Nano Antenna Integrated Diode (Rectenna) For Infrared Energy Harvesting

Thesis by

Mena Nasef Gadalla

In Partial Fulfillment of the Requirements for the Degree of
Master of Science

King Abdullah University of Science and Technology
Computer, Electrical, and Mathematical Sciences and Engineering Division
Electrical Engineering – Electromagnetics and photonics

Thuwal, Makkah Province, Kingdom of Saudi Arabia

January, 2013
The dissertation/thesis of Mena Nasef Gadalla is approved by the examination committee.

Committee Chairperson: Dr. Atif Shamim
Committee Member: Dr. Andrea Fratalocchi
Committee Member: Dr. Boon. Ooi
ACKNOWLEDGMENTS

Firstly I want to dedicate this thesis work to the soul of my father Dr. Nassif Massoud Gadalla, I wish I could thank him for all of his support and guidance along the years till his honorable departure on 07/01/2011.

My sincere gratitude to my mother Dr. Isis Kamel for her limitless emotional and financial support and for her unflagging love throughout my life; this thesis work and Masters degree would have been impossible without her.

I would also like to express my heartiest thanks to my sisters Dr. Nermine and Dr. Mary Gadalla how are by far my best friends. I am also thankful for my brothers in law Dr. Marco Anton and Eng. Maged Nakhla, who never fails to pick me up from the airport every time I go to Egypt.

I would like to express the deepest appreciation to my supervisor, Dr. Atif Shamim, for all the knowledge, encouragement and editing assistance. Also for providing a perfect research environment and motivating spirit. He is not only an extraordinary academic advisor but also a perfect leader.

Especial thanks to Dr. Mohamed Rami Abdelrhman for his co-supervision and the provided laboratory training. In addition to his continuous technical help. Dr. Abdelrhman is genuinely very caring professor with an extremely friendly personality.

Last but not least, thanks be to God for my life through all tests in the past two years. Leading me through a studying journey starting from Egypt, going through USA and finally in Saudi Arabia. May his name be exalted, honored and glorified.

"This work was performed in part at the Electro-Optics Lab, Prince Sultan Advanced Technologies Research Institute (PSATRI), King Saud University".
TABLE OF CONTENTS

ACKNOWLEDGMENTS .................................................................................................................. 3
TABLE OF CONTENTS .................................................................................................................. 4
ABSTRACT ........................................................................................................................................ 11
1. INTRODUCTION ...................................................................................................................... 13
   1.1 RENEWABLE VS. NON-RENEWABLE ENERGY RESOURCES ........................................... 13
   1.2 MOTIVATIONS ..................................................................................................................... 14
       1.2.1 SOLAR ENERGY AND SOLAR SPECTRUM ............................................................... 14
       1.2.2 SOLAR CELLS DISADVANTAGES ........................................................................... 15
   1.3 PROPOSED IR ENERGY HARVESTING TECHNIQUE ......................................................... 15
       1.3.1 RECTENNA ............................................................................................................... 16
   1.4 OBJECTIVES ....................................................................................................................... 18
   1.5 Challenges ......................................................................................................................... 18
   1.6 CONTRIBUTIONS ............................................................................................................... 19
   1.7 THESIS ORGANIZATION .................................................................................................. 20
2. REVIEW OF LITERATURE ......................................................................................................... 21
   2.1 RECTENNA HISTORY ........................................................................................................ 21
   2.2 MICROWAVE RECTENNA ................................................................................................. 24
   2.3 OPTICAL NANO ANTENNAS (VISIBLE AND NEAR-INFRARED) ...................................... 25
   2.4 28.3 THZ ANTENNAS ....................................................................................................... 30
   2.5 SUMMARY OF OPTICAL NANO ANTENNAS .................................................................. 31
   2.6 MIM DIODE ....................................................................................................................... 32
   2.7 SUMMARY OF PREVIOUSLY PUBLISHED MIM ............................................................... 38
   2.8 10.6μm ANTENNA INTEGRATED DIODE ......................................................................... 39
3. THEORY AND DESIGN OF PLASMONIC NANO ANTENNAS ................................................... 42
   3.1 ANSOFT HFSS .................................................................................................................... 42
   3.2 OPTICAL PROPERTIES OF METALS .............................................................................. 46
       3.2.1 DRUDE MODEL ........................................................................................................... 46
       3.2.2 COMPLEX REFRACTIVE INDEX .............................................................................. 50
       3.2.3 METAL REFLECTIVITY AND FREE CARRIERS CONDUCTIVITY ......................... 51
# TABLE OF FIGURES

