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Design, Fabrication and Characterization of Thin-Film M-I-M Diodes for Rectenna Array

Subramanian Krishnan

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Design, Fabrication and Characterization of Thin-Film M-I-M Diodes for
Rectenna Array

by

Subramanian Krishnan

A thesis submitted in partial fulfillment
of the requirement for the degree of
Master of Science in Electrical Engineering
Department of Electrical Engineering
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DESIGN, FABRICATION AND CHARACTERIZATION OF THIN FILM M-I-M DIODES FOR RECTENNA ARRAY

Subramanian Krishnan

ABSTRACT

A Metal-Insulator-Metal (MIM) diode is a high frequency device used for energy harvesting purpose in the RECTENNA. The main objective of this thesis work is to design, fabricate and characterize a thin-film MIM diode. A key issue associated in this research work is the development MIM diode with nanometer thin insulator region. The reason for the development of MIM diode is to rectify a wide spectrum of AC signal to usable DC power. In this thesis work, a planar MIM diode with Aluminum/Aluminum-Oxide/Gold has been fabricated. The thickness of the insulator region obtained was about 3nm. The Metal and insulator depositions were done by sputtering and plasma oxidation, respectively. I-V Characteristics of the diode was measured by making use of in-house set-up and 70% of the devices on a single wafer yielded with better result. Most of the I-V curves obtained was highly non-linear and asymmetric. Based on the I-V measurement, the logarithmic derivative of I vs. V was plotted and the tunneling behavior was also observed.
CHAPTER 1
INTRODUCTION

In many developing countries, abundant and affordable sources of energy are required to improve the standards of an upcoming society. Over the last 20 years, there has been a tremendous increase in demand for energy. This increase in demand is likely to continue. The demands ideally need to be satisfied with renewable source of energy. One such source of energy is the solar radiation, which is unlimited in supply, is clean and renewable. Solar energy already indirectly plays a significant role in the need for, and production of, energy for diverse applications. However, a widespread commercial usage of solar energy is very rarely seen, principally because of low conversion efficiencies. Some of the emerging developments, leveraging the developments in nanotechnology may change this situation.

Photovoltaic cells are the only mature technology that’s been utilized all over the world to generate electricity from solar radiation. Present photovoltaic technologies are based on the quantum nature of light which are fundamentally limited by the semiconductor band-gap energies. Conversion of solar energy to electricity using photovoltaic cells is based on this principle. Although there has
been an increase in conversion efficiency of solar cells over the past decade they are still significantly lower than 50%. A significant amount of radiation is lost as heat. An alternative for the photovoltaic cell that are more efficient for energy conversion is the rectenna, which is a combination of rectifying diode and a receiving antenna.

1.1 Overview of Rectenna

William C. Brown of the Raytheon Company, a pioneer of microwave power transmission, coined the term “rectenna”, for rectifying-antenna which was invented to absorb the microwave beam and simultaneously convert it to DC power. Initial rectenna concept was proposed for microwave power transmission. Under an Air Force contract he demonstrated in 1964, on the CBS Walter Cronkite News, a microwave powered helicopter that received all the power needed for flight from a microwave beam. The helicopter was tethered with a payload of rectenna elements to convert microwave power to dc power. In order to keep the helicopter in stable position, wires were passed through the center of the helicopter and through the ends. This microwave powered helicopter demonstration lasted for 10 hours with the helicopter hovering at an altitude of 60 ft [1].

This was the first rectenna ever built. It was composed of 28 half-wave dipoles with point-contact semiconductor diodes. Later, the point contact semiconductor
diodes were replaced by silicon Schottky-barrier diodes which raised the microwave-to-DC conversion efficiency from 40 % to 84 % [2].

Figure 1.1: William C. Brown Demonstrating Microwave Powered Helicopter [2]

The concept of Satellite Power System was first proposed by P. E. Glaser in 1968 to meet both space-based and earth-based power needs. The SPS was to generate electric power using photovoltaic cells and transmit the generated power via a microwave beam to the rectenna site [2]. An important milestone in the history of microwave power transmission was the three-year study program called the DOE/NASA Satellite Power System Concept Development and Evaluation Program, started in 1977. This program was conducted for the study of the Solar Power Satellite (SPS), which is designed to beam down the 5 to 10 GW from one SPS toward the rectenna site in the ground [2].
Extensive work of the SPS ended in 1980 considering not only the technological
development with high efficiency and high safety, but also effect of microwave
impact onto the space environment [2].

As described earlier, rectenna was originally proposed for power transmission by
radio waves for remote powering of aircraft. Later it was proposed for energy
harvesting. Since, Solar cells are limited by the band-gap of the photovoltaic
material; the conversion efficiency is also limited. In contrast, an antenna array
can be used as an ideal device to collect the solar radiation and rectify the signal.
A radical approach suggested by Professor Robert Bailey in 1972 pivots around
the wave nature of light. Professor Bailey suggested that broadband rectifying
antennas called “rectennas” could be used for direct conversion of solar energy
to DC power [3].

The rectenna concept unlike, the photovoltaic cell utilizes the wave nature of
light, successfully collecting the longer wavelengths at the desired band These
rectennas would not have the fundamental limitation of semiconductor band-gap
limiting their conversion efficiencies. Using the idea of Rectenna one can harvest
solar energy from a large part of the spectrum. Thus Rectenna has been used
only in the microwave frequency and this has to be extended to the infrared and
visible regime for more useful solar power conversion [3].
The conversion efficiency of the antenna based solar collector thus could approach 100%. A greater challenge is the ability of the system to rectify the received signals to DC as a usable output.

![Frequency Spectrum](image)

**Figure 1.2: Frequency Spectrum**

### 1.1.1 Basic Structure of a Rectenna

A typical rectenna element consists of a dipole antenna and a fast tunneling diode. Different antenna arrangements like slots, dipoles, spirals, bow-tie etc., can be used in the rectenna.
An input filter (Low pass filter) between the antenna and the diode forms the impedance match. The input filter also prevents re-radiation by the antenna due to the higher harmonics generated by the rectifier. An output filter (DC pass filter) is necessary to smooth the rectified signal to DC. Initially a low power Schottky diode was used for rectification in the low frequency regime. Since Schottky diode cannot perform in high frequency region, Metal-Insulator-Metal (MIM) diodes were considered. What is required is the development of MIM diodes for the efficient conversion of input AC signal to usable DC output. Currently active research is being pursued on thin-film MIM diodes being fabricated with small contact areas [4].

1.1.2 MIM Tunnel Diode – A Brief Introduction

There are a number of issues related to the development of a rectenna. Firstly, the antenna elements need to be extremely small. Although the concept of the
rectenna has been around for three decades, it is only in the past few years that the tools to fabricate such a device, requiring structures in nanometer scales, have become available. Another difficulty is making diodes with small physical size, small turn-on voltage, efficient operation at light frequencies and the ability to rectify the received signals to DC as a usable output. Such high frequency rectification is quite a challenge, and may be feasible through Metal-Insulator-Metal tunneling diodes. Fabrication and characterization of thin film insulators is the main issue to be covered in this work. The major challenge to be faced is the design and fabrication of thin film MIM diode.

1.2 Objective

The objectives of this research work in developing metal-insulator-metal diodes were.

- Development of fabrication process of rectennas: For faster response time and more sensitivity, the size of the contact area has to be small. One of the objectives is to keep the device area as well as the contact area a minimum. The smaller the contact area the more uniform is the dielectric deposition and also higher the probability of tunneling.

- Selection of materials for fabrication: Selection of material should be done, compromising the conductivity to obtain large work function difference between the metals. In order for tunneling to occur, the metal electrodes
chosen in the MIM diode should have a large difference in their work function

- Development of ultra-thin dielectric films: For direct tunneling to occur, the dielectric layer should have a maximum thickness of 5nm maintaining uniform insulator coverage over the entire contact area. This is the most critical section in the manufacturing of the MIM diode.

- Testing and Characterization: The characteristics of the diode should be sufficiently non-linear to maintain asymmetry for high efficiency of conversion.

1.3 Organization of Thesis

This thesis will report on the design and fabrication of thin-film metal-insulator-metal tunnel diodes and also the characterization and experimental results of the diode. This thesis is presented in an organized way, presenting the main idea or the reason for this process and then proceeding with manufacturing of the device. Chapter 2 starts with a discussion on the tunnel diode, its operation and typical characteristics of a tunnel diode. Then it discusses the MIM tunnel diode, its application and development in the area of rectenna. It also reviews the early development of MIM diode for rectenna application. Chapter 3 discusses the design and fabrication aspects of the MIM tunnel diode. The design issue, design problems, factors affecting the design, fabrication issues and the general processing techniques followed in the fabrication of MIM diodes are discussed.
Chapter 4 discusses the actual device processing, characterization and testing for normal operation. I-V characteristics are measured and discussed. Chapter 5 presents the conclusion and recommendations for future-work. The appendix section discusses the fabrication procedure followed to build the device and the parameters set for obtaining thin-films.
CHAPTER 2
MIM TUNNEL DIODE

2.1 Introduction

The occurrence of quantum-mechanical tunneling takes place when a particle travels through a thin potential barrier instead of overcoming it, without any energy variation. This tunnel effect cannot be explained on the basis of classical particle mechanics. According to classical particle mechanics, the behavior of electrons in an electric field can be described as a repulsive force acting on the electron thus decreasing its velocity until it is brought to rest and then, thrown back with its velocity reversed. The wave mechanics, description of interaction of an electron in an electric field is more similar to the particle mechanics, except that, in wave mechanics the electron has a finite probability of penetrating beyond the classical repulsive reflecting point. This penetration is called the tunnel effect [5].

