscript{x}/Al diode is fairly symmetrical about zero-bias, as the metal electrodes are the same. The small asymmetry is due to charges trapped in the oxide near the metal-oxide or oxide-metal interfaces as
discussed in Section 2.2. In addition, different oxygen content in the electrodes can lead to asymmetries in the I-V characteristic [86]. The zero-bias diode resistance is 13.2 MΩ, the zero-bias curvature is 0.13 V⁻¹, and the peak curvature coefficient is 1.7 V⁻¹ at a biasing point of -1 V.

A current-voltage characteristic of an Al/AlOₓ/Pt MOM diode fabricated using an air oxidation is shown in Figure 4.2.

Figure 4.2: I-V characteristic (upper left), resistance (upper right), diode nonlinearity (lower left), and curvature (lower right) for an air oxidation Al/AlOₓ/Pt ACMOMD. The asymmetry about zero-bias is due to the fact that the comprising metals of the MOM diode are aluminum and platinum, which have different work functions.
This structure’s energy band diagram, under equilibrium and with an applied bias, is shown in Figures 2.3 and 2.4, respectively.

The I-V characteristic of this ACMOMD is not symmetric about zero-bias, as the metal electrodes are dissimilar. The zero-bias diode resistance is 312 MΩ, the zero-bias curvature is 1.4 V⁻¹, and the peak curvature coefficient is 4.9 V⁻¹ at a bias of 0.50V. While the curvature of this air-oxidation device is promising, for high-performance detectors it is desirable to reduce the resistance while maintaining high curvature. S. Yngvesson derived that the current sensitivity $S_I$ of an antenna-coupled diode [55], based on the equivalent circuit shown in Figure 2.11, is:

$$S_I = \frac{\alpha}{2\left(1 + \frac{r}{R_D}\right)^2 \left(1 + \frac{\omega^2 C_D r R_D^2}{r + R_D}\right)}$$

where $\alpha$ is the inverse of the thermal energy. It is clear that the current sensitivity decreases as $R_D$ increases and as such, it is desirable to reduce $R_D$.

Reducing diode resistance can be achieved by varying the parameters of the fabrication process, as discussed below. As mentioned in Section 4.1, numerous material combinations were pursued in fabricating ACMOMDs. The zero-bias curvature will be used to determine the best diode materials to use for reduced resistance devices. Table 4.2 shows those metal combinations which were found to be repeatable, which were the aluminum-based devices, and their average zero-bias curvature. In each case, 20 ACMOMDs fabricated with an air oxidation were used to calculate the values in Table 4.2.
Since Al/AlOₓ/Pt devices have the highest zero-bias curvature for air oxidation devices, they were chosen to be pursued for controlled-oxidation reduced resistance devices. Table 4.2 follows the assertion that be using metals with larger work function separations, listed in Table 4.1, would create more asymmetry in the I-V characteristic and hence a greater zero-bias curvature.

### 4.1.2 Controlled Oxidation

The I-V characteristic of a typical Al/AlOₓ/Pt controlled-oxidation MOM diode, discussed in Section 3.3.3.2, is shown in Figure 4.3. The oxygen exposure used for this oxidation was 1200 s at 50 mTorr, yielding a 60 torr-sec exposure. The zero-bias resistance has been reduced to 220 kΩ and the zero-bias curvature and peak curvature have decreased to 0.62 V⁻¹ and 0.82V⁻¹, respectively.

<table>
<thead>
<tr>
<th>ACMOMD Composition</th>
<th>Curvature Coefficient (V⁻¹)</th>
<th>Standard Deviation (V⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al/AlOₓ/Al</td>
<td>0.00</td>
<td>0.02</td>
</tr>
<tr>
<td>Al/AlOₓ/Ti</td>
<td>0.08</td>
<td>0.03</td>
</tr>
<tr>
<td>Al/AlOₓ/Ni</td>
<td>0.45</td>
<td>0.15</td>
</tr>
<tr>
<td>Al/AlOₓ/Pt</td>
<td>0.74</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Since Al/AlOₓ/Pt devices have the highest zero-bias curvature for air oxidation devices, they were chosen to be pursued for controlled-oxidation reduced resistance devices. Table 4.2 follows the assertion that be using metals with larger work function separations, listed in Table 4.1, would create more asymmetry in the I-V characteristic and hence a greater zero-bias curvature.

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Figure 4.3: I-V characteristic (upper left), resistance (upper right), diode nonlinearity (lower left), and curvature (lower right) for an Al/AlOx/Pt ACMOMD fabricated with a controlled oxidation. There is still some asymmetry in the I-V characteristic about zero-bias, but it is less than that of the air oxidation ACMOMD.

As can be seen, the controlled oxidation diodes have much lower resistance, but also lower zero-bias and peak curvature. The relationship between oxygen exposure and these three diode parameters has been studied with devices fabricated with various oxygen exposures. In each case, the partial O₂ pressure was 50 mTorr and the time was varied to reach different oxygen exposures. The results of this study are shown in Figure 4.4.
Figure 4.4: Diode resistance and curvature coefficient as a function of oxygen exposure time. In each case, the oxygen pressure was held at 50 mTorr and the time was varied to reach the different oxygen exposures. The thickness of the barrier increases for increasing oxygen exposures. The resistance increases exponentially and curvature increases linearly with increasing oxygen exposure.

The diode resistance, represented by the dashed red line, has an exponential dependence upon the oxygen exposure time. On the other hand, peak curvature and zero-bias curvature, represented by the blue and green dashed lines, respectively, have a linear dependence on the oxygen exposure time. By reducing the oxygen exposure and hence the thickness of the alumina layer, the resistance can be decreased exponentially while curvature reduces in a linear fashion. The results shown in Fig. 4.4 were found to be repeatable, offered a yield of approximately 90%,
and provided a high level of precision between devices and fabrication runs, due to the in-situ control of oxygen pressure.

4.2 Infrared Response Characteristics

The experimental testing arrangement which was built to provide for the infrared spectroscopic measurements of the antenna-coupled metal-oxide-metal diodes fabricated in this research consists of six main parts: a CO$_2$ laser, a beam splitter and attenuator, a mechanical chopper, a power meter, a micrometer stage, and electrical signal sensing equipment. A block diagram of the testing arrangement is shown in Figure 4.5. Each part of the system will be explained in detail.

Figure 4.5: Layout of experimental infrared testing arrangement. This setup provides for the infrared testing of ACMOMDs. By illuminating the devices with 10.6 μm radiation from a CO$_2$ laser and monitoring their response, the detection characteristics can be measured and compared to other detector technologies.
The CO₂ laser model is a Synrad 48-2 Series laser with a rated output power of 25 W but capable of producing a stable output beam between 3 and 30 W. The beam diameter specification is 3.5 mm, with 4 mrad divergence, and the polarization is linear in the vertical direction. The laser can be operated in both pulsed and continuous wave modes, depending upon the input signal. For the pulsed-operation mode, a pulse-width modulation input signal at 5 kHz, 10 kHz, or 20 kHz is generated by the laser controller to set the output power.