Figure 1.2-1: Solar Energy Spectrum [6]........................................................................................................14

Figure 1.3-1: Black body radiation at 287 K [9]. ..........................................................................................16

Figure 1.3-2: rectenna equivalent circuit [11]. .........................................................................................17

Figure 1.3-3: rectenna versus solar cells.....................................................................................................18

Figure 2.1-1: William C. Brown demonstrating the First rectenna powered vehicle [12]. ...................22

Figure 2.1-2: Brown’s space vehicle rectenna [13]. ..................................................................................22

Figure 2.1-3: Bailey’s conical array of electromagnetic wave energy..........................................................22

Figure 2.2-1: NEC prototype on flexible substrate and Nantenna made on 4-inch square coupons [23]. 25

Figure 2.3-1: Relative electric field intensity distribution. (a) λ=329nm. (b) λ=375nm. (c) λ=406nm. (d) λ=470nm [50]. .........................................................................................................................27

Figure 2.3-2: Current distribution at a 16nm gap [51]. .................................................................................28

Figure 2.3-3: Substrate coupling for a fabricated nano bowtie antenna [51]. ..................................................28

Figure 2.3-4: Geometry and dimensions of split ring antenna and near field intensity distribution [55].30

Figure 2.6-1: Sharp tip tungsten wire with point contact............................................................................34

Figure 2.6-2: Planar MIM diode. ..................................................................................................................35

Figure 2.6-3: SEM image showing antenna integrated diode [67]. ...............................................................36

Figure 2.6-4: Gold electric leads for DC signal extraction [67]. .................................................................36

Figure 2.6-5: Planar antenna coupled diode and diode sensitivity [68]. .....................................................37

Figure 2.6-6: Asymmetric diode sensitivity and pointed polysilicon triangle [68]. ..................................38

Figure 2.8-1: Equivalent circuit model for antenna integrated rectifier [77]. ............................................39

Figure 3.1-1: Original and equivalent problem based on image theory.....................................................44
Figure 3.1-2: Frequency dependent relative permittivity. Data obtained from [83] and was plotted using Matlab.

Figure 3.1-3: Hofmann’s simulation results [81].

Figure 3.1-4: Our replicated results for the same problem using HFSS.

Figure 3.2-1: Drude model for a bounded electron. Figure 3.2-2: Electron’s momentum time evolution.

Figure 3.2-3: Lightly damped metal reflectivity as a function of frequency [84].

Figure 3.2-4: Experimental reflectivity of Al, Ehrenreich et al.(1963), © American Physical Society.

Figure 3.2-5: Band diagram of Al, Segall (1961), © American Physical Society.

Figure 3.3-1: Simulation results for Sphere, bowtie and torus nano antenna.

Figure 3.3-2: Spiral nano antenna.

Figure 3.4-1: Electrons oscillations and Formation of surface plasmons.

Figure 3.4-2: Surface charge oscillations and the electric field lines distribution.

Figure 3.4-3: Dielectric/Metal interface.

Figure 3.4-4: Dispersion relation of traveling surface plasmon. The curve was plotted for free space dielectric. Blue curve shows Surface plasmon polariton dispersion. Red line represents free space dispersion.

Figure 3.5-1: Linearly polarized electric field incident on a nano sphere with dielectric function $\varepsilon$ immersed in a medium. with a dielectric constant $\varepsilon_m$.

Figure 3.5-2: Variation of the polarizability factor with incident energy.

Figure 3.6-1: Simulated surface current vector distribution for bowtie nano antenna.
Figure 3.6-2: (a) phase and group velocity are zero at the tip of a cone. (b) Electric field enhancement along propagation direction z. ................................................................. 70

Figure 3.8-1: Near filed intensity calculated at the gap center for different gap sizes. ......................... 71

Figure 3.8-2: Near field intensity variation with tip angle. ...................................................................... 72

Figure 3.8-3: Near field intensity variation with antenna length. ............................................................ 73

Figure 3.8-4: Near field intensity variation with angle of incidence in 3-D. ............................................. 74

Figure 3.9-1: Frequency dependent effective permittivity for Silicon substrate..................................... 76