Tunneling is the controlling mechanism in (a) current flow through a thin oxide film in a metal-oxide-metal structure (this applies to most metal-metal contacts since films of oxide or contamination are generally present), (b) electrical breakdown in solid dielectrics (Zener tunneling), (c) current flow across a narrow semiconductor p-n junction (Esaki tunneling) [5].
The tunneling phenomenon is a majority carrier effect. In addition, the tunneling time of carriers through the potential barrier is not governed by the conventional transit time concept, but rather by the quantum transition probability per unit time. This tunneling time is very short, enabling the use of tunnel devices well into the millimeter-wave region [6]. Tunnel diodes are in principle capable of fulfilling almost all circuit functions, but they are most useful as microwave diodes or fast diodes.

2.2 Tunnel diode

In 1958, Leo Esaki, a Japanese scientist, discovered the current flow in a negative-resistance region of a semiconductor diode. A peak was observed at low voltage in the forward direction of the current-voltage characteristics in a p-n junction. The peak was caused by quantum-mechanical tunneling of electrons through the junction [7].

![Characteristics Curve of Tunnel Diode and PN Junction](image-url)

Figure 2.1: Characteristics Curve of Tunnel Diode and PN Junction
This effect was observed in highly doped diodes. In normal junction diode, the level of doping is very low, in the order of say, one impurity atom for ten-million semiconductor atoms. When the doping level is low, there exists a wide depletion region. Conduction occurs in the normal junction diode only if the voltage applied to it is large enough to overcome the potential barrier of the junction [7].

In the tunnel diode, the doping concentration of the semiconductor materials used in forming a junction is very high to the extent of one-thousand impurity atoms for ten-million semiconductor atoms. This heavy doping produces an extremely narrow depletion zone. Also because of the heavy doping, a tunnel diode exhibits an unusual current-voltage characteristic curve as compared with that of an ordinary junction diode [7].

The three most important aspects of this characteristic curve are (1) the forward current increase to a peak \(I_P\) with a small applied forward bias, (2) the decreasing forward current with an increasing forward bias to a minimum valley current \(I_V\), and (3) the normal increasing forward current with further increases in the bias voltage. The portion of the characteristic curve between \(I_P\) and \(I_V\) is the region of negative resistance [7].

Tunneling occurs when a biasing voltage is applied. The electron may tunnel from valence band to conduction band or vice versa. The conditions for tunneling are, (1) occupied energy states exist on the side from which the electron tunnels, (2) unoccupied energy states exist at the same energy level as in (1) on the side
to which the electron can tunnel, (3) the potential barrier height is low and the barrier width is small for finite tunneling probability, and (4) momentum is conserved in the tunneling process [6].

Figure 2.2: Energy Band Diagrams of Tunnel Diode [8]

Figure 2.2 a shows electron tunneling from the valence band into the conduction band when reverse bias is applied. The corresponding current is also designated by the dot on the I-V curve. When a forward bias is applied (figure 2.2c) a band of energies exists for which there are filled states on the n side corresponding to states which are available and unoccupied on the p side. The electron can thus tunnel from the n side to the p side. When the forward voltage is further increased there are fewer available unoccupied states on the p side (figure 2.2d). If forward voltage is applied such that the band is “uncrossed”, that is, the edge
of the conduction band is exactly opposite the top of the valence band, there are no available states opposite filled states. Thus at this point the tunneling currents can no longer flow. With still further increase of voltage the normal thermal current will flow (figure 2.2e), and will increase exponentially with applied voltage. One thus expects that as the forward voltage increases, the tunneling current increases from zero to a maximum $I_p$ and decreases to zero when $V=V_n+V_p$, Where $V$ is the applied forward voltage, $V_n$ and $V_p$ are the amount of degeneracy's on the n side and p side, respectively. The decreasing portion is obtained after the peak current gives rise to the negative resistance region [8].

2.3 MIM Tunnel Diode

A metal-insulator-metal (MIM) tunnel diode is a thin-film device in which the electrons tunnel through the insulator layer from the first metal layer to the second metal. MIM diodes operate due to the tunneling effect that occurs between the metals through the thin layer of the insulator region. When the work function difference of the metals being used in the MIM diode is fairly large then there exists an asymmetric behavior of the I-V characteristics. Quantum tunneling occurs if the barrier region is extremely thin, say in the order of few nanometers. The probability of electron tunneling is greater when the barrier distance is small and the barrier height is smaller [8].

MIM tunnel diodes are the most readily available infrared and optical radiation detectors [9]. Initially the MIM tunnel diodes that were developed were
conventional point contact MIM diodes. These MIM diodes that were fabricated were called “cat-whisker” diodes. Cat-whisker diodes are the ones in which a metal plate is pressed with a tungsten wire to form a tunneling junction. These types of diodes were difficult to fabricate as the barrier layer that was formed was due to some dirt collected on the surface or some native oxide layer. In-spite of the reproducibility issues, the point-contact configuration /Cat-whisker diodes were fabricated and used in the communication field for over twenty years in high frequency rectification from few gigahertz to 150 THz [10, 11]. The MIM diodes are also used in the field of image display. MIM diode is been used in the Thin Film Transistors Liquid Crystal Displays technology (TFT –LCD) as a switching device. Due to the high production cost of TFT-LCD’s, MIM-LCD’s are being considered as suitable candidates for active matrix displays [12].
2.3.1 Factors limiting MIM

The MIM tunneling diode rectifies the AC field across the antenna providing DC power to an external load. There are certain factors to be considered for using MIM’s in the rectenna concept. For high frequency diodes the limiting factor is the presence of parasitic capacitance. For complete energy harnessing, the characteristics of a MIM diode has to be non-linear and asymmetrical with no external bias applied. Though using external bias might be of use in some applications, it also reduces the efficiency of the device leaving it useless. Hence a zero bias response diode is needed. MIM diodes fabricated with dissimilar metals result in higher efficiency energy conversion than with similar metals. Another factor is the integration and stability of a point contact MIM configuration in the infrared and optical region. As the stability of MIM point-contact diode has been lower, it has so far only been used for laboratory experiments. Thin film MIM tunnel diodes are being developed as an alternative to point-contact MIM’s [11].

Figure 2.4: I-V Characteristics of a Cr/CrOx/Au MIM Diode [13]
A typical characteristic I-V curve for a micron scale MIM tunnel diode is shown in the figure 2.4. The above micron scale curve shows significantly high nonlinearity, slight asymmetry. For efficient energy harvesting, I-V characteristics similar to the micron scale have to be obtained even at the nanometer scales, with improved asymmetry. This requires further optimization of the device.

2.3.2 Schottky Diode

Due to the fact that MIM diodes can operate in the infrared region, they are considered the most eligible devices to be used in rectennas for power rectification. Other diode configurations like the Schottky Barrier Diode were also considered for energy harvesting purposes.

The Schottky Barrier Diode (SBD) is more similar to the point-contact diode. But in SBD the metal semiconductor junction is a surface rather than a point contact. Because of the large contact area between the metal and the semiconductor, the Schottky barrier diode exhibits certain advantages over the point-contact diode. The most important advantages of the Schottky barrier diode are the lower forward resistance and lower noise generation. The applications of the Schottky barrier diode are similar to that of the MIM point-contact diodes. The low noise level generated by Schottky diodes makes them very suitable for microwave receiver detectors and mixers. But the potential of Schottky diodes is limited to frequencies less than 5THz. Hence, thin-film MIM diodes are better suitable for the infrared and optical ranges [11, 14].
2.3.3 Characteristics of MIM Diodes

For tunneling to occur the metal electrodes used in the MIM tunnel diodes have to be dissimilar with enough work function difference.

![Figure 2.5: Theoretical Tunnel Resistance as a Function of Applied Voltage for an Asymmetrical MIM Structure][15]

Figure 2.5 illustrates the tunnel resistance as a function of $V$ for $d = 20, 30$ and $40\text{A}$, $\Phi_1 = 1\text{V}$, and $\Phi_2 = 2\text{V}$. The tunneling area in the MIM diode can be explained by the statistical nature of the formation of insulating films on a metal substrate. Only the thinnest portion in the insulator film is responsible for the tunneling.
current. Because of the statistical fluctuation of the thickness, the capacitance of the MIM structure is always larger than the calculated average thickness of the insulator film [15].

From the above characteristics of the MIM diode, it can be deduced that, as the barrier thickness increases by one nanometer, the tunnel resistance changes significantly. This resistance of the MIM diode has to be kept fairly low to match the antenna network. As can be seen in the above figure, the resistance across the diode drops as the voltage is increased. But in real-time, the operating voltage of the MIM depends on the antenna voltage. Hence at lower voltages, the resistance of the diode being very high, development of thinner insulator region is required for MIM diode to operate effectively, obeying the quantum tunneling phenomenon. When operating in higher frequencies, greater optimization of the device is required to address low impedance and high non-linearity. The frequency response of the diode is governed by the RC (resistance-capacitance) time constant. Since the impedance matching of the antenna and the diode needs to be fairly close, the capacitance needs to be minimized, requiring the minimization of the device area. Therefore the area of the device should also be kept as small as possible. This is explained in the following section.
2.3.4 Theoretical Model of MIM Diode

The equivalent circuit diagram of an antenna coupled to MIM diode is shown in figure 2.6. It consists of a fixed resistor $R$ and a non-linear resistor $R_d$ connected parallel to a capacitor $C_d$. The antenna resistance $R_a$ is in series with $C_d$ and $R_d$.