At the output of the laser, the beam travels into a closed-loop power control kit and is passed through a ZnSe disc beam splitter oriented at 45° with respect to the beam path, where 92% of the beam is transmitted and 8% is reflected to a diffuser and thermopile detector. ZnSe is a material which has very little absorption in the thermal infrared region and hence is ideal for optical components such as beam splitters and lenses [87]. The thermopile detector signal is continuously monitored by the laser controller, where the pulse widths are modulated to provide for constant average power of the laser within ± 2%. The output wavelength of the beam can shift between 10.2 μm and 10.8 μm. While the specific lasing mode is not controlled, the power output does not change dramatically as the laser hops between modes. However, by monitoring the power, it is possible to determine when a mode hop occurs.

Since the wavelength of the CO₂ laser is not visible to humans, a 5 mW red diode laser diode, with wavelength 650 nm, is aligned to the output of the laser, at the output of the closed loop kit, so that the beam position can be tracked. It is important
to be able to track this position since CO₂ lasers can be used as cutting devices in industrial applications; therefore, precautions must be made to protect the users of this system. The laser diode is aligned to the CO₂ beam via a ZnSe disc, oriented at 45°. Near-field and far-field adjustments can be made on the apparatus, which control the beam position and the angle of the ZnSe disc, both in two axes. By adjusting both the near- and far-field beam positions, the visible diode pointer can be aligned with the CO₂ beam along its entire path, creating a safer environment for users and making it possible to position the beam on the devices very accurately. In addition, users wear safety glasses which have an optical density of greater than 5 for 10.6 μm wavelength radiation.

The output power of the CO₂ laser is very high, so the beam then travels to a ZnSe wedge, where 99.4% is transmitted through the wedge where it is incident upon a firebrick beamstop. This serves as a heatsink, as well as controlled stray reflections of the CO₂ beam. 0.6% of the original beam is reflected towards the device under test, where the power can be further reduced by CaF₂ neutral density (ND) filters. Up to four ND filters can be used: three of which are 3mm thick and provide 30% transmission at 10.6 μm, and another which is 1mm thick, providing 65% transmission. This arrangement allows the peak power incident upon the devices to be controlled from approximately 100 mW down to 80 μW.

The attenuated beam then travels through a mechanical chopper, which provides for square-wave modulation of the infrared radiation. The chopping
frequency can be controlled from 4 Hz to 3.7 kHz. A reference signal provides the chopping frequency to the lock-in amplifier.

After the chopper, the beam again passes through a ZnSe beamsplitter, where half of the beam power is reflected to an Ophir 30-A broadband laser power detector and Ophir Laserstar meter. The transmitted beam falls incident upon the device under test. The power meter provides for real-time monitoring of the laser power, allowing for more robust results. The device under test is positioned using a 5-axis micrometer stage. Adjustments can be made in the x, y, and z directions to within 0.001”, while the rotational axes provide for ~0.5° precision. With the diode laser pointer on, the beam can be precisely aligned to the device under test. After the device is positioned at the center of the beam, the visible beam is turned off so that it will not interfere with the infrared measurements. The x, y, and z micrometers on the stage allow for the precise positioning of the device under test with relation to the beam. The rotational axes $\phi$ and $\theta$ are used for polarization dependence and angle of incidence measurements, respectively. A photograph of the experimental infrared testing setup is shown in Figure 4.6. The edges of the beam-stop bricks are wrapped in red duct tape to avoid scratching the surface of the optical bench. These bricks are anchored to the optical bench to prevent them from being moved, which could allow a stray CO$_2$ beam to leave the table area.
Figure 4.6: Photograph of experimental infrared testing arrangement. All components of the setup, with the exception of the control and measurement circuitry, are anchored to the optical table so that the beam will not leave the table area.

The devices fabricated in this research are connected to titanium-gold leads. The substrate is affixed within a 44-pin LCC. Aluminum wirebonds form the electrical connection between the leads on the substrate and the LCC. The LCC is then placed into a chip socket, which is soldered onto a printed circuit (PC) board. The PC board connects the corresponding pins from each device to a female SMA connector. An SMA connector is a RF coaxial connector which features a smaller size compared to that of BNC connectors. A photograph of the PC board and the SMA connectors that provide an electrical connection for 20 devices is shown in Figure 4.7.
Figure 4.7: PC board with SMA connectors, 44-pin LCC, and ACMOMDs. The wirebonded LCC is inserted in the chip socket, which is connected via PC board traces to SMA connectors. An SMA to BNC cable connects the devices to the current preamplifier and lock-in amplifier to measure the device output.

The device numbers and corresponding pin connections are silk-screened on the PC board to allow for easy recognition of the DUT. In this case, device 7 (D7) is currently connected; D7 is the device between pins number 15 and 16 of the bonding pad array and LCC.

The PC board is connected to a machined aluminum bracket with 4 ¼-20 screws. This bracket is connected to the rotational stage, which provides for rotational movement in the $\phi$ direction. Another bracket was machined from aluminum to attach this rotational stage to another rotational stage, providing for $\theta$-
direction rotation. Lastly, this entire arrangement is attached to the x-y-z micrometer stage.

The device is connected to a Stanford Research Systems 570 current preamplifier by an RG-188 cable. This cable has an SMA connector on one end and a BNC connector on the other end to connect to the PC board and preamplifier, respectively. The preamplifier amplifies the tunneling current rectified by the MOM diode. The output signal is passed to a Stanford Research Systems 830 DSP Lock-In Amplifier, which is synchronized with the positive edge of the square-wave reference signal of the mechanical chopper and reads out the detector signal in volts. By dividing the displayed output voltage of the lock-in by the sensitivity of the preamplifier (V/A), the rms current at the detector can be calculated. The lock-in amplifier is connected to a PC via a standard GPIB interface. With this connection and Data Acquisition and Analysis Software (DAAS), written by Dr. Greg Bazan (1994), the data can be continuously monitored and recorded.

The beam of the CO$_2$ laser was characterized to determine the transverse extension of the beam, the beam shape, and the intensity profile using a knife-edge scan across the beam. The knife-edge, in this case a razor blade, was attached to the micrometer stage and precisely positioned at DUT plane to obtain the shape of the beam exactly at the point where infrared testing of the ACMOMDs is performed. The laser power meter was placed behind the razor-blade. Initially, the razor blade completely blocked the beam. The razor blade was scanned in 0.01” (2.54 mm) increments to ‘uncover’ the beam and the beam power was measured until the beam
was no longer blocked. This same test was performed in both the x- and y-directions. Figure 4.8 shows the normalized beam intensity for scans in the x- and y-direction. At zero intensity, the beam is completely blocked by the razor blade, and at full intensity the beam is completely unblocked. The data points represent the measured data and the line represents a ninth-order polynomial fit.

Figure 4.8: Normalized beam intensity as a function of beam scan position. At a relative beam position of -3 mm, the razor blade completely blocked the laser beam (beam intensity of 0). The razor blade was then scanned across the beam in 0.01” (0.254 mm) increments and the power measured. At a relative beam scan position of +3 mm, the beam is completely unblocked and the beam intensity is 1.
The derivative of this polynomial-fit was calculated, which determines the beam intensity as a function of position. This is shown in Figure 4.9, again for both the x- and y-direction, along with a comparison to an ideal Gaussian beam. There is agreement between the beam profile and the ideal Gaussian beam. The deviation is due to errors in the polynomial fits of the original beam scan, and occur near the edge of the beam.