Figure 3.9-2: Coupling from substrate side............................................................................................ 76

Figure 3.9-3: Frequency dependent gold relative permittivity................................................................. 78

Figure 3.9-4: Near field intensity for non-optimized (blue curve) and optimized (red curve) bowtie nano antenna. ..................................................................................................................... 78

Figure 3.9-5: Variation of near field intensity in a 50nm gap with both length and bow angle simultaneously at 2.3THz.................................................................................................................. 79

Figure 3.9-6: Optimized near field variation with different gaps. ............................................................ 80

Figure 4.1-1: I-V characteristic curve of a regular PN diode and tunnel diode. [93] .............................. 81

Figure 4.2-1: Sharp tip tungsten wire with point contact...................................................................... 83

Figure 4.3-1: Antenna coupled diode. [77] ......................................................................................... 86

Figure 4.3-2: Conversion efficiency as a function of q (ωc RA). [77] ..................................................... 87

Figure 4.3-3: Variation of tunnel resistance with applied voltage for 3 oxide thicknesses [98]............. 89

Figure 4.4-1: Gold back reflector to ensure substrate coupling............................................................ 91

Figure 4.4-2: SiO2 Matching section over silicon wafer. ................................................................. 93

Figure 4.4-3: 950PMMA A Resists Solids: 2% - 7% in Anisole. .......................................................... 94

Figure 4.4-4: Sample stack up before lithography.............................................................................. 94
Figure 4.6-1: Measured MIM diode performance.

Figure 4.6-2: Damaged resist after ALD.

Figure 4.7-1: Copper and Gold frequency dependent optical properties.

Figure 4.7-2: Near Field Intensity variation with both flare angle and bowtie length.

Figure 4.7-3: 10 nm gap Copper Bowtie

Figure 4.7-4: Copper bowtie nano antenna radiation pattern.

Figure 4.7-5: Simulated overlapped bowtie.

Figure 4.7-6: Near Field Intensity variation with both flare angle

Table 4.7-2: Maximum near field intensity for Copper-Gold nano antenna

Figure 4.7-7: Overlapped nano antenna radiation pattern

Figure 4.7-8: Overlapped Copper-Gold antenna with bias pads.

Figure 4.7-9: Near Field Intensity variation with both flare angle and bowtie

Figure 4.7-10: Fabricated rectenna device.

Figure 4.7-11: MIM device 1 performance.

Figure 4.7-12: MIM device 3 performance.
ABSTRACT

NANO ANTENNA INTEGRATED RECTIFIER FOR THZ HARVESTING

MENA N. M. GADALLA

In this work full parametric analysis of nano antennas is presented. To begin with, optical or electronic properties of noble metals such as gold and copper were studied in details to get a clear understanding of their reaction to an incident electromagnetic wave. Complex frequency dependent dielectric functions indicated that in THz metals acts as a dielectric with significant absorption. Simultaneous optimization of the length and the bow angle of a bow-tie antenna resulted in relative electric field intensity enhancement of 8 orders of magnitude for 0.5nm gap and 4 orders of magnitude for 50nm around 28THz resonance frequency. These results are at least 2 orders of magnitude greater than the published optical antennas. Physical reasons behind field localization and intensity enhancement are discussed in details. The solution of Maxwell’s equations at the interface between metallic nano antenna and air is also present in this piece of research. The derived dispersion relation of surface plasmons shows momentum matching at 28.3 THz between free propagating electromagnetic fields’ modes in air and localized modes at the interface. Consequently, Propagating electromagnetic waves are ensured to couple to localized surface propagating modes producing filed enhancement. The integrated SiO₂ matching section is theoretically proven to increase transmission to substrate to 75% (compared to
40% without it) which in turn improves the coupled power by 40 times. nano antennas were fabricated in house using Electron beam lithography with a precise gap of 50nm. In addition, THz diode was designed, fabricated and integrated to the nano antennas to rectify the enhanced THz signal. The integration of the nano diode required a precise overlap of the two arms of the antenna in the rage of 100nm. In order to overcome two arms overlap fabrication challenges, three layer alignment technique was used to produce precise overlap. The THz rectifier was electrically tested and shown high sensitivity and rectification ability without any bias. Finally, nano antenna integrated diode is under optical testing using a 10.6µm Co$_2$ laser at Electro-Optics Lab, Prince Sultan Advanced Technologies Research Institute (PSATRI), King Saud University due to the unavailability of the measurement setup in KAUST.
1. INTRODUCTION

Energy sources are divided into two main categories, renewable and non-renewable sources. Science community is investing heavily to alleviate the dependency on non-renewable energy sources and shift to renewable ones.