![Equivalent Circuit of Antenna Coupled MIM Diode](image)

**Figure 2.6: Equivalent Circuit of Antenna Coupled MIM Diode**

The rectification of the captured signal from the antenna occurs in the nonlinear resistor $R_d$. In order to reduce the losses that are caused by the currents flowing through the capacitor, the capacitance has to be kept small. According to Sanchez et al., the cut-off frequency of the device is defined as,
The frequency of operation can be increased by keeping small values of capacitances. This can be obtained by increasing the thickness $d$ of the dielectric layer or by reducing the contact area $A$. The nonlinearity of the I-V curve of the diode, and the probability of the tunneling decreases considerably if the thickness of the insulator is increased beyond 5nm. Hence, the requirement of lower
capacitance is attainable only if the contact area A is minimized. For operation of the MIM diode in the optical regime i.e., 650THz (visible light region), the contact area required is approximately 17nm \times 17 \text{ nm}. This makes the fabrication of the MIM diode extremely challenging [9].

The tunneling probability of the particle is established by the barrier height and width. The transmission probability is given by the modified Schrödinger Wave equation,

$$D = \exp\left(-2d \left[2m (V-E)/\hbar^2\right]^{1/2}\right)$$

Here, V is the barrier height and E is the energy of the particle. D is the transmission probability and d is the thickness of the dielectric. For a particle with a mass of an electron, the tunneling probabilities for d=1Å, 10 Å and 100 Å are 0.68, 0.02 and 3 \times 10^{-17}, respectively. Thus an electron can tunnel through a high barrier with distance in the size of an atom or a molecule. However, once the distance gets increased more than atomic dimensions, the tunneling probability goes small [16].
Figure 2.7 shows the asymmetry in the behavior of the diode under forward and reverse bias. This is mainly due to the difference in the work functions of the two metals. Current flow across the diode occurs due to the tunneling of electrons through the insulating layer. In the forward biased case the average height of the barrier is seen to be lower than in the reverse case and the tunneling probability (and hence the current flow) is therefore larger. The limiting factor in the potential performance of a MIM diode is the difference in the work functions of the two metals. In order to achieve a high degree of asymmetry in the I-V curve it is therefore desirable to use metals with highly different work functions. This is a primary aspect in the fabrication of MIM diodes [23].

Based on the above theoretical studies, the MIM tunnel diode is designed to operate in the desired frequency with certain presently obtainable parameters with equipment available in our laboratories.
2.4 Previous Development of MIM for Rectenna Concept

The development of MIM tunnel diode for rectennas has been going on for over two decades hence there are quite a number of publication on the manufacture of MIM diodes with optimized parameters. Some of the developments are discussed below.

In the earlier developmental stages, MIM point-contact diodes were more efficient than thin film MIM diodes. The W-Ni MIM diode was the most successful material combination (used for high-frequency application) [9]. Institute of Quantum Electronics, Zurich, has successfully implemented nanometer thin-film diode for 30 THz radiation using E-Beam Lithography tool [9]. They were able to manufacture thin-films to a thickness of 40nm which they were able to identify by the Rutherford Back Scattering technique. To reduce the capacitive effects of MIM diodes, the contact area was designed to be as small as 0.056µm². The response speed of the device also improves by reducing the size of the active area. Non-linear characteristics were observed when the metal-oxide layer was thin [9].

Planar type MIM diodes using Ti/TiOx/Pt metal were developed using Scanning Probe Microscopy (SPM) based lithography technique for well defined structures. Scanning Tunneling Microscopy (STM) and Atomic Force Microscopy (AFM) were used to selectively oxidize the surface of the deposited metal to obtain a thin metal-oxide layer. Oxidation using AFM in the presence of ambient air is
called AFM Nano-oxidation. By controlling the power supply and the scanning speed of the AFM, the width and the height of the metal oxide layers can be controlled. Metal oxides with a feature size of ~10nm can be easily obtained using this fabrication process. The electrical characteristics of the device were measured under a two-terminal arrangement in shielded surroundings. Non-linearity was clearly observed and the current was suppressed by thicker oxide wires. The temperature dependence of I-V characteristics on MIM were also investigated. The current is markedly decreased by decreasing the measurement temperature. The barrier heights are altered by changing the applied bias. This study was done by some Japanese researcher’s at the Electrotechnical Laboratory and Tokyo Institute of Technology.

ITN energy systems, a Denver based firm collaborated with University of Central Florida for the production of a Direct Conversion Device (DCD), which operates on the rectenna concept. ITN Energy Systems were fabricating optical antennas integrated with nano-patterned diode using dissimilar metals to achieve higher conversion efficiency. The active area of the MIM diodes that were fabricated by ITN Energy Systems were 500 nm X 500 nm, 225 nm X 225 nm, 100 nm X 100 nm, 50 nm X 50nm. Two kinds of process steps were followed for the manufacture of thin metal oxide; plasma oxidation and dirty oxidation. The resistance of the device manufactured were 0.5 – 2.5 KΩ for plasma oxidation and 70 KΩ - 20 MΩ for native oxide. The fabricated devices were categorized as (a) very high impedance > 5 MΩ and high non-linearity (b) very low non-linearity
(close to resistor) and lower impedance ~2000Ohms. I-V characteristic shows non-linearity only for devices with huge active area. As the contact area goes down, the curve gets closer to a resistance curve [10].

These are the most recent developments in MIM Tunnel diodes, made possible because of the available technological advancements.
3.1 Introduction

The MIM tunnel diode is a recent concept, therefore several design issues were considered before manufacturing of the actual MIM device. Since the development of the first MIM diode, there have been no ideal established criteria on the properties and characteristics of the device. Based on the early development of MIM and literature review, an assumption was made that the thin-film development and the size of the active area are the two major issues that define the characteristics of the tunnel diode. Considering the above parameters on which the design of MIM devices is based, masks are prepared with probe contact areas in the millimeter and the active diode area in micron-length scale. The fabrication process of the MIM device involves lithography, Physical Vapor Deposition (PVD) processes and lift–off techniques. Lithography is done to pattern each layer of the mask on to the substrate. Once lithography is done, the patterned substrate is deposited with the selected metal by PVD techniques such as sputtering and evaporation.
3.2 Design Issues

As mentioned earlier, the most important factor to be considered in the design of the MIM Tunnel Diode is the size of the contact area between the metal layers and the insulator layers. The reason for keeping a smaller contact area and the need for a thin layer of insulator were discussed in section 2.3.3. A MIM device has inherent impedance in its device structure. By lowering the size of the active area, the impedance can be reduced [13]. With these issues in mind, the MIM was designed with contact areas ranging from 50µmX 50µm to 150µmX 150µm. The structure of the MIM diodes used in this work is shown in figure 3.1.

![Figure 3.1: Design Structure of MIM Diode](image)
3.3 Mask Designing and Development

Two sets of designs, a planar type and a sliding type design were developed and the masks were prepared for the fabrication of MIM diodes. The planar type MIM design was constructed with contact areas in the range of $1\text{mm}^2$ to $2\text{mm}^2$ and the sliding type of mask design was developed in the micron scale length with contact areas from $90\mu\text{m}^2$ to $150\mu\text{m}^2$. A schematic of the planar and sliding type MIM diode is shown in Figure 3.2 and Figure 3.3.

![Figure 3.2: A Schematic of the Planar MIM Diode](image-url)
The sliding type design of MIM is developed to retain smaller size of contact area. The design includes two gold pads on which the metals will be deposited. The gold pads are used as the contact pads, which is dedicated to probe the device for measurement. These contact pads ensures that the metals deposited on them are properly bonded. In this design, on the glass substrate gold pads are deposited initially. Then a metal arm is deposited from the top gold pad and oxidized to form metal oxide. The grey region shown in the schematic is the base metal with metal oxide on it. Another thin strip of gold is deposited on the lower gold pad. The intersection of both the metal forms the MIM device. These are the two sets of MIM design which is used in the fabrication of MIM tunnel diode. The sliding type design has multiple devices in a
single mask, allowing us to test a variety of devices with slight changes in the contact area.

Figure 3.4: Mask Design of MIM diode

Figure 3.4 is captured from the mask development tool. Design and mask development of thin-film MIM diodes was done using CoventorWare and AutoCAD. Using the CoventorWare a perspective view of the design was made, to show how the structure will look like as a final device with metal layers deposited on it. The 3D view of the MIM diode is shown in figure 3.4, taken from CoventorWare. The blue region is the substrate on which the device is placed. The substrate on which the metals are deposited is Borosilicate Pyrex Glass substrate. The base electrode/metal is deposited on top of the substrate; shown by the green area. Also the metal-oxide layer is deposited over the base.
electrode layer. The counter electrode or the top metal layer is the red patch deposited on top of the metal with metal-oxide to form the main contact area or the active area which is responsible for the tunneling phenomenon to occur. The size of those contact areas differs between each row. To ensure that the masks are aligned properly in each layer of lithography, certain cross hairs have been designed. These cross hairs will be used as alignment markers, to align the layers below.