Figure 4.9: CO₂ laser beam intensity profile. The derivative of the polynomial fits of the x- and y-direction beam scans are plotted along with the expected Gaussian distribution. The 1/e² beam radius is approximately 1.8 mm in each direction.
The $1/e^2$ beam radius, which is approximately 13.5% of the peak beam intensity, is approximately 1.8 mm in both the x- and y- directions. This is denoted by the arrows from the relative zero beam position to the beam intensity along the $1/e^2$ level, and can be used to calculate the irradiance on the ACMOMDs. The $1/e^2$ beam radii were calculated using the Gaussian fitting of the derivative of the beam scans. It is believed that deviations of the fitted data from the expected Gaussian distribution below the full-width half-max level are due to the fitting errors of the beam-scan shown in Figure 4.8.

To give a reference of the size of the beam in comparison to the bonding pads and ACMOMDs, the beam intensity is shown in Figure 4.10 along with an image of the bonding pads. From end to end, the ACMOMDs spread across a 300 $\mu$m distance, as shown in Figure 3.13. This is very small in comparison to the beam of the CO$_2$ laser. The dotted-line circle in Figure 4.6 shows the area on the bonding pads where the ACMOMD array is located. Over this area, the beam intensity ranges from 98% at the edges to the peak intensity, or 100%, in the middle. It is most accurate to align the laser to the center of the bonding pads, and therefore it is possible to test all devices within a single array without moving the position of the devices in relation to the laser. In addition, this arrangement allows for rotation without constantly repositioning the devices.
Figure 4.10: Beam shape and intensity compared to bonding pad and device array. The ACMOMD array is approximately 300 μm from end to end. When the beam is centered on the bonding pad, intensity ranges from 98% to 100% across the ACMOMD array, which aids in the testing of multiple devices.
Figure 4.11 represents an electromagnetic wave incident on an ACMOMD. For this research, this incidence is linearly polarized 10.6 μm radiation from a CO2 laser. The polarization angle of the incident radiation is represented by $\phi$, where $\phi$ rotates in a plane parallel to the surface of the wafer.

Figure 4.11: Electromagnetic wave incident upon antenna. When the electric field of the incident wave is parallel to the antenna ($\phi=0^\circ$), it is referred to as p-polarization. S-polarization is when the electric field of the incident wave is perpendicular to the antenna ($\phi=90^\circ$). Angle of incidence is represented by $\theta$. 
The polarization of the incident radiation with the electric field parallel to the antenna axis ($\phi=0^\circ$) is commonly referred to as p-polarization, while irradiation with the electric field perpendicular to the antenna axis ($\phi=90^\circ$) is referred to as s-polarization. The angle of incidence is represented by $\theta$.

4.2.1 IR Detector Characterization

There are many types of measurements that can be carried out to characterize the performance of the antenna-coupled MOM diode detectors fabricated for this research, which will be discussed in detail. Noise sources will be described and presented with an experimental analysis. The figures of merit that will allow for comparison to other IR detector technologies will be presented. Polarization dependence, antenna-length dependence, and angle of incidence dependence will also be presented.

The current response of an Al/AlO$_x$/Pt ACMOMD with respect to the infrared input power has been measured and is shown in Fig. 4.12. As the incident power of the laser is increased, the device current increases linearly. Hence, the detector functions as a square law detector; the response is proportional to the power of the incident radiation. This detector signal is measured with the polarization of the incident infrared radiation parallel to the antenna, referred to as p-polarization.
Figure 4.12: Al/AlOx/Pt ACMOMD device signal as a function of infrared input irradiance. Device current increases linearly with input power and hence the device functions as a square-law detector.

4.2.1.1 CO2 Laser Mode Hopping

There are four emission branches for most CO2 lasers – 9R, 9P, 10R, and 10P – which cover a wavelength range from 9.16 – 10.86 μm. There are 20 vibrational-rotational emission lines in each of the branches, each with a unique and specific wavelength. Depending on the laser, all, some, or none of the lines can be utilized. The CO2 laser used for this testing, the Synrad 48-2 Series 25 W, mainly functions in the 10P band (10.46 – 10.86 μm), but can emit radiation in the 10R band (10.11 – 10.37 μm) also. The user, however, has no control over the branch or line at which
the laser is emitting radiation. Further, the user has no control over the time period the laser will emit radiation on a specific line or which line it may shift to.

When testing a device, these line shifts can cause vast differences in the detected signal. Due to reflections within the substrate at the Si/SiO₂ interface – where the device is located – this can cause constructive or destructive interference between the reflected beam and the beam incident on the surface. Figure 4.13 shows the response of an Al/AlOₓ/Pt ACMOMD over time compared to the incident power on the device.

![Figure 4.13: Response of an Al/AlOₓ/Pt ACMOMD over time with reference to the incident power on the device.](image)

In this case, the response of the device changes when the incident power, and hence emission line, of the laser changes.
The output power of the laser can serve as an indicator of when a mode-hop occurs. However, not all mode-hops cause a change in output power of the laser.

The change in the magnitude of the response of an ACMOMD does not always change in the same direction of the laser power change when a mode hop occurs. Figure 4.13 shows a change which occurs in the same direction, i.e. when the laser power increases, so does the device response, but this is not always the case.

If the emission line of the CO₂ laser can be controlled, the response of devices as a function of the emission line, and therefore wavelength, can be determined. C. Fumeaux et al. have measured the device response of a Ni/NiO/Ni dipole antenna-coupled metal-oxide-metal diode as a function of the free-space incident wavelength (10P branch line) for a fixed angle of incidence [69], as shown in Figure 5.1. The length of the antenna was 3.1 μm and the substrate was a double-side polished 385 μm Si wafer with 1.5 μm SiO₂ layers on each side. It is clear that a shift from one emission line to an adjacent line causes a large detected signal variation. This is due to reflections within the SiO₂ that cause constructive or destructive interference between the reflected beam and the beam incident on the surface, similar to the case in Figure 4.13.
Figure 4.14: Oscillation of the detected signal of a Ni/NiO/Ni ACMOMD as a function of the free-space wavelength of laser emission from C. Fumex et al. The response of each line between from the 10P(10) line to the 10P(32) line show that an oscillating device response behavior forms.

It would be desirable to have a laser which could be tuned to a specific vibrational-rotation line and held at that emission wavelength for a long period of time.

The Synrad 48-2 Series 25 W laser used for the research does not have this capability. The user has control over the power, as pointed out in Section 4.2, but the laser hops from line-to-line with no fixed pattern. Often times, the laser will periodically hop between approximately 3-6 modes over a period of about 5 minutes. This, however, changes depending on how long the laser has been operating. Ideally,
each device would be tested under identical conditions. However, this isn’t possible, so the user must rely on the periodicity of the laser so that each device measurement can be performed with the same emission line. The results which have been gathered will be presented in the proceeding sections.

4.2.1.2 Figures of Merit

The responsivity, SNR, NEP, and normalized detectivity of antenna-coupled MOM diode detectors can be determined by measuring the response of the detector to infrared radiation normal to the sample. With the polarization of the electric field of the incident radiation parallel to the antenna axis, as shown in Figure 4.11, the detector response is the highest. These figures of merit can be calculated according to the equations described earlier in section 1.3.