1.1 RENEWABLE VS. NON-RENEWABLE ENERGY RESOURCES

The world has witnessed an unprecedented increase in its energy requirements over the last few decades driven by the increasing population, industrial development and our increasing level of activity. The amount of energy each one of us uses has also increased, with the global average per capita consumption of all forms of energy rising by 50% in the last 40 years alone [1]. The total current energy consumption is greater than 55235 Terra Watt-hour currently and is growing at 2.5% per year [2]. The report presented in [2] clearly depicts the dominating dependence on fossil fuels, with oil and coal having 33.1% and 30.3% share in year 2011 and the latter witnessing a record 5.4% increase in the same year. In contrast, the share of all renewable energy sources including solar, wind, biofuels and others is a meager 2.1%. For example, the amount of energy produced by coal, nuclear power and solar energy are 1000, 400 and 5 Giga watts/hour respectively [3]. In comparison to the increasing energy demands, the growth in supply and production of energy is lagging behind. In fact, many studies reveal that the world has already consumed half of its oil reserves and passed the peak oil production in 2005 [4]. It is forecasted that in 2050 oil production would only be 18% of what it is today. Similarly, coal and natural gas
are predicted to have peak productions around 2025 and there-on experience decline similar to oil. The above scenario clearly indicates the urgent need to reduce dependence on fossil fuels and seek renewable sources of energy. In addition, Non-renewable energy sources cause air pollution, acid rains and global warming and are very expensive. Renewable energy sources on the other hand are non-polluting, surplus and free.

1.2 MOTIVATIONS

1.2.1 SOLAR ENERGY AND SOLAR SPECTRUM

The increasing energy demands of a growing world population and depleting fossil fuel reserves indicate the urgent need of seeking long lasting alternative renewable energy resources. Solar energy is considered the most abundant source of renewable energy with 174 petawatts/hour delivered at the upper atmosphere [5].

![Solar Energy Spectrum](image)

Figure 1.2-1: Solar Energy Spectrum [6].

Unfortunately, solar energy is not fully, or even partially, utilized as the main source of energy. Even though the sun provides earth every hour with as much energy as human
civilization uses every year [5], wide spread solar energy usage is rarely seen. Solar energy oscillates over a wide range of frequencies or wave lengths. Most of this energy is concentrated in the visible (0.4-0.7μm), whereas small amount is distributed over the ultraviolet (UV 0.001-0.4 μm) and infrared (IR 0.7-100 μm) as shown in figure 1.2-1[6].

1.2.2 SOLAR CELLS DISADVANTAGES

The main reason for low solar energy utilization is the low conversion efficiency of solar cells. In spite of their developed industry, solar cells conversion efficiency doesn’t exceed 30%. Solar cells performance is mainly limited by the band gap of the material. Take for example silicon Solar cells. Silicon has a band gap of 1.1ev at room temperature, consequently silicon cannot absorb light energy less than 1.1ev. In addition, Solar cells need mechanical tracking for normal incidence of sun rays, they also do not work at night or unclear weather.

1.3 PROPOSED IR ENERGY HARVESTING TECHNIQUE

30% of the solar radiation is reflected by the atmosphere and lost in space, 51% is absorbed by earth and organic life and then reemitted around 10 μm. 19% is absorbed by air particles and reradiated between 7-14 μm [7]. Generally heated bodies emit electromagnetic radiation. Stefan-Boltzmann law gives the amount of radiation from a heated perfect black body [8]. Even though earth reflects 30% of the incident radiations it can be approximated as a black body at 287 K with reemission spectrum shown in figure 1.3-1 [9].
As shown in figure 1.3-1 the peak of the earth’s emissivity is at 10.6 μm, thus for efficient collection of the earth’s radiation the designed antenna should resonate at 10.6 μm or 28.3 THz.

### 1.3.1 RECTENNA

The conventional photovoltaic (PV) technology harvests energy only from the visible range of the spectrum using solar cells whereas the other major energy component in the IR range remains completely untapped. The proposed research project aims to exploit this source of IR energy abundantly available in the environment for a reliable future source of green energy.