Figure 3.5: A Perspective View of the MIM Structure

The aforementioned designs were developed into glass mask at USF facility. The finalized designs from AutoCAD are converted into DXF format which is used for photo-plotting. After photo-plotting the masks are optically captured on a glass plate under a typical photo developing environment. Mask development is done for a pre-calculated time, which would give a better resulting pattern after
development. These masks are the patterns that will be used in the lithographic tool for pattern transfer of layers.

3.4 Fabrication Issues

After the design and development of the mask for the MIM diode, there are certain processing issues that have to be considered before proceeding to manufacturing of the real MIM Tunnel diode.

- Proper selection of metals needs to be made in order to have enough work function difference (Table 3.1 documents the work function of various elements). The materials used on the device will also alter the characteristics of the diode like asymmetry and non-linearity. The materials selected should be stable and allow processing in the open equipment laboratory.

- Based on literature search, it is known that the metal deposition process is carried out through physical vapor deposition techniques like, evaporation and sputtering. After a review of equipment and their performance, sputtering was chosen as the technique to deposit the metal.

- A process to grow/deposit thin films of metal oxides needs to be determined. This is usually done by exposing the wafer to dry oxygen or oxidizing through plasma oxidation. Another technique for growing the metal-oxide is by exposing the metallized wafer to air, to form a native
oxide. This is called “dirty” oxidation, but in this process the metal will be deposited with many contaminants along with the native metal-oxide. This metal-oxide growth needs to be done in a controlled fashion in order to get a very thin layer of deposition, in the order of a few nanometers. For this reason, the oxide deposition has to be characterized to find, the rate of deposition for various times and pressures.

- One other method by which this dielectric layer can be deposited is through the CVD (Chemical Vapor Deposition) technique. PECVD can be followed to get a uniform and more controlled dielectric growth. This will ensure that the film is free of pin-holes and the possibility of leakage is prevented and the probability of tunneling is enhanced.

These are some of the factors that had to be addressed before the fabrication of the tunneling device.

### 3.5 Material Selection

Material selection is based on the conductivity and the work function of the metal. In order to have non-linear and asymmetrical characteristics, two dissimilar metals with enough work function difference are chosen. Various metals were considered to be used in the MIM structure. Initially Chromium was chosen as the base electrode with gold as its counter electrode. Due to the readily oxidizing nature of the chromium (when exposed to air), some other metals were considered. Depending on the availability of the metal and the work function
difference with gold, an alternative choice of Gadolinium was selected. Gadolinium and Gold had a very large work function difference. The work function of Gd and Au are 3.1eV and 5.1eV respectively. Gadolinium is a Ferromagnetic metal and it also oxidizes, but not as previous metal (Chromium), when exposed to air forming loosely adhering native Oxide of Gadolinium. This native metal oxide aids in forming the insulator layer. Later other metals like Aluminum were also used, known to form a stable native oxide. The work function of aluminum is 4.28eV, which is about 0.9eV lower when compared to gold. This preference is based on existing literature studies as one of the successful metal-metal-oxide combination. Table 3.1 lists the metals that has been considered and were used as base-electrode and counter electrode in the MIM structure.

Table 3.1: Metals Considered and their Work-Function

<table>
<thead>
<tr>
<th>Element</th>
<th>Work-function (eV)</th>
<th>Conductivity ($10^7$/Ωm)</th>
<th>Resistivity ($10^{-8}$/Ωm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>4.5</td>
<td>0.78</td>
<td>12.9</td>
</tr>
<tr>
<td>Gd</td>
<td>3.1</td>
<td>0.07</td>
<td>134</td>
</tr>
<tr>
<td>Al</td>
<td>4.28</td>
<td>3.65</td>
<td>2.74</td>
</tr>
<tr>
<td>Au</td>
<td>5.1</td>
<td>4.55</td>
<td>2.2</td>
</tr>
<tr>
<td>Pd</td>
<td>5.12</td>
<td>0.95</td>
<td>10.5</td>
</tr>
<tr>
<td>Pt</td>
<td>5.65</td>
<td>0.96</td>
<td>10.4</td>
</tr>
</tbody>
</table>
3.6 Basic Processing Steps

There were several process flows that were considered and few were chosen in the processing of MIM tunnel diodes. Developing an efficient process for the fabrication of MIM diodes requires easily scalable, high throughput techniques with the potential to yield high efficiency devices. Understanding the complex issues of thin film deposition, junction formation and how these are affected by processing is crucial for successfully converting laboratory processes into a manufacturing process. A procedure with high deposition rate, low cost and a prospective for high conversion efficiency will make a good candidate for manufacturing purposes.

One of the greatest advantages in the fabrication of MIM diodes is that, there is no complex methodology involved with regard to the deposition technique. All the deposition methods are properly established for the development of MIM diodes. To assess processing options, it is necessary to understand the material and determine the critical properties needed in the thin film and other parts of the device structure. There are plenty of techniques and it is necessary to identify a process that would be feasible to be done in the laboratory and also capable of providing better results. Finally, the reproducibility and uniformity must be assessed and means for the controlled development of the process. Different deposition techniques for the MIM include E-beam lithography, E-beam evaporation, thermal evaporation, sputtering, Ion beam evaporation, anodic oxidation, plasma oxidation, thermal oxidation, STM Nano-oxidation are a few to
mention. In all cases, sufficient deposition rates have been demonstrated with controllable dielectric thickness. The basic steps involved in the fabrication of MIM diodes are explained below.

### 3.6.1 Photolithography

Photolithography is the process of transferring geometric shapes on a mask to the surface of a substrate. The steps involved in the photolithographic process are wafer cleaning, photoresist application, soft baking, mask alignment, exposure and development, and hard-baking.

- **Wafer Cleaning, and Photoresist Application:** The first step is to clean the wafers chemically to remove particulate matter like organic, ionic, and metallic impurities from the surface. After cleaning the wafer, the photoresist is applied to the surface of the wafer. The wafers are coated with resist by high speed centrifugal spinning. This technique is known as "Spin Coating", which produces a thin uniform layer of photoresist on the wafer surface. There are two types of photoresist: positive and negative. For positive resists, the resist is exposed to UV light wherever the underlying material is to be removed. In these resists, exposure to the UV light changes the chemical structure of the resist so that it becomes more soluble in the developer. The exposed resist is then washed away by the developer solution, leaving windows of the bare underlying material [17]. Negative resists behave in just the opposite manner. Exposure to the UV
light causes the negative resist to become polymerized, and more difficult to dissolve. Therefore, the negative resist remains on the surface wherever it is exposed, and the developer solution removes only the unexposed portions. Masks used for negative photo resists, therefore, contain the inverse (or photographic "negative") of the pattern to be transferred [17]

![Figure 3.6: Main Process in Photolithography [17]](image)

- **Soft-Baking**: Soft-baking is the step done after coating the wafer with the photo resist. Soft-baking is done to remove all the solvents from the resist
coating. Soft-baking plays a very critical role in photo-imaging. The photoresist coatings become photo-sensitive only after soft-baking. Over soft-baking will degrade the photosensitivity of resists by either reducing the developer solubility or actually destroying a portion of the sensitizer. Under soft-baking will prevent light from reaching the sensitizer [17].

- Mask Alignment and Exposure: One of the most important steps in the photolithography process is mask alignment. A mask is a square glass plate with a patterned emulsion of metal film on one side. The mask is aligned with the wafer, so that the pattern can be transferred onto the wafer surface. Each mask after the first one must be aligned to the previous pattern. Once the mask has been accurately aligned with the pattern on the wafer's surface, the photoresist is exposed through the pattern on the mask with a high intensity ultraviolet light. There are three primary exposure methods: contact, proximity, and projection. They are shown in the figure 3.6. In contact printing, the resist-coated wafer is brought into physical contact with the glass photo-mask. The photoresist is exposed with UV light while the wafer is in contact position with the mask. Because of the contact between the resist and mask, very high resolution is possible in contact printing. The problem with contact printing is that debris, trapped between the resist and the mask, can damage the mask and cause defects in the pattern [17].
Figure 3.7: Methods of Photolithography [17]

- Development: One of the last steps in the photolithographic process is development. After the wafer is exposed, the device is differentiated in the photoresist as regions of exposed and unexposed resist. The pattern is developed in the resist by the chemical dissolution of the un-polymerized resist regions. Problems resulting from poor developing process are either under-development, wherein the resist will be still sticking in the patterned areas or over-development, which removes too much resist from the pattern edge or top surface. Hence the resist development has to be properly timed to get a better pattern [17].

- Hard-Baking: Hard-baking is the final step in the photolithographic process. This step is necessary in order to harden the photoresist and improve adhesion of the photoresist to the wafer surface [17].
3.6.2 Metal and Metal Oxide Deposition

The depositions of metal and metal oxide are done in two ways. The metals can be deposited either by DC Sputtering or by E-beam evaporation. Sputtering is a high energy process, i.e., the deposition rate will be more uniform than the evaporation process. In the process of the MIM fabrication, sputtering was preferred as the mode of metal deposition due to its high level of consistency. For the deposition of the top electrode, E-beam evaporation was used, since the top electrode was not readily available as a sputter target. The metal oxidation can be carried out either by means of plasma oxidation or by exposing the metal deposited sample to air and allow it to form a native oxide.