To determine these figures of merit, an effective area for the ACMOMD detectors must be established. C. Fumeaux et al. were able to determine the spatial response of a 3.1 μm dipole antenna-coupled MOM detector by deconvolution of the beam profile of the incident 10.6 μm CO2 laser radiation [88]. The antenna collecting area is represented as an ellipse. For a 3.1 μm dipole antenna, the full-width antenna response along the arms is approximately 12 μm, which indicated the existence of a fringe field that extends approximately one dielectric wavelength beyond the physical ends of the dipole arms [88]. The axial ratio of the ellipse is \( \frac{y_{ant}}{x_{ant}} = 0.54 \), which agrees with the theoretical estimates presented by G. Boreman et al. [89]. This ellipse, of approximate dimensions 12 × 6.5 μm, corresponds to an effective area
equal to 61 $\mu$m$^2$. Since the geometry and substrate of the devices fabricated in this research are the same as those presented by G. Boreman, this effective area will be assumed for the ACMOMDs presented in this work.

Several figures of merit based on the measured characteristics have been calculated for these ACMOMDs. For a beam power of 62 mW, which corresponds to an input infrared irradiance of 498 mW/cm$^2$, a detected current signal-to-noise ratio of 48.5 dB has been obtained for a measurement bandwidth of 10 Hz for Al/AlO$_x$/Pt devices fabricated with high oxygen exposure doses. Ambient light was found not to affect device response. The SNR was determined by using a Stanford Research Systems SR785 2-Channel Dynamic Signal Analyzer. This spectrum analyzer computes a Fourier transform, which was performed with a uniform window. The bandwidth and number of bins (100, 200, 400, or 800) determine the line width or bin width. A SNR can be calculated by integrating the noise and signal levels.

There are various sources of noise that contribute to the measured noise, due to the preamplifier and ACMOMD. The preamplifier noise is due to the Johnson noise of the feedback resistor in addition to the internal electronic noise of the amplifier, $V_{NA}$. The noise of the ACMOMD has been determined to be mostly Johnson noise. These three sources of noise can be represented by the expression [90]:

$$V = \sqrt{4kTR_I \left( \frac{R_F}{R_I} \right)^2 B + 4kTR_FB + V_{NA}^2 \left( 1 + \frac{R_F}{R_I} \right)^2 B}$$
where $R_i$ is the ACMOMD resistance, $R_F$ is the feedback resistance, and $B$ is the bandwidth in Hz. The first term is the Johnson noise of the input resistance, which takes into account the gain of the amplifier, the second term represents the Johnson noise of the feedback resistor, and the third term represents the noise of the operational amplifier. These terms correspond to the amplifier circuit shown in Figure 4.15.

![Preamplifier circuit used to measure the signal and noise characteristics of ACMOMDs. The gain is determined by the ratio of resistances $R_F$ to $R_i$. These resistances contribute Johnson noise and the amplifier, which is an AD743 operational amplifier, also contributes a noise figure.](image)

The output of the preamplifier $V_o$ is passed to a second gain stage, which amplifies the signal by a factor of 50. This signal is then passed to the SR830 lock-in amplifier. The buffered Monitor Out output is connected to the SR 785 spectrum analyzer input. The gain of this output is controlled by the input sensitivity of the lock-in: for input sensitivities of 2 mV, 20 mV, and 200 mV, the input gains are 2200,
Using metal film resistors with values of $R_I$=1 kΩ, $R_F$=100 kΩ, and using the 200 mV input sensitivity on the lock-in amplifier, the noise components were measured at a frequency of 1 kHz. The total noise value was measured to be approximately 470 nV/Hz$^{1/2}$. The contribution from the Johnson noise in the feedback resistor noise is known to be $4kT\Delta f R$, which is 40.7 nV/Hz$^{1/2}$. The Johnson noise contribution from the 1 kΩ resistor measured at the output is 407 nV/Hz$^{1/2}$. These noise sources sum in quadrature, and since the total noise and Johnson noise contributions are known, the value of the operational amplifier noise can be solved, which gives 2.45 nV/Hz$^{1/2}$. The operational amplifier noise, according to the Analog Devices AD743 Data Sheet, is approximately 2.5 nV/Hz$^{1/2}$. Therefore, the expected value for the total noise is very close to the measured value. For large ACMOMD resistances, that is on the order of tens of kΩ to MΩs, the preamplifier noise is the dominant noise source. However, when ACMOMD resistances are on the order of approximately 1 kΩ, the measured noise value will increase.

A plot of the frequency response of an Al/AlO$_x$/Pt device signal, device noise, and preamplifier noise is shown in Figure 4.16. For this plot, the line width is 0.125 Hz. The signal, when 10.6 μm is incident on an ACMOMD, is shown as the blue solid line. The signal when the radiation is blocked is shown by the red dotted line, and the amplifier noise is shown by the green dashed line.
Figure 4.16: Frequency spectrum of an Al/AlOx/Pt ACMOMD device signal with illumination (signal), without illumination (noise), and the noise portion due to the preamplifier. The device signal shows the response at the chopping frequency, which was approximately 1033 Hz in this case. Due to the frequency drift of the chopper, the response does not appear as a delta function.

Since the sensitivity of the current preamplifier is large, the noise generated by the lock-in amplifier and spectrum analyzer can be neglected. The measured noise leads to an estimated noise equivalent power (NEP) of $1.15 \text{ nW/Hz}^{1/2}$. This was calculated using the effective area of the antenna, a $6.5 \mu m \times 12 \mu m$ ellipse. Therefore, the normalized detectivity ($D^*$) for shadow evaporation ACMOMDs has been calculated as $2.15 \times 10^6 \text{ cm-Hz}^{1/2} \cdot \text{W}^{-1}$. This exceeds the performance of any previously-reported MOM-based infrared detector [36].
4.2.2 Polarization Dependence

The polarization dependence of a detector can lend insight into its operation mechanisms. For an antenna-coupled MOM diode, the response should be strongest for p-polarization, i.e. where the electric field of the incident radiation is parallel to the antenna axis ($\phi=0^\circ$). For this polarization, the incident radiation induces waves which resonate in the antenna and are rectified by the MOM diode. A smaller response for s-polarization, i.e. where the incident electric field is perpendicular to the antenna axis ($\phi=90^\circ$), is referred to as the polarization-independent contribution. For this orientation, the incident radiation does not induce any resonant current in the antenna. However, there still may be a small current present of thermal origin.

For the devices fabricated in this research, the polarization-independent signal is present regardless of the polarization of the incident radiation. The polarization-dependent response is represented by the signal response for p-polarization less that of the response for s-polarization. The response of these devices can be represented by the sum of a constant, thermally-generated polarization-independent response, plus a cosine-squared polarization-dependent signal. The detected signal current $I(\phi)$ can be expressed as:

$$I(\phi) = I_{ip} + I_p(\phi) = I_{ip} + I_p \cos^2(\phi_0 - \phi)$$

where $I_{ip}$ is the polarization-independent contribution, $I_p$ is the polarization-dependent contribution, $\phi_0$ is the location of the maximum polarization response, and $\phi$ is the angle between the antenna axis and the polarization direction [69].

Figure 4.17 shows the polarization response of Al/AlO$_x$/Pt ACMOMD.
Figure 4.17: Polarization response of an Al/AlOx/Pt ACMOMD. The electric field of the incident radiation is parallel to the antenna at 90° and 270°, where the maximum response was measured. The polarization ratio for this device, which is the maximum response divided by the minimum response, is about 10.