An alternative for solar cells that has higher efficiency for energy conversion is rectenna. A rectenna is a combination of a receiving antenna and a rectifying diode. Unlike photovoltaics, rectenna concept utilizes the wave nature of light. Rectenna in principle have no efficiency limitations since the major problem of semiconductor band gap does not apply here. Efficient collection by the antenna, perfect matching between the diode and antenna and efficient rectification nominate rectenna to have a theoretical conversion
efficiency of 100%. Rectenna has been used in microwave regime with conversion efficiency up to 90% [10]. Rectenna element is made of a receiving antenna and a rectifying diode. The Antenna can be dipole, spiral, slot, or bowtie. Figure 1.3-2 [11] shows a block diagram of rectenna circuit model.

![Rectenna Circuit Diagram](image)

Figure 1.3-2: rectenna equivalent circuit [11].

The low pass filter provides impedance matching between the receiving antenna and the diode. It also prevents the higher order harmonics generated by the rectifier from being reradiated by the antenna. The DC filter is present to smooth the signal before delivery to the load.

In addition to efficiency advantage, nano-antennas based energy collection concept is better in many other ways as compared to the traditional solar cells approach. Unlike solar cells, rectennas can operate during night time and independently of weather conditions such as humidity and cloud cover. Rectennas radiation, being isotropic in nature, does not require a certain orientation for energy collection, contrary to solar cells operation. Moreover, rectennas can be fabricated on substrates much cheaper than silicon. Unlike visible light, IR is not limited to sun only rather all industrial processes generate waste heat that can also be
harvested using rectennas. In addition, because infrared energy is the mechanism used to transmit heat between objects, arrays of rectennas could be used to cool buildings and other structures, transforming the once wasted heat into electrical energy. These advantages are summarized in table 1-1 below.

<table>
<thead>
<tr>
<th></th>
<th>Solar Cells</th>
<th>nano-rectennas</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Functionality along the day</strong></td>
<td>Day time only</td>
<td>Whole day</td>
</tr>
<tr>
<td><strong>Weather condition</strong></td>
<td>Requires clear and dry weather</td>
<td>Works under all weather conditions</td>
</tr>
<tr>
<td><strong>Orientation sensitivity</strong></td>
<td>Very sensitive</td>
<td>Less sensitive</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Waste heat harvesting</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Figure 1.3-3: rectenna versus solar cells.

### 1.4 OBJECTIVES

- Conducting a theoretical study for surface waves propagation at metal/dielectric interface.
- Design and fabrication of an efficient nano antenna to resonate at 28.3 THz with electric field intensity enhancement greater than that reported in the literature.
- Design and fabrication of a nano diode to work as THz signals rectifier.
- Integration of the nano antenna to the THz nano rectifier.
- Producing rectenna device which is able to generate DC electric current without any external electric source.

### 1.5 Challenges
Nano antennas are challenging when it comes to the theory of operation, design and fabrication. Theory of optical antennas needs a strong background in electromagnetics, in addition the THz rectifier needs a deep understanding of quantum mechanics. Optical or electrical properties of noble metals that are used to fabricate nano antennas need to be investigated since they are frequency dependent in high frequencies. Fabrication of nano antennas needs advanced machines like electron beam lithography (EBL). Characterization of these machines for a certain stack up is required to produce precise nano patterns. In this thesis we characterized the EBL for our substrate and sharp edges nano structures were obtained. The integration of the nano antenna to the THz rectifier places a lot of challenges to the fabrication of the rectenna device in addition, the very high input impedance of the THz rectifier leads to high miss match between the diode and the nano antenna. Finally, nano antennas simulations require great computational resources due to the very small geometric features.

1.6 CONTRIBUTIONS

- Deriving dispersion relation for surface waves via the solution of Maxwell’s equations to ensure momentum matching.
- Full parametric analysis of nano antennas that resulted in 2 orders of magnitude greater than the published optical antennas.
- Precise nano antenna fabrication with zero gap and 130nm overlap length.
- Production of THz nano antenna diode that is able to rectify AC energy without any external source of electricity (at zero bias).
1.7 THESIS ORGANIZATION

- Chapter 2 of the thesis gives a review on the history of rectennas. In addition to, a review on the most recent achievements in rectenna devices. For instance, the greatest field enhancement at nano gap and the highest sensitive THz diode.