3.6.2.1 Sputtering

The main application of sputtering is for the deposition of thin films. Sputtering is a physical vapor deposition (PVD) technique used for precision coatings of thin films in vacuum. In sputter deposition unlike other vacuum deposition processes, the material usually arrive in atomic or molecular form. The atom diffuses around the substrate with a motion determined by its binding energy to the substrate. Usually the atoms migrate and then re-evaporate and combine with other atoms to form nucleation sites. This in turn grows into an island. Eventually the islands grow large enough to touch; this is the agglomeration or coalescence stage. The coalescence proceeds until the film reaches continuity, this may not occur in some cases until the film is several hundred Angstroms in average thickness.
In the case of MIM diode, the film is about 150Å. The formation of thin films from islands of atoms is shown in figure 3.7.

Figure 3.8: Sequence of Steps Showing Thin-Film Deposition Process [20]
Figure 3.9: Top View of Sputtering Chamber

The set-up of a typical sputtering chamber is shown in figure 3.8. The substrate is placed in a vacuum chamber with a target of the material to be deposited. Plasma is generated in a passive source gas like Argon in the chamber, and the ion bombardment is directed towards the target, causing material to be sputtered off the target and condense on the chamber walls and the substrate. Sputtering can either be RF or DC. A strong magnetic field (magnetron) can be used to concentrate the plasma near the target to increase the deposition rate. The deposition rate depends on the pressure, gas flow rate, RF power, substrate temperature and target-substrate spacing. In our process, the sputtering system used is a home built system with two DC guns and one RF gun. It can handle a
maximum power of 500W and can run continuously for more than 3 hours. The metal deposition is carried out in DC power source. The metal target is pre-sputtered for a minute, with the desired power and set pressure. And then the gun shutter is opened for metal deposition to take place. With a quartz crystal monitor, the thickness of the deposited metal is calibrated. The substrate is kept at a distance of 10cm from the target and it is constantly rotated by a DC motor in order to get a uniform metal deposition. Thus the metal deposition is done using the sputtering system.

3.6.2.2 Metal-Oxide Deposition

- **In-Situ Oxidation:** In-Situ oxidation is one of the methods for depositing a thin oxide layer without exposing the material to the atmosphere. In-situ oxidation is the process, wherein the substrate is oxidized under vacuum conditions. This is done to prevent the coated film from getting contaminated with atmospheric particles and also reduces the formation of native metal oxide on the metallized surface. In this process, the substrate is coated with the metal. Then ultra high purity oxygen is allowed in to the deposition chamber with a controlled flow rate. Thus in-situ oxidation is performed.

- **Dirty Oxidation:** One other oxidation technique followed for the formation of metal oxide is through “dirty” oxidation. Dirty oxidation as its name is a dirty process. In this method, the deposited metal is exposed to the
atmosphere for 3 days and allowed to get oxidized through its native oxide growth. Since its kept exposed to the environment, there are chances of getting contaminants deposited on the metal film along with the metal-oxide. This process since has only native oxide growth has a thickness of only 3nm- 4nm, which is perfect for tunneling to occur in the MIM diode. This method was followed in the early development of the MIM, where point contacts were utilized for this effect.

- Dry Oxidation: A method in which only oxygen is used in the oxidation process is called dry-oxidation. If only oxygen is used, it must be free of any water vapor or the oxide growth would be that of water vapor. In this process the sample to be oxidized is kept in a tube furnace and oxygen is passed on the sample. This process can be carried out in atmosphere as well as higher temperatures. Dry oxygen oxidation process is the preferred method for growing very thin oxide layers. Usually dry oxidation gives a conformal formation of metal oxide on the sample.

- Plasma Oxidation: Radio frequency magnetron sputter deposition is widely used for the growth of insulators such as silicon oxide, aluminum oxide and other oxides where the substrate temperature limits preclude other techniques, or where compositional control is easier to achieve than for alternate methods and the films or targets are insulating. The plasma is initiated between the cathode and the anode at pressures in the milli-Torr range by the application of high voltage. The plasma is sustained by the
ionization caused by secondary electrons emitted from the cathode due to ion bombardment which are accelerated into the plasma across the cathode sheath. RF sputtering of insulators yields much more conformal deposition of dielectrics than by dirty oxidation. Unlike the dry oxidation method, it is known that, through RF sputtering of the target; only that particular dielectric is deposited than any other compounds. And through this method, the thickness of the dielectric that has been deposited on the metal is known, which is not possible through any of the other processes [18].

3.6.2.3 E-Beam Evaporation

Vacuum evaporation is used for the deposition of metals on discrete devices. E-beam evaporation is one such vacuum deposition process. The need for evaporation control and low contamination led to the development of electron beam evaporation. E-beam evaporation is the process where in the electron beam is used to melt the metal target and which in turn is evaporated onto the sample. This evaporation source consists of a wafer cooled copper crucible with a center cavity to hold the metal source. At the side of the crucible is a high-temperature filament. A high current is passed through the filament, which, in turn, boils off the electrons. The negative electrons are bent $180^\circ$ by a magnet so that the electron beam strikes the center of the charge in the cavity. The high-energy electrons create a pool of liquid metal in the center of the charge. The metal evaporates from the pool into the chamber and deposits on the wafers in
the holders at the top of the chamber. The water cooling mechanism maintains
the outer edges of the charges in solid state, thus preventing contaminants from
the graphite crucible from evaporating. E-beam evaporation is relatively
controlled for an elemental source.

E-beam evaporation takes place inside an evacuated chamber. The chamber is a
stainless steel enclosure inside which there is a mechanism to evaporate the
metal, wafer holder, and thickness monitors and pressure sensors are present.
The chamber is connected to a turbo vacuum pump, which evacuates the
chamber. The foremost reason or requirement for the process to be carried in
vacuum is to maintain uniform coating. When the pressure is sufficiently reduced,
the mean free path of the coating atoms is increased to exceed the dimensions
of the chamber. This ensures that the depositing atoms will strike the wafers
before hitting each other causing non-uniform depositions.

Film thickness is controlled by shutters and by rate and thickness monitors. A
closed shutter in the path of the evaporating materials allows the evaporation to
reach a steady rate before depositing on the wafers. The shutter also allows
rapid shutoff of the deposition. In-chamber monitors located near or above the
wafer holders, feed back information to the E-gun power supply which controls
the evaporation rate. Rate control is important for consistent and uniform film
structure [21].
3.6.3 Lift-Off Technique

“Lift-off” is a simple, easy method for patterning films that are deposited on the substrate. A pattern is defined on a substrate by coating a photoresist using photolithography technique. A film, usually metallic, is blanket-deposited all over the substrate, covering the photoresist and areas in which the photoresist has been cleared. During the actual lifting-off, the photoresist under the film is removed with solvent, usually acetone, taking the film with it, and leaving only the film which was deposited directly on the substrate.

Any deposited film can be lifted-off, provided:

- During film deposition, the substrate does not reach temperatures high enough to burn the photoresist.
• The film quality is not absolutely critical. Photoresist will outgas very slightly in vacuum systems, which may adversely affect the quality of the deposited film.
• Adhesion of the deposited film on the substrate is very good.
• The film can be easily wetted by the solvent.
• The film is thin enough and/or grainy enough to allow solvent to seep underneath.
• The film is not elastic and is thin and/or brittle enough to tear along adhesion lines.

Lift-off can be accomplished by immersing in acetone. The length of time for lift-off will depend on the film quality (generally, the higher the film quality, the more impermeable it is and the longer it will take to lift-off.) Depending on how robust the film and substrate are, sidewalls from deposited film can be removed using a gentle swipe of a clean-room swab or a directed stream of acetone from a squeeze bottle. As a rule, keep the substrate immersed in acetone until all the film has been lifted-off and there are no traces of film particulates -- once particles dry on the substrate, they are notoriously difficult to remove [22].
CHAPTER 4

DEVICE TESTING AND RESULTS

4.1 Introduction

In the previous chapter, the methods involved in the fabrication of MIM tunnel diodes were described. This chapter discusses the actual device processing procedures, the steps carried out in manufacturing the diode, the characteristics studies made for the best suited parameter for depositing the thin film insulator. The measurement techniques used to obtain the desired I-V characteristic curve of the MIM diode and the test bed that is set-up for measuring the device are also described.

4.2 Device Processing

The MIM fabrication process discussed here is based on all the standard techniques of fabrication. The MIM diode was fabricated using in-house resources as much as possible. The step by step process flow is described in the Appendix section. The substrate on which the MIM diode is fabricated is a Borosilicate Pyrex 7740 Glass, which is optically flat and smooth on both sides. The reason for using a glass substrate is that it’s a transparent material. Yet another reason is that, if Silicon is used, it needs to oxidize to form SiO₂ before the metals could be deposited. This is done to prevent shorting out of metals with
the substrate. All of the above mentioned steps can be avoided if a glass substrate is used. With the above mentioned substrate, the rest of the process is build upon to fabricate the MIM diode. The individual steps involved in the processing are described below.