As expected, the maximum signal was obtained when the electric field of the incident infrared radiation was parallel to the antenna (90°, 270°), while the minimum was measured with the electric field perpendicular to the antenna (0°, 180°). The data points represent the average response for each polarization angle, while the error bars represent the standard deviation of a time-averaged response for each polarization angle. The cross-polarization response is due to thermionic emission because of heating of the structure. Electrons with higher energies due to heating can gain
enough energy to surmount or tunnel through the oxide barrier, as discussed in Section 2.3.

In agreement with antenna theory, the device response follows a cosine-squared dependence, denoted by the dotted line. The polarization ratio, which is the ratio between the maximum and minimum signal, is around 10. The variations in detector response are due in part to mode hopping in the CO₂ laser used for testing. In addition, small fluctuations in the angle of incidence, which is desired to be normal for polarization dependence measurements, can impact the measured signal. These errors can be caused if the sample is not affixed parallel to the LCC, the LCC is not seated properly in the chip socket, the chip socket is not mounted parallel to the PC board, or if the PC board is not parallel to the rotational stage. Every effort was made to minimize these errors by ensuring the beam was incident normal to the sample, but small fluctuations can cause the experimental errors shown in the

4.2.3 Antenna Length Dependence

The response of an antenna-coupled detector depends on the antenna geometry and the frequency of the incident electromagnetic irradiation. The peak current at the center of a half-wavelength dipole occurs when the antenna length is equal to half the wavelength of the desired detection wavelength. For an antenna on a substrate, the length of the dipole corresponds to the equivalent substrate wavelength of the incident radiation. For dipole antennas fabricated on a silicon substrate with 1.5 µm silicon dioxide matching layers irradiated by 10.6 µm laser radiation, the
optimum dipole length has been found to be 3.1 μm [41]. For antennas of 3.1 μm length, the maximum signal response is for p-polarized 10.6 μm illumination and the minimum signal is found for s-polarized illumination. The ratio of the maximum signal to the minimum signal is the polarization ratio. Depending on the antenna length, incident 10.6 μm radiation will cause varying degrees of resonance. Along those lines, the polarization dependent portion of the response will vary depending on length.

Figure 4.18 shows the polarization ratio, which is the ratio of the maximum signal measured to the minimum level measured, as a function of antenna length for Al/AlOx/Pt shadow-evaporation ACMOMDs. This is commonly shown as the relationship between the polarization-dependent response and antenna length, but polarization ratio is shown in an effort to normalize response from numerous detectors of the same length and minimize the impacts of mode-hopping of the CO2 laser. A zero polarization-dependent response corresponds to a polarization ratio of one in this case, and therefore the theoretical sin⁴(πL/2λ) dependence on antenna length still holds and is shown by the dotted line in the figure.
Figure 4.18: Polarization ratio as a function of antenna length for Al/AlOx/Pt ACMOMDs. A polarization ratio of 1 means there is no polarization dependent signal. The data points represent the average of no less than eight devices for each antenna length and the error bars represent the standard deviation of the response.

The first maximum, or resonance, occurs at the expected optimum antenna length, but there is some deviation from the expected result. For shorter antenna lengths, the electrical leads can have an effect on the detected polarization-dependent signal. This impact is assumed to be somewhat small, due to the fact that lead currents would be attenuated due to the Coleman effect since the leads are long, and the fact that the large lead widths used allow transverse currents, as discussed in Sections 2.5 and 2.1, respectively. For the first minimum, the second maximum, second minimum, and third maximum, the measurements closely match the theory.
However, beyond the third maximum, the attenuation of the antenna current is dominated by the Coleman effect. By fitting the data to a theoretical $\sin^4\left(\frac{\pi L}{2\lambda}\right) e^{-\frac{\Gamma_{\text{exp}} L}{2}}$ dependence [68], the calculated experimental attenuation constant $\Gamma_{\text{exp}} = 0.40 \ \mu m^{-1}$. This takes into account all forms of attenuation such as Coleman effect and surface attenuation. The theoretical attenuation due to Coleman effect $\Gamma_C = 1.48 \ \mu m^{-1}$ and the theoretical surface attenuation constant is $\Gamma_{sr} = 22.7 \ \mu m^{-1}$. Since the experimental attenuation constant is much smaller than the surface attenuation constant, it can be concluded that this imparts a negligible attenuation and that the experimental antenna current attenuation is due to the Coleman effect. This has also been confirmed by I. Wilke and C. Fumeaux [29, 68].
CHAPTER 5
CONCLUSION

Dipole antenna-coupled metal-oxide-metal diode detectors have been fabricated to detect electromagnetic radiation in the thermal or long-wave infrared band. Although there are several types of detectors currently commercially available, none provide for each and every project constraint detailed in Section 1.1. These include the ability to: function without cooling at room temperature, provide frequency selective and fast response in a compact $10 \times 10 \, \mu m$ detector area, and offer CMOS compatible fabrication. Although this type of detector has been previously researched, this project is the first to apply a one-step lithography, shadow-evaporation technique to fabricate ACMOMDs.

5.1 Comparison with Currently Available IR Detectors

The infrared response of the detectors fabricated for this research has been characterized; the results were presented in Chapter 4. The devices perform as expected in terms of polarization-dependent and antenna-length response. Table 5.1 provides an opportunity to compare the results from this research to current infrared detector technologies.
From this evaluation, it can be concluded that of radiation-field detectors, those presented in this research provide the highest reported $D^*$ at $2.15 \times 10^6$ cm·Hz$^{\frac{1}{2}}$·W$^{-1}$. However, to be a commercially viable technology, normalized detectivity should be in the $10^8$ cm·Hz$^{\frac{1}{2}}$·W$^{-1}$ range. While, the detectors provide for all of the constraints outlined in Section 1.1, the $D^*$ value must be increased by roughly 50 times in order to be viable candidates for integration with commercial night-vision systems.

### Table 5.1

**Comparison of ACMOMDs to Current IR Detectors**

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>Area (mm$^2$)</th>
<th>Operating Temp. (K)</th>
<th>Response Time (ms)</th>
<th>$D^*$ ($\frac{cm\sqrt{Hz}}{W}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HgCdTe</td>
<td>~0.25</td>
<td>77</td>
<td>$10^{-3}$</td>
<td>$1 \times 10^{10}$</td>
</tr>
<tr>
<td>Pyroelectric</td>
<td>0.78 – 63.6</td>
<td>300</td>
<td>$10^{-4}$</td>
<td>$10^9$</td>
</tr>
<tr>
<td>Thermistor</td>
<td>0.25 – 25</td>
<td>300</td>
<td>5</td>
<td>$3 \times 10^8$</td>
</tr>
<tr>
<td>Thermopile</td>
<td>~5</td>
<td>208 – 343</td>
<td>5</td>
<td>$7 \times 10^8$</td>
</tr>
<tr>
<td>Bolometer (Ge)</td>
<td>~5</td>
<td>0.3 – 2.0</td>
<td>0.5</td>
<td>$3 \times 10^8$</td>
</tr>
<tr>
<td>Antenna-coupled Bolometer (Nb)</td>
<td>0.0001</td>
<td>300</td>
<td>$10^{-4}$</td>
<td>$6 \times 10^5$</td>
</tr>
<tr>
<td>Antenna-coupled MOM Diode</td>
<td>0.0001</td>
<td>300</td>
<td>$10^{-10}$</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>Shadow-evaporation ACMOMD</td>
<td>0.0001</td>
<td>300</td>
<td>$10^{-10}$</td>
<td>$2.15 \times 10^6$</td>
</tr>
</tbody>
</table>
5.2 General Comments and Measurement Observations

Overall, the objective of this research project has been satisfied. Prototype infrared sensors, capable of detecting LWIR radiation at room temperature without cooling, have been fabricated and characterized. These detectors function as the theory suggests. The polarization-dependent measurements as well as the antenna-length dependence measurements prove that the functionality of this detector is based on radiation-induced currents in the antenna that are rectified by the MOM diode. There are, however, a few points that should be brought to light.