- Chapter 3 provides a detailed analysis of surface plasmons theory, their dispersion relation and conditions of coupling between optical antennas localized surface modes and free propagating modes in air. Moreover, in this chapter the design and the optimization of 28.3 THz antennas for maximum field enhancement is present.

- Chapter 4 contains the theory of tunneling diode and the design of THz rectifier. The detailed steps of the whole fabrication process, in addition to electrical and optical testing results are presented in this Chapter.

- Finally chapter presents future work and conclusion.
2. REVIEW OF LITERATURE

Design and fabrication of THz rectenna have not been studied enough. Consequently, there is not much work published about THz rectenna. That is why in this chapter we give an overview of the evolution of rectenna device. First, rectenna history and its usage in wireless transmission are discussed. Second, an overview of microwave rectenna is given. Finally, optical nano antennas and antenna integrated diode are analysed.

2.1 RECTENNA HISTORY

The first idea of a rectenna was introduced by William C. Brown. Brown who is by far considered as the father of microwave power transmission suggested the use of microwaves for wireless power transmission. In 1964, with an air force contract, Brown demonstrated electrical energy transmission without the need of wires [12]. He demonstrated a helicopter powered by a rectenna that transforms an incident microwave beam at 2.4GHz into DC energy. Figure 2.1-1 shows the helicopter with strings passing through the centre and the end to keep its balance in air. The helicopter kept flying at 60ft altitude for 10 hours. This experiment is considered the first spark for energy harvesting using antennas.
Since single element antenna is limited in power harvesting, normally it generates fraction of watts, Brown assembled 28 half-wave dipoles that resulted in 40 to 70 percent conversion efficiency to be used in aerospace applications with no fuel source. Brown arranged rectenna elements as a four arm bridge network, with different configurations for instance, parallel, series, and parallel-series using a whisker element semi conductor rectifying junction connected to a non directional receiving antenna. Brown used a microwave source to feed a horn antenna via a transmission line in order to form the microwave beam as shown in figure 2.1-2 [13].
J.C. Fletcher of NASA and R.L. Bailey of the University of Florida were the first to introduce the idea of solar into electrical energy conversion [14]. In 1973 Bailey designed a broadband electromagnetic energy converter by treating visible light as microwave radiation to be a proof of concept. He modified the well-known dipole antenna into a conical or pyramidal elements attached to half wave rectifier which is used for DC current generation as shown in figure 2.1-3. With center frequency of 475MHz and 200-700MHz pass band, Bailey was able to obtain 12-13% conversion efficiency. He also noticed that by increasing the element length relative response passband shifts to lower frequency. In 1984 Marks was able to achieve a rectenna device with theoretical 67% efficiency[15]. He used a microarrays of submicron antenna connected to a submicron semiconductor rectifier made of amorphous silicon. Antenna element was made of dipoles 180nm in length and 10nm in width. Marks’ patent was significant because his device operated from the near ultraviolet to the near infrared. Marks’ design differed from Bailey’s in two main points. First, Marks’ rectenna operated from 0.35µm to 0.8 µm. Second, Marks used a broadside antenna array with the output signal from different dipole elements feeding a transmission line and then rectified. Never the less, the stated 67% of Marks’ device was calculated and not measured. In 1986 Marks patent a rectenna with theoretical 60% to 80% conversion efficiency [16]. The new device was made of oriented molecular dipoles contained in a solidified sheets. In 1988, Marks invented a Femto Diode to work with light frequencies [17]. The device used a cylinder like antenna with an asymmetric metal insulator metal (MIM). Marks was able to achieve a theoretical efficiency of 90% for visible light with this diode. In 1990, Marks introduced a different idea of using chain of iodine molecules as conducting elements [18]. Marks designed efficient rectennas, however he did not measure conversion efficiency of
any of them and totally ignored in his calculations the missmatch between the antenna and the rectifier which is the major challenge in any rectenna design. This also proves that fabrication and testing of a rectenna are major challenges. In 1988 Farber of university of Florida extended rectenna study for solar energy conversion to higher frequency bands 0.3-2, 10 and 100GHz [19]. The system was composed of two parts. First, a broadband microwave transmitting station made of metallic pyramidal antenna elements. Second, dielectric antenna elements and a rectifier that was used to generate DC current to operate a small motor as a proof of concept.