4.2.1 Photolithography

Since glass is being used as the substrate material for the MIM deposition, it needs to be cleaned before any patterning is done. To clean the surface of the substrate, the glass is dipped in 50:1 HF for 20 sec. This is done to ensure that the resist sticks to the glass wafer. For all the photolithography steps involved in the fabrication of the MIM diode, 3000PY photoresist was spun on the glass wafer. 3000PY is a negative resist, which yields a resist thickness of 3.3µm at a spin speed of 3000 rpm for a spin time of 40 sec. The spinner used was P-6000 Spin Coater, Model P 6204. Before spinning the resist, a dehydration bake at 100°C for 2 min on an oven was done. This further helps the resist to stick better onto the wafer surface by removing any residual moisture present. After the dehydration bake, the wafer was allowed to cool for 1-5mins before spinning on the resist.

After spinning, the resist was soft-baked on a hot plate at 155°C for 60 sec and thereafter was cooled before exposing. The bottom electrode layer patterns were transferred to the resist-coated wafer using a Quintel contact aligner with an exposure time of 18 sec. In any photolithography steps, the exposure time and
the developing time are critical. After exposure the wafers were hard-baked on a hot plate at 110°C for 60 sec. Then the wafers were developed in RD-6 developer for 25 sec and examined under an optical microscope for pattern verification. The resulting pattern is shown in Figure 4.1. The mask with the metal1 layer comprises the alignment marks to which all the successive masks are aligned.

The same lithography process step is followed while patterning other layers on the base metal pattern layer. As mentioned above, with the alignment marks that are already on the substrate, the successive layers are matched and aligned to be in line. Without the alignment markers it would be very difficult to move around the whole mask or the wafer to get the next layer aligned.

![Figure 4.1: Metal1 Layer Photo-resist Pattern after Developing and before Metal Deposition. The Lighter Region is Photo-resist and Darker Region is Glass Wafer](image)
4.2.2 Metal-Insulator-Metal Deposition

The materials used in the MIM structure are Al-Al$_2$O$_3$-Cr/Au. Aluminum is used as the bottom electrode with aluminum oxide as the dielectric layer and Gold is supposedly as the top electrode. Since Gold does not adhere well with Al$_2$O$_3$, Chromium (Cr) is used as the adhesion promoter. Since Al$_2$O$_3$ is in contact with Cr the final MIM structure is Al-Al$_2$O$_3$-Cr. Aluminum is deposited in a sputtering chamber for a thickness of 100nm, using a DC magnetron sputter at 120W power and 30mTorr working pressure. On top of the Aluminum layer, the insulator is deposited as a thin layer. The dielectric layer is deposited by two methods;

- By flowing ultra high purity oxygen in the sputtering chamber while the aluminum metal is deposited at much lower power of about 30W, causing the film to get plasma oxidized.

- By sputtering a thin layer of Al$_2$O$_3$ using a ceramic alumina target at a lower power of 30-40W and a pressure of 30mTorr or lower.

Aluminum gets oxidized very quickly when exposed to atmospheric conditions, i.e., by breaking the vacuum. Hence the process of Aluminum and aluminum oxide deposition is carried out one after another inside the deposition chamber without exposing the sample to air. This prevents the contamination of Aluminum base layer and also avoids the formation of a native oxide. The same procedure was followed for the deposition of the insulator through an Alumina target.
4.3 Optimization of the Fabrication Process

There were several issues that need to be highlighted here during the process of fabricating the MIM diode. The problems faced in the processing steps and the counter measures taken to avoid those problems are addressed here in this section. The process flow on the development of the MIM diode with the fabrication flaws and the way to avoid these problems are described.

Initially for the fabrication of MIM diodes, the metals chosen were Chromium and Gold. The aforementioned metals were deposited on a glass substrate by an E-beam evaporation process. The insulator used was Silicon Mono-oxide, which was readily available as an evaporating target. Since Chromium oxidizes readily on exposure to air, the silicon mono-oxide did not stick to the surface forming agglomerations. This also resulted in two insulators on metal layer forming M-I-I-M diode. Figure 4.2 is the AFM image of this sample. The samples shows significant hillock due to agglomeration and some of the hillocks are greater than the reliability thickness of the dielectric.
Figure 4.2: AFM Images Showing Agglomeration Sites
The solution to this problem was,

- To use a material that will not oxidize readily to air.
- Use sputtering to deposit metal, since sputtering is a high energy process, which will provide more uniform metal deposition.

Since Gadolinium and silicon nitride were readily available as sputtering target, they were used as the bottom electrode and the dielectric layer with gold as the top electrode. In this process, the metal was sputter-deposited, followed by nitride deposition. Since the dielectric deposition was in the range of a few nanometers, a selective etching could not be done. Nitride etch back turned out to be difficult to control in wet etching because of its small thickness. Additionally, Gadolinium was attacked by the nitride etchant. The etch rate was so high and resulted in etching away the metal and the glass. Nitride etchant is very powerful and the etch time was hard to measure because the thickness of the nitride was only a few nanometers. A feasible solution is to do nitride lift-off rather than going for etch back.

Based on previous results, Gadolinium and Silicon Nitride were patterned individually and sputtered on the glass substrate. Then the metal-oxide was lifted-off. Later the top electrode was patterned and gold deposition was applied through E-beam evaporation. The original idea was to wire-bond from top electrode to an external contact pad. Since, the adhesion was not good enough to bond the wire on top of the gold electrode, the external contacts could not be
connected for testing the device. Hence, another design was considered, which
would not require wire-bonding and still be able to allow diode testing. The
description of this design was already presented in section 3.3 of this chapter.

At this point, based on literature search, it was described to use metal-oxides as
the dielectric layer to be used in the MIM device. This way as the bottom
electrode is deposited, the metal-oxide is also formed. Hence a set-up is
arranged to apply in-situ oxidation of the metal by passing ultra high purity
oxygen in the sputtering chamber for a set period of time at a particular pressure.
This aids in the formation of the metal oxide as the dielectric layer.

Now a metal and easily forming metal-oxide materials were chosen. Aluminum
was selected as the bottom electrode with Aluminum oxide as the dielectric layer
and gold as the top electrode. Aluminum readily forms its native oxide when
exposed to atmosphere. Henceforth, the substrate is patterned for aluminum
deposition and the target is sputtered on the substrate followed by aluminum
oxide deposition. This is done by controlling the oxygen flow in the chamber to
form a uniform metal-oxide deposition. However, the composition of the
deposited Aluminum Oxide was difficult to establish. To resolve this issue, a
ceramic Al$_2$O$_3$ sputtering target was used. The sputtering of the dielectric layer
was done using this target with additional flow of oxygen to make sure the
composition of Al$_2$O$_3$ is preserved.
In order to get an approximate value of the thickness of the insulator region, some dummy wafers were introduced in the sputtering chamber and aluminum oxide was deposited on the wafers by changing the deposition time and the gas flow ratio of argon and oxygen at a particular power under constant pressure. By carrying out this experiment we were able to observe the characteristic changes and identify the best parameter suited for the thin-film deposition.

The characteristic changes like dielectric thickness and surface analysis were studied using Null point ellipsometry, Rutherford Backscattering Spectroscopy, and Atomic Force Microscopy. Table 4.1 shows the thickness variation. The AFM image of the dielectric layer is also shown in Figure 4.3, 4.4, and 4.5.

**Table 4.1: Surface Analysis Using Various Metrology Tools**

<table>
<thead>
<tr>
<th>Gas Ratio (Ar: O₂)</th>
<th>Time (mins)</th>
<th>Ellipsometry (Å)</th>
<th>RBS (Å)</th>
<th>AFM roughness analysis (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar only</td>
<td>20</td>
<td>30 – 32</td>
<td>34±4</td>
<td>1.2</td>
</tr>
<tr>
<td>1:1</td>
<td>20</td>
<td>28 – 30</td>
<td>23</td>
<td>2.2</td>
</tr>
<tr>
<td>2:1</td>
<td>20</td>
<td>18 – 22</td>
<td>22</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Figure 4.3: Aluminum Oxide Sputter-Deposited with 1:1 (Ar:O₂) Gas Ratio
Figure 4.4: Aluminum Oxide Sputter-Deposited with 2:1 (Ar:O₂) Gas Ratio
Figure 4.5: Aluminum Oxide Sputter-Deposited only with Argon
Based on the previous experiments, 2:1 (Ar:O\textsubscript{2}) gas ratio was selected and the dielectric was deposited on the metal surface. This substrate was kept for lift-off in a beaker with Acetone. Once the unwanted metal peels off from the surface of the wafer, it is dipped in an ultrasonic bath for some additional particulate removal. Then the wafer is cleaned and dried. Now the wafer with Aluminum and Aluminum Oxide is taken to the lithography step in order to pattern for the top metal layer. The same lithography steps are followed throughout the process.

The top metal layer deposited was pure Chromium, which has a work function of about 4.5eV. The patterned wafer with the metal and insulator were introduced into the E-Beam Evaporation chamber. A thin layer (30nm) of chromium is deposited on the substrate topped with a thick layer (200nm) of gold. The metal deposition was applied at a pressure of 10\textsuperscript{-7}Torr. After the deposition of Chromium and gold on the wafer, the same lift-off procedure was followed until the unwanted gold peeled off from the substrate.