5.2.1 Response to Visible Light

The ACMOMDs fabricated for this research respond to visible light in addition to LWIR radiation. This was discovered by monitoring the device signal when the visible alignment laser, of wavelength 650 nm, was turned on. The response of ACMOMDs to optical frequencies has been previously reported [75, 76], but the mechanism of detection for visible light is different than for the detection of infrared. Section 2.3 of this dissertation discusses different detection mechanisms of an MOM diode, including photon-assisted tunneling and photon interactions which allow electrons to surmount the barrier. These detection mechanisms were discarded because low photon energies, as in the case of infrared photons, cannot cause conduction in this manner. However, a photon of wavelength 650 nm has an energy of 1.908 eV. The barrier height of Al/AlO$_x$ is typically 2 eV [47]. However it has
been shown to decrease as a function of increasing barrier thickness [86] and can be approximated by:

\[ \phi_{AlO_x} \approx \frac{1.5}{d^2} \text{eV}, \]

where \( d \) is the barrier thickness in nm. This proves that for this visible frequency of light, conduction of electrons is possible by either photon-assisted tunneling or electrons surmounting the barrier. This response is polarization independent; that is, this phenomenon does not arise in the antenna, but rather at the MOM overlap area. This response can be reduced by employing a visible filter.

5.3 Methods for Detector Improvement

While increasing \( D^* \) of the devices fabricated in this research by roughly two orders of magnitude may seem beyond reach, device optimization could make this realizable. Possible methods for improvement include: tailoring the resistance or curvature of these ACMOMDs, fabricating these devices with two lithography steps allowing expanded material combinations or processing options, or employing a cavity-backed detector approach to reflect incident radiation and reduce surface waves.

5.3.1 Resistance/Curvature Tailoring

The ideal diode in these antenna-coupled devices would have a low resistance and high nonlinearity. As shown in Section 4.1, it is possible to fabricate ACMOMDs with reduced resistance compared to air-oxidation devices. The
drawback to reducing the diode resistance, which is done by reducing the barrier width, is that the nonlinearity of the device also decreases.

A. Csurgay et al proposed that by employing a dual-barrier MOM diode, a larger nonlinearity could be realized versus a single-material barrier of the same thickness [91]. This can be accomplished experimentally by first growing an aluminum oxide layer on the first evaporated metal layer, which is aluminum, and then depositing a second dielectric, such as SiO₂ before the second metal shadow evaporation.

An I-V characteristic for an Al/AlOₓ/SiO₂/Pt ACMOMD is shown in Figure 5.1, along with the resistance, second derivative of the current, and the curvature. The AlOₓ thickness is approximately 10 Å and the SiO₂ deposition is approximately 15 Å. The zero-bias diode resistance is 187 kΩ, the zero-bias curvature is 2.45 V⁻¹, and the peak curvature coefficient is 4.2 V⁻¹ at a biasing point of -0.5 V. This zero-bias curvature is much larger than any single-barrier layer devices of the same resistance. However, the yield is of dual-layer barrier ACMOMDs is very low compared to single-layer barrier ACMOMDs made with a controlled oxidation. This is most likely due to inconsistencies (e.g. pinholes, large grains, and/or areas of thick deposition) of the deposited SiO₂ layer.
Figure 5.1: I-V characteristic (upper left), resistance (upper right), diode nonlinearity (lower left), and curvature (lower right) for an air oxidation Al/AlO\textsubscript{x}/SiO\textsubscript{2}/Pt ACMOMD. This device fabricated with a double-layer barrier provides for high zero-bias curvature with a relatively low diode resistance.

The thickness of low-density films, such as SiO\textsubscript{2}, is difficult to control, especially for thin depositions such as the aforementioned one here. With more investigation into the fabrication, however, it should be possible to attain this high curvature, low resistance combination with dual-barrier antenna-coupled MOM diodes. One promising avenue for which to employ a double-layer barrier would be through the use of atomic layer deposition (ALD). ALD provides high quality films
with atomic layer control; layers as thin as a single monolayer can be deposited [92]. Atomic layer deposition is a technology that has yet to be used for the fabrication of MOM diodes, but is utilized in current 45 nm CMOS technology. Due to the growth chemistry of ALD, the deposited films are conformal, pin-hole free, and chemically bonded to substrates, even of varying composition [93]. ALD would provide a greater level of quality and precision than other dielectric deposition techniques. By not being constrained to native oxide-forming metals such as aluminum, a greater variety of material combinations can be investigated for the MOM diodes. This would provide for more versatility in terms of diode resistance, nonlinearity, and antenna integration.

5.3.2 Two-step Lithography Antenna-coupled MOM Diodes

The double-angle evaporation technique detailed in Chapter 3 allows fabrication of the antenna-coupled MOM diodes in this research using just one evaporation step. However, these devices can also be fabricated using two separate lithography and metal deposition steps, one for each antenna arm [29, 40, 69, 88, 94].

The substrate and resist stack remain unchanged, while the metal deposition procedure is simply modified so that deposition is normal to the sample. The first antenna arm is defined using EBL on a PMMA/MMA coated bonding pad array sample. The pattern is composed of a lead which connects to the bonding pad along with one half of the dipole. Metal is then deposited on the sample, followed by a lift-off procedure. The sample is then coated again with the same resist stack as in the
case of the first layer. The second antenna arm is then patterned with EBL. If the metal chosen for the first layer readily forms a native oxide in air, this will serve as the oxide barrier of the MOM diode. If the first metal layer does not form an oxide, one must be deposited, such as SiO$_2$ or HfO$_2$, before the second metal layer can be deposited. Once the second metal layer is deposited, a lift-off procedure is performed and the antenna-coupled MOM diode devices are complete. Figure 5.2 shows an optical micrograph of the two-step lithography devices connected to the electrical leads.

Figure 5.2: Optical micrograph of two-step lithography ACMOMDs. Each half of the dipole is fabricated with separate lithography and metal evaporation steps. The tunnel barrier can either be grown on the first metal or deposited by various means.

Figure 5.3 is a scanning electron micrograph of the structure, which shows the overlap of the two antenna arms.
Tiwari et al. have investigated fabrication techniques which provide for an in situ oxide growth [94]. In this process, the first antenna arm is patterned, developed, and aluminum is deposited on the sample. The second antenna arm is then patterned and developed. However, before the second metal evaporation, a Kaufman Ion Source is used to remove the native oxide of the first aluminum layer at the overlap area by argon bombardment. Oxygen can then be introduced to the chamber to reform an oxide on the first antenna arm and then the second metal evaporation can
take place. By using an etch and re-growth method of the oxide barrier, control over
diode characteristics, similar to those of shadow-evaporation devices shown in Figure
4.4, can be created.