2.2 MICROWAVE RECTENNA

Microwave rectenna have been used as a proof of concept for their infrared counterparts, in principle they can achieve 100% efficiency. Many trials and experiments were conducted to improve microwave rectenna. In this section we show the development of microwave antenna integrated diode. In 1992 Yoo and McSpadden did an experimental study for 10 and 35 GHz using a microstrip dipole antenna and off the shelf mixer diode [20]. Conversion efficiency of 60% and 39% were achieved respectively for the mentioned resonance frequency. In 2000, Suh presented rectenna at higher frequency [21]. He used a GaAs Schottky barrier diode as a DC converter with a circularly polarized square patch antenna to achieve 60% conversion efficiency at 5.82GHz. Berlan et al., in 2001 at the ITN Energy System Inc. [22] anticipated 85% efficiency for infrared rectenna. They built a rectifying antenna array at 10 GHz with 50% conversion efficiency. Kotter et al. explored new efficient way for infrared Nantenna Electromagnetic collectors (NEC) [23]. Kotter designed and implemented RF rectenna array as a proof of concept. He intended to
improve the efficiency by adding a dielectric stand off layer of quarter wavelength to act as optical resonance cavity. He fabricated 10 billion NEC on a 8-inch silicon wafer. In collaboration with Micro Continuum, Inc. Kotter was able to produce a fully automated roll-to-roll sheet of NEC fabricated on polyethylene as shown in figure 2.2-1.

![Figure 2.2-1: NEC prototype on flexible substrate and Nantenna made on 4-inch square coupons [23].](image)

Even though the prototype was designed and fabricated to operate for millimetre waves Kotter Designed and fabricated infrared nano antenna to resonate at 10µm. He claimed 92% efficiency based on emissivity measurements. It is worth noting that designing and fabricating a millimeter wave rectenna is not as challenging as their THz counterpart, especially when it comes to diode antenna matching.

### 2.3 OPTICAL NANO ANTENNAS (VISIBLE AND NEAR-INFRARED)

Optical antennas are very similar to microwave antennas, never the less there is no established theory for optical antenna design. Over the past 15 years scientific community heavily invested in the investigation of optical properties of metallic nano particles [24-32].
It was observed that when a visible or infrared light is incident on an antenna’s surface it excites surface plasmon oscillations and drive current towards the feed point of the antenna creating a hot spot at which the field intensity is enhanced, this phenomenon can be used to design antennas for visible light [32, 33]. Optical antennas can be used for many applications, such as antennas for nano scale imaging and spectroscopy [34-38], improving solar cells efficiency [39-45], and coherent control [46, 47]. In this piece of research we are interested in nano antennas for energy harvesting applications. In 1985 Yasuoko presented the first experimental observation for an infrared rectenna. A thin film antenna was connected to a Schottky diode for rectification at 10.6µm [48]. The first experimental observation of a nano antenna structure working in the visible light was reported by Lin et al. in 1996 [49]. Lin used a dipole antenna array connected together to form metallic groves over a p-type doped boron single crystal wafer with 3 nm oxide layer for rectification. Lin’s results were important because they provide validation for electric rectification and light resonance in the visible frequencies. Kottman in 2000 [50] introduced the idea of using irregular nano particles to produce greater near filed enhancement, he compared the field enhancement due to an irregular nanoparticle to that due to a regular one. With numerical analysis (finite element method) Kottman showed that an equilateral triangle of side length 27nm can produce field enhancement of four orders of magnitude compared to the incident field at resonance wavelength of 329nm, however with an irregular triangle he achieved five orders of magnitude right at the triangle tip for a resonance wavelength of 470nm as shown in figure 2.3-1.
Sundaranurthy and Crozier of Stanford University were able to fabricate two opposing gold bowties with only 16nm tip to tip separation [51] to study nano antennas response and gap effect in the optical regime. The bowtie was 88nm in length with an apex of 60° and 12nm radius of curvature as shown in figure 2.3-3. The antenna’s thickness was 20nm of Au mounted on 4nm of chromium as an adhesion layer. Sundaranurthy used Indium tin oxide layer over a fused silica substrate to improve lithography using electron beam. Finite difference time domain analysis was done to detect electric field enhancement due to Plasmon resonance around the bowtie