Thus a Metal-Insulator-Metal structure was obtained by following the above procedure. Figure 4.6 shows the MIM structure after the completion of all fabrication process. In order to make sure that the insulator is deposited uniformly over the bottom electrode, a sample deposited with Aluminum, aluminum oxide and gold was cross sectioned using Focused Ion Beam and placed in a TEM grid to view the cross section of the tri-layer structure.
The TEM image in figure 4.7 shows the cross section of the substrate, a thin layer of Aluminum and Aluminum oxide and Chromium, topped by a thick gold layer. The black area is the region where thick layer of gold is deposited. The reason the edges of the gold are tapered is due to the deposition and lift-off technique. When the metal is deposited on the wafer with patterned resist on it, it tends to deposit a lesser quantity because of the high aspect ratio of the side-walls. Later the metal was deposited uniformly over the surface. Figure 4.7(c) shows a clear picture of the layers formed. Figure 4.7(d) is a closely zoomed in image which shows the three layers with clear demarcation between the layers. The tri-layer image that is seen in the image is Aluminum, Chromium and Gold. In between the Aluminum and chromium lies the thin layer of oxide. Since the
deposition of Aluminum Oxide is very thin, the TEM needs to be resolved more to get a clear view of the insulator layer.

Figure 4.7: Cross-Sectional TEM Analysis of MIM
4.4 Theoretical Calculations and I-V Characteristics

Figure 4.8: Potential Barrier between Dissimilar Electrodes

When a thin insulating region is sandwiched between two electrodes with different work functions, there exists a large intrinsic field. The field $F_i$ within the insulator, which arises because of the contact potential difference between the two electrodes, is given by

$$F_i = \frac{(\psi_2 - \psi_1)}{es},$$

where $s$ is the thickness of the insulating layer, $\psi_1$ and $\psi_2$ are the work functions of the metals and $e$ is the electronic charge which is assumed to be unity. The
effect of $F_i$ is to produce an asymmetrical potential barrier between the two electrodes as shown in figure 4.8. The intrinsic fields are significant in tunnel diodes where the insulator is very thin (<100Å). In our MIM junction, in which the insulator film is ~25Å thick and the work functions are $\psi_1 = 4.2\text{eV}$ and $\psi_2 = 4.5\text{eV}$. Therefore, the intrinsic field is calculated to be,

$$F_i = (0.3 \times 10^8)/25 = 1.2 \times 10^6 \text{V/cm}$$

And, the breakdown voltage of the device is calculated to be the difference of the breakdown voltage $V_1 - V_2$ in terms of the work functions of the electrodes.

$$\Delta V = 2(\psi_2 - \psi_1)/e$$

$$= 2(0.3) = 0.6\text{V}$$

Thus the breakdown voltage of the MIM diode is calculated as 0.6V. Therefore, the voltage sweep during the measurement of I-V characteristics should be kept within the above evaluated range to operate the device in safe mode. A knowledge of the difference in work function of the electrodes facilitates the computation of the difference in barrier height at the metal-insulator interfaces for

$$\Phi_2 = \Phi_1 + (\psi_2 - \psi_1).$$

The barrier height at the Al and Al$_2$O$_3$ interface is found to be 1.8eV according to previous work done. Based on that, the barrier height of Au and Al$_2$O$_3$ interface is found to be 2.6eV. [24]
4.4.1 Frequency and Capacitance Calculations

The operating frequency of the designed and fabricated MIM Diode can be calculated using the formulae presented in chapter 2. The cut-off frequency of the device is given by the following equation,

\[ f_c = \frac{1}{2 \pi R_a C_d} \]

Where, \( R_a \) and \( C_d \) are the input resistance of the antenna and capacitance of the device, respectively. In order to evaluate the cut-off frequency, the capacitance of the device needs to be calculated. The capacitance of the diode is obtained from,

\[ C_d = \frac{\varepsilon_o \varepsilon_r A}{d} \]

where, \( \varepsilon_r \) and \( \varepsilon_o \) are the dielectric constant of the aluminum oxide and permittivity of free space, \( A \) is the contact area of the MIM diode and \( d \) is the thickness of the
dielectric. From the above equations the capacitance and hence the cut-off frequency keeping the input resistance as 50Ω are calculated to be 160pF and 20MHz.

4.5 Measurement set-up

A MIM device has a significant capacitance inherent in its device structure. The capacitance associated with the MIM devices causes a considerable amount of noise in the current measurement. The capacitance can be reduced by increasing the thickness of the metal-oxide layer, or by reducing the contact area.

Figure 4.10: Test Set-up for Measuring MIM Diode
The test bed that was set-up to measure the I-V characteristics of the fabricated MIM tunnel diode is shown in Figure 4.8. The test bed includes a voltage supply and current measurement unit, which is automated through a software program. A GPIB interface with the computer stores the recorded data in a spreadsheet which also plots the data. The automation software used is called LabTracer™ from Keithley instruments. The source meter used is Model 2400 from Keithley instruments, which can vary the voltage from ±5µV to ±200V and can measure current from ±10pA to ±1A. The source measurement unit is connected to a shielded probe station. The whole set-up is kept near a shielded probe station and the measurements were taken so that any noise interference affecting the device was avoided. This way a test bed was set-up in which the device testing is done.

4.6 Device Testing

The diode current versus voltage characteristic curve of the MIM diode was measured using the aforementioned Keithley 2400 Source meter Unit (SMU). The electrical characteristics were measured under a two-terminal arrangement. The measurements were taken in forward and also reverse biased conditions and also reversing the polarity of the supply.

Based on the literature search, it was known that the voltage sweep range has to be kept low in the values of few milli-volts to a Volt in order to get a proper I-V
characteristic. With these known conditions and set-up, the diodes were measured.

Since the breakdown voltage of the fabricated device was theoretically calculated to be 0.6V, the sweep voltage was maintained within this range. The DC probes used to make measurements are Titanium coated tips with 1µm diameter. The probes are kept at a 45º angle to prevent the device from penetrating through the metal accidentally. The probes are lowered very slowly, so that the probe making contact with the top electrode is just in contact and the second probe on the bottom electrode is scraped a bit to ensure proper contact with the aluminum.

Initially the voltage was swept from 0 to 100mV with steps of 10 mV and then slowly the voltage source was increased to 500mV increasing the steps to 50mV and then to 1V with a step size of 100mV. At every instance/step the current was measured by the source meter unit and it was stored either locally or in a computer. The stored value could be recalled and then plotted to observe the I-V characteristics.

By the time the measurements were done, the SMU was not interfaced with the computer. Hence the unit was not automated to retrieve the data points to a computer. Instead, the output current was stored in a local memory of the SMU, which could be recalled instantly after one set of measurements. Since the data points had to be collected manually, the I-V curves of the measured MIM diodes
were plotted manually in a spreadsheet and this data is presented in the next section.

4.7 Experimental Results and Discussion

The MIM’s were characterized and tested using Keithley 2400 Source Meter Unit (SMU). The MIM diodes were characterized to check for characteristic curves as mentioned in the earlier section. For this work, the testing and characterization is still in progress. As a result only a few devices were tested by the time this thesis was written.

A Keithley 2400-SMU in series with a micromanipulator probe station, was used for studying the behavior of the fabricated devices. For preliminary characterization selected devices on the wafer were tested by sweeping the voltage. Data from each sample was recorded manually and plotted in a spreadsheet as part of a device performance database.
Figure 4.11: Al-Positive Bias and Cr- Negative Bias
Figure 4.11
Figure 4.11
Figure 4.12: Al-Negative Bias and Cr- Positive Bias
Figure 4.13: I-V Characteristics of Al/Al₂O₃/Cr MIM Diode Showing Slight Linearity

Figure 4.14: I-V Characteristics of Al/Al₂O₃/Cr MIM Diode Showing Linear Curve
Figure 4.11, 4.12, 4.13, 4.14 shows measured I-V characteristics of an Al- Al$_2$O$_3$-Cr diode for both directions of bias voltage taken in the shielded probe station and measured in high accuracy range. In Figure 4.11, aluminum is supplied a positive voltage. In Figure 4.12, Chromium is supplied with a positive bias and aluminum is supplied with negative bias. The current when the Al layer was positively biased is larger than that when Cr layer is positively biased. The yield on the device was more than 70%. The yield was estimated from the I-V curves resulted by testing all the diodes in the wafer. Some the devices gave a linear output (Figure 4.14) and a couple of the devices showed symmetric behavior. This variance was on random devices and not on a particular area. The reason for the linearity might be due to the top metal penetrating through the insulator and shorting with the bottom electrode. Hence care should be taken when placing the probes on the metal pads.

Typical features of the I-V characteristics were as follows a) for small voltage (v<0.1V), the current is proportional to the applied voltage, b) for medium voltage (0.1 -0.5V) the current increases exponentially, and c) for higher voltages (0.5 – 2V) the current increases rapidly and breaks-down at 1.9V. These were the characteristics noted during the time this thesis was written. Some more studies like evaluating the barrier height of the interfaces can be studied for further analysis and modeling of the diode.

According to Gundlach and Hölzl, the logarithmic derivative of the tunneling current with respect to the applied voltage exhibits a tunneling characteristic. This
behavior is due to the voltage dependence of the tunneling length of the MIM junction. Since the shape of $d \ln I/ dV$ vs. $V$ curve is unique for the tunneling current in MIM junctions, the observation of such a curve in an actual MIM diode indicates that the measured current is, at least predominantly, due to electron tunneling.