A representative polarization-dependence response of a two-lithography
Al/AlO$_x$/Pt ACMOMD fabricated by Tiwari is shown in Figure 5.4.

![Figure 5.4: Polarization response of two-step lithography Al/AlO$_x$/Pt ACMOMD [94]. The electric field of the incident radiation is parallel to the antenna at 90° and 270°, where the maximum response was measured. The polarization ratio for this device, which is the maximum response divided by the minimum response, is about 7.](image-url)
5.3.3 Cavity-backed Dipole Antenna-coupled MOM Diodes

A cavity-backed dipole antenna-coupled MOM diode consists of the normal antenna-coupled structure described throughout this document, but with a dielectric-filled resonator beneath the detector as simulated by Sun [42]. The structure of the cavity-backed detector is shown in Figure 5.5.

![Figure 5.5: Cavity-backed ACMOMD. The cavity is formed with an etching process and lined with metal. A dielectric then fills the cavity and the wafer is planarized. Bonding pads can then be fabricated and the ACMOMD fabricated as usual.](image)

The purpose of the resonator is two-fold. The incident radiation is not only reflected by the bottom interface as in the case of detectors fabricated on a Si/SiO₂, but also the cavity resonance enhances the response. In addition, surface waves can be reduced
by the resonator structure. The cavity confines surface waves, which in a normal Si/SiO₂ structure would propagate away from the antenna structure along the dielectric/air interface, and thus contribute to losses. The cavity sidewalls do not necessarily have to be vertical [42].

The cavity can be created using numerous processes, using both wet and dry etching. Dry etching of the cavity can be done with either RIE or deep reactive ion etching (DRIE), while wet etching can utilize either isotropic or anisotropic etchants. The etching process controls the sidewall angle and surface roughness of the cavity.

Z. Sun calculated the optimum cavity dimensions for various filling dielectrics in the along-arm direction $Y$, and direction perpendicular to the antenna axis $X$, and depth $H$ [42], which are shown in Table 5.2. The antenna half-length is denoted by $L$, with a 50 nm antenna width for all cases.

<table>
<thead>
<tr>
<th>$\varepsilon_r$</th>
<th>L (μm)</th>
<th>X (μm)</th>
<th>Y (μm)</th>
<th>H (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2.50</td>
<td>15.0</td>
<td>10.0</td>
<td>2.55</td>
</tr>
<tr>
<td>1.5</td>
<td>2.20</td>
<td>13.5</td>
<td>9.25</td>
<td>2.20</td>
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<tr>
<td>2.25</td>
<td>1.85</td>
<td>12.5</td>
<td>8.50</td>
<td>1.90</td>
</tr>
<tr>
<td>2.7</td>
<td>1.75</td>
<td>12.0</td>
<td>8.00</td>
<td>1.80</td>
</tr>
<tr>
<td>3.3</td>
<td>1.63</td>
<td>11.2</td>
<td>7.45</td>
<td>1.67</td>
</tr>
<tr>
<td>3.6</td>
<td>1.59</td>
<td>10.85</td>
<td>7.25</td>
<td>1.62</td>
</tr>
</tbody>
</table>
A process flow for the fabrication of these cavity-backed structures is shown in Figure 5.6. While this process is shown for the case of anisotropic KOH etching, the process remains much the same for other types of etching. The process starts with a bare silicon wafer. Step (a) shows that using photolithography, the cavity dimensions can be defined. A SiO₂ layer may patterned and used as a mask layer if the chosen etchant attacks photoresist. The anisotropic KOH etch properties of silicon per bulk micromachining procedures [95] define the cavity shape, as illustrated by (b). The etch angle is 54.7°, calculated from the plane of the wafer to the sidewall edge. The KOH etchant concentration and temperature determine the etch rate of each crystallographic direction, so the cavity depth can be controlled [95].

The cavity can also be dry-etched with RIE, which provides control over the cavity sidewall angles by controlling the composition of the reacting plasma, gas pressure, and substrate bias. The photoresist is removed in (c) and the cavity is coated with a metal reflector, shown in (d), by sputtering or evaporating a metal. The cavity can then be filled with a low \( \varepsilon_r \) dielectric, such as benzocyclobutane (BCB) where \( \varepsilon_r=2.7 \) or silicon dioxide, where \( \varepsilon_r=3.9 \), shown by step (e) in the process. The dielectric constant of the material in the cavity will determine the radiation symmetry of the antenna. Once the cavity is filled with a dielectric, the wafer must be planarized by means of chemical-mechanical polishing (CMP). This is shown in step (f), where the wafer is polished to the plane of the wafer, leaving a filled dielectric cavity.
Figure 5.6: Cavity-backed detector fabrication process. Various etching methods can be used to form the cavity and various materials can be used to fill the cavity. After planarization, ACMOMDs can be fabricated as shown in Chapter 3.
When the metal deposited for the metal reflector is removed from the wafer, the CMP step is complete. Another layer of SiO₂ can then be applied using PECVD, shown in (g) to insulate the electrical leads and bonding pad structure from the substrate and underlying structure. The devices are then fabricated as described in Section 3.2.1, as shown in (h).
APPENDIX A

CMOS IMAGING CHIP INTEGRATION

The ability to fabricate infrared detectors which respond to thermal IR radiation has been demonstrated in the preceding chapters of this dissertation. However, implementing these devices in an array, which might ultimately lead to the capability of producing an image similar to the thermal IR image of Figure 1.1, would prove commercial viability. This chapter discusses processes which can be used to integrate an $8 \times 8$ array of ACMOMDs with a CMOS imaging chip. The chip used in this case the Eutecus Xenon-NC V1 chip, shown in Figure A.1. The area left of the center of the chip, which is outlined by a square, denotes where ACMOMD infrared detectors developed, fabricated, and characterized for this project are to be integrated. The image in Figure A.1 is a screenshot of the layout of the CNN chip, while the image in B is an optical micrograph. The area in the box denotes the integration location for the ACMOMDs.
Figure A.1: (A) Layout, (B) optical micrograph of Eutecus Xenon-NC V1 CNN chip. This CMOS imaging chip contains an area where an $8 \times 8$ array of detectors can be implemented. ACMOMDs are chosen to provide for infrared detection.

The scanning electron micrograph in Figure A.2 shows this integration area. This area is composed of $8 \times 8$ identical cells, each connected to amplification and computation circuitry. The ACMOMDs will be electrically connected between each of the $8 \times 8$, or 64 total, vias, which are the light gray squares, and the pad ring around the perimeter of the image. The inset image shows a magnified view of one cell, where the via is located at the center. One lead of the ACMOMD detector will be connected to the via, while the other connection will be made to the pad ring, which is extended throughout the chip so that identical connections can be made for each ACMOMD.
Figure A.2: Scanning electron micrograph of IR detector integration area on CNN. The inset image shows the integration area for one device; the light gray area in the center is a via contact, where one lead of the ACMOMD is connected.

The size of the entire chip is just $5 \times 5$ mm, and the thickness just $282 \, \mu m$. This presents a challenge in terms of processing the chip and integrating our devices. First, the small size of the chip makes handling difficult. Merely handling the chip with tweezers can lead to resist chipping near the edges of the chip, as shown in Figure A.3A, in addition to damage to the chip itself, shown in Figure A.3B.
Figure A.3: (A) Resist chipping and (B) wafer damage due to handling. The resist chipping can lead to electrical shorts between contacts when metal is deposited on the sample. The wafer damage is due to handling with tweezers.

In addition, the size of the chip is small enough where the edge bead of the photoresist prohibits suitable contact lithography. An edge bead forms due to surface tension during the photoresist spin-coating process; the photoresist near the corners of the $5 \times 5$ mm chip can be greater than 100 times thicker than the photoresist at the center of the chip. Since the lithography requires intimate contact between the patterning mask and the chip, any gap can cause pattern distortion due to light diffracting around the edges of the features on the patterning mask.

To mitigate this issue, along with the chip handling and damage issues, a process to fabricate a chip ‘carrier’ was invented. This is a square of silicon, roughly $15 \times 15$ mm in size and $625 \, \mu \text{m}$ thick, the thickness of a standard 100 mm wafer. In this square of silicon, deep reactive ion etching (DRIE) is employed to make a cavity $5 \times 5$ mm in size with depth roughly the same thickness of the CNN chip. A process for this fabrication is outlined in Figure A.4. The silicon is first patterned using photoresist and then etched using the Bosch process, which maintains vertical
sidewalls as a pattern is etched into the silicon. The depth of the cavity is on the order of 282 nm, depending on whether an adhesive is used to affix the CNN chip within the chip carrier. Lastly, the CNN chip is placed in the chip carrier where it can be processed per usual. The CNN chip remains in the chip carrier for all steps of the processing.

Figure A.4: Chip carrier fabrication process outline. A bare piece of silicon is patterned and then the cavity is etched using DRIE. The resist is then removed and the CNN can be placed in the cavity. This provides a reliable means of handling the 5 mm × 5 mm CNN chips without causing resist chipping or damage.

Another challenge associated with integrating devices on a prefabricated chip arises from the topography present on a chip due to many layers of interconnect circuitry. These interconnects are separated by layers of either a silicon nitride or silicon dioxide, and are planarized by CMP after each interconnect level is completed. However, there is still topography, on the order of 500 nm, present on the wafer. In addition, there is even greater topography, approximately 1.5 μm, from the surface of the CNN chip, where the ACMOMD detectors are to be integrated, down to the vias where they are to be electrically connected. This presents a challenge since the thickness of the metal lines of our antennas are just 30-40 nm thick, and these lines would surely be broken after traversing such topography.
To combat this issue a device interconnect process has been developed. There are specific areas within each cell of the $8 \times 8$ array on the CNN chip which are flat enough, with roughness on the order of 10-20 nm, to provide ideal locations for the integration of our devices. First, titanium-platinum pads are deposited on the chip, where each ACMOMD will be integrated, to provide for reliable electrical connections to the devices. Then, aluminum lines are sputtered to connect one titanium-platinum pad to the via, where the CNN chip reads the device current, and the other pad to the pad ring, where the electrical connection is completed. Sputtering is a conformal deposition process, where the sidewalls and tops of the features alike are coated with metal. This is desirable since it will provide for robust electrical conductivity over topography. The last step in the process is the integration of the ACMOMDs.

Figure A.5 shows the surface profile, or topography, on the CNN chip and how these devices will be connected in each cell. The red pads denote the titanium-platinum pads that will be deposited on the CNN chip first. These pads will then be connected to either the pad ring or cell via by sputtered aluminum, which is denoted by the blue lines. As is shown by the surface profile, the blue sputter-deposited aluminum lines provide for a conformal deposition. Lastly, the ACMOMD is integrated by the fabrication process outlined earlier in this document.
Figure A.5: Surface profile of CNN chip and corresponding device connections. The sacrificial metal used to aid in planarizing the wafer cause some topography. The red rectangles indicate the location of the Ti/Pt contacts. The blue lines represent the sputtered Al interconnects which connect the vias to the Ti/Pt contacts. ACMOMDs are then fabricated between the Ti/Pt as set forth in Chapter 3.

When completed, the devices will be connected as shown in Figure A.6. This scanning micrograph shows each identical $8 \times 8$ cell. The red overlay denotes the titanium-platinum pads, the blue denotes the sputtered aluminum interconnects, and the green denotes the integrated ACMOMDs. As can be seen, the first four columns
of ACMOMDs are connected singularly, while the last four columns are connected in parallel, done in an effort to increase the signal-to-noise ratio.

Figure A.6: Connection diagram for ACMOMD integration. This figure shows the overall connection scheme for the devices. The devices in the left four columns are connected singularly, while the devices in the right four columns are connected in parallel to increase SNR.

The Ti/Pt pads are patterned with Clariant AZ 5214-E negative photoresist, utilizing the process set out in Section 3.1. Electron beam evaporation is used to
deposit the titanium and platinum pads of thickness 5 nm and 20 nm, respectively. A
lift-off procedure in acetone removes the photoresist and any metal not contacting the
CNN chip.

The CNN chip is then placed in the Perkin Elmer 2400 sputtering system. To
make robust electrical connections to the vias, the sample is first backspattered for 30
s at 1000 W. This removes any native oxide present on the aluminum vias. 100 nm
of AlSi is then sputtered at 1050 W, which takes 3 minutes to deposit. The chip is
then patterned with Shipley Microposit 1813 positive photoresist to define the
aluminum detector interconnects. The CNN chip is then etched using a PlasmaTherm
790 Series Reactive Ion Etcher (RIE). The RIE provides for a means to dry etch the
aluminum, which allows for control over the sidewall angle. The process used to etch
the aluminum is a CH$_4$:Cl$_2$ etch of ratio 10:30 with a pressure of 60 mTorr, 94 W
power, and 90 V bias for 3 minutes. In general, a lower gas pressure and higher bias
create more vertical sidewalls. A five minute process with 90 mTorr pressure, 80 W
power, and 45 V also produced favorable results. For these aluminum interconnects,
the sidewall angle is not critical so either recipe is acceptable.

The integration process is outlined in Figure A.7. This collection of images
shows the entire 5 × 5 mm CNN chip, the 8 × 8 array integration area, and a single
cell with integrated device, along with three scanning electron micrographs showing
the cell, completed device, and dipole antenna.
The last step in the process is wirebonding the completed CNN chip for testing with the Bi-I system [REF]. There are 168 pins on the CNN chip; the package used is a 181-pin ceramic package. An image of the completed CNN chip, integrated with ACMOMDs and wirebonded and ready for testing is shown in Figure A.8.

The preceding steps could be used to integrate ACMOMDs with a CMOS vision chip. Numerous antenna geometries could be employed to provide for multi-spectral image acquisition. This would provide for a powerful image acquisition solution which could have endless possibilities.
Figure A.8: Completed CNN chip after ACMOMD integration and wirebonding. 168 aluminum wirebonds connect the contacts on the edge of the CNN chip to the pins on the chip socket. Once a measurement test bench is finalized, the response of the array of ACMOMDs could be measured.
REFERENCES