The plot of log derivative of current vs. bias voltage is given in figure 4.15. From the plots it can be concluded that the peaks occurring are the tunneling phenomenon which is typical to observe. These plots were not drawn for all the devices, which is yet to be done, since the characterization is still in progress.

![Figure 4.15: $d \ln I/ dV$ vs. V Characteristics of Al/Al$_2$O$_3$/Au Junction](image-url)
Thus the design, fabrication and testing modules were put together after a series of production steps for final fabrication and measurement of MIM diodes.

4.8 Summary

Design and fabrication of a MIM diode with thin-film insulator was successfully completed in house, utilizing the resources available at USF as much as possible. The wafers were sent out to Advanced Material Processing and Analysis Center (AMPAC), University of Central Florida for determining the thickness of the insulator through Rutherford Backscattering Spectroscopy (RBS) and to determine the uniformity of the deposited insulator through TEM analysis. The whole fabrication process was done in the NNRC clean room and MEM’s Laboratory. There were some errors encountered while fabricating the device, such as deposition of metal and dielectric, and etch back issues. These problems were overcome by further probing in processing techniques.

There was some erroneous data measured initially, due to the fact that there was no proper set-up for measuring the I-V characteristics of the MIM diode. These flawed data were obtained by the usage of following equipments. Initially, the device was tested in a micromanipulator probe station which was connected to HP4145B parametric analyzer. No desired output was produced.

It was concluded after the initial characterization to make a new device, since the device might have been shorted. A new device was tested with a different measurement unit using the same probe station. This also did not yield a
favorable output. Later, by testing a commercially available schottky diode, it was found that the probe station was faulty. The output obtained is shown in Figure 4.16.

![Figure 4.16: I-V Curve Measured in a Flawed Probe Station](image)

The devices were then tested in a home made probe station set-up connected to a Keithley 4200 Semiconductor Characterization System. These measurements were made at Modelithics, Inc. Since the measurements were taken at a company, it was hard to measure the device regularly, but it resulted in some satisfying graphs, an example is produced here in Figure 4.17.
No significant conclusion can be drawn from the characterization results obtained, since other calculations and evaluations were not complete at the time this thesis was written. The main concern after testing these devices is the non-repeatability of the device DC behavior. Further fabrication and characterization has to be done to determine a good working device to be used with the antenna for energy conversion.
5.1 Conclusion

In this work, the design, fabrication and characterization of MIM tunnel diodes were presented. The development of thin-film metal oxide layers and their preliminary I-V characteristic performance were reported. Based on literature search, a design of the MIM diode was made and a photolithographic mask set for the proposed design was procured. The process developed was based on the available resources to fabricate the device in house. The devices were fabricated and characterized utilizing the resources within the MEMS Lab and NNRC at USF as much as possible. The MIM diodes were fabricated on a glass substrate and the processing details were presented. The breakdown voltage of the MIM diode with thin film insulator thus fabricated was theoretically calculated and was observed experimentally. By the time of this thesis writing only a few devices were tested due to time constraints. From the preliminary measurements, the required non-linearity and a symmetry were observed with 50% of the devices yielding the same characteristic curve. Characterization of the MIM diodes is still continuing and should be completed by the end of summer 2004.
5.2 Future Work

In the future, thin-film MIM diodes may be fabricated in-house with the help of the already procured masks and also with some optimization with scaling down the feature size of the contact area. The frequency of operation of the currently developed MIM diode calculated theoretically is much lower than what we need for the solar rectification. The MIM diode was fabricated to operate in the lower MHz range. In order to increase the operating frequency, the lithography techniques need to be changed that is capable of patterning in the sub-micron range. Lithography techniques like E-Beam lithography or direct patterning using Atomic Force Microscopy can be utilized to obtain smaller feature sizes. Since the process parameter has been established and characterized in this work, the same can be carried out for fabricating thin-film diodes over a smaller region of operation.

The preliminary data obtained can also be improved and further studies on the characteristics curve can be done in the future. Some of the characterization works that need to be carried out after the I-V measurements are listed below,

- Determining the barrier height and hence the tunneling current.
- Experimental evaluation of the operating frequency.
- Measurement of the impedance and hence the capacitance of the diode.
Thus the work can be concluded as a process, through which thin film insulators can be deposited reproducibly and uniformly. Once the device is optimized to operate at higher frequency ranges, then it can be modeled and incorporated as a rectifier in the rectenna.
REFERENCES


[4] Efficiency of Antenna Solar Collection, Richard Corkish, Martin A. Green, Tom Puzzer and Tammy Humphrey, Centre of Excellence for Advanced Silicon Photovoltaics and Photonics, University of New South Wales, Sydney, Australia.


APPENDICES
### Table A.1: Process Flow for Fabrication of MIM Diode

<table>
<thead>
<tr>
<th>Step</th>
<th>Process</th>
<th>Description</th>
<th>Process Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Wafer Clean and surface roughing</td>
<td><em>Organic clean: Solvent Bench</em>&lt;br&gt;Acetone, IPA, DI</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wet Bench&lt;br&gt;DI:HF dip</td>
<td>50:1 for 25 sec&lt;br&gt;1 cycle rinse</td>
</tr>
<tr>
<td>2.</td>
<td>Mask1 (Metal layer1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Photolithography</td>
<td><em>Dehydration Bake: Oven</em>&lt;br&gt;Spin Coat: Spinner Model P 6204&lt;br&gt;Futurrex 3000 PY&lt;br&gt;<em>Soft Bake: Hot Plate</em>&lt;br&gt;<em>Expose Pattern: Quintel</em></td>
<td>T= 110°C for 5 min&lt;br&gt;Spin Speed - 3000rpm&lt;br&gt;Spin Time - 40 sec&lt;br&gt;Spin coat negative resist&lt;br&gt;T=155°C for 60 sec&lt;br&gt;17 sec exposure to UV</td>
</tr>
<tr>
<td>Process</td>
<td>Details</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>---------</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hard Bake:</strong> Hot Plate</td>
<td>( T = 110^\circ C ) for 60 sec</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Develop:</strong> Solvent Bench</td>
<td>Immersion developing @ room temp for 25 sec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RD6 Developer</td>
<td>Nitrogen blow dry wafer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DI, ( N_2 ) dry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pattern check: Optical Microscope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Metal deposition</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sputtering:</strong> DC magnetron</td>
<td>Power: 120 Watts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sputtering</td>
<td>Deposition time: 20 mins</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum Deposition</td>
<td>Pressure: 34 mTorr</td>
<td></td>
<td></td>
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<tr>
<td><strong>Oxide deposition</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Insulator sputtering:</strong></td>
<td>Power: 40 Watts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Al_2O_3 ) sputtering in the presence of oxygen flow</td>
<td>Deposition time: 20 mins</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pressure: 36 mTorr</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gas Ratio 2:1 (Argon: Oxygen)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table A.1: (Continued)

<table>
<thead>
<tr>
<th>Step</th>
<th>Process Details</th>
</tr>
</thead>
</table>
| Lift-Off | *Lift-off and Ultrasonic clean*  
Acetone, Methanol, DI  
N$_2$ Dry  
Immerse wafer in Acetone till all metals lifts off  
Lift-off aided with ultrasonic bath  
Rinse in Methanol  
Rinse in DI Water |
| 3. | *Mask2 (Metal layer2)* |
| Photolithography | *Dehydration Bake: Oven*  
T = 110°C for 5 min  
*Spin Coat: Spinner Model P 6204*  
Futurrex 3000 PY  
Spin Speed - 3000rpm  
Spin Time - 40 sec  
Spin coat negative resist |
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soft Bake</strong></td>
<td><strong>Hot Plate</strong></td>
</tr>
<tr>
<td></td>
<td><em>T</em>=155°C for 60 sec</td>
</tr>
<tr>
<td><strong>Expose Pattern</strong></td>
<td><strong>Quintel</strong></td>
</tr>
<tr>
<td></td>
<td>17 sec exposure to UV</td>
</tr>
<tr>
<td><strong>Hard Bake</strong></td>
<td><strong>Hot Plate</strong></td>
</tr>
<tr>
<td></td>
<td><em>T</em>=110°C for 60 sec</td>
</tr>
<tr>
<td><strong>Develop</strong></td>
<td><strong>Solvent Bench</strong></td>
</tr>
<tr>
<td></td>
<td>RD6 Developer</td>
</tr>
<tr>
<td></td>
<td>DI, N₂ dry</td>
</tr>
<tr>
<td></td>
<td>Immersion developing @room temp for 25 sec</td>
</tr>
<tr>
<td></td>
<td>Nitrogen blow dry wafer</td>
</tr>
<tr>
<td><strong>Pattern check</strong></td>
<td><strong>Optical Microscope</strong></td>
</tr>
</tbody>
</table>

Table A.1: (Continued)
| Metal deposition | Chromium Evaporation: Electron Beam Evaporation | Pressure: 30µTorr  
Current: 0.26 A  
Deposition rate: 2.2Å/sec |
|------------------|-----------------------------------------------|--------------------------------------------------|
| Lift-Off         | Lift-off and Ultrasonic clean                 | Immerse wafer in Acetone till all metals lifts off  
Lift-off aided with ultrasonic bath  
Rinse in Acetone, Methanol  
Rinse in DI Water |
|                  | Acetone, Methanol, DI                         |                                                  |
|                  | N₂ Dry                                        |                                                  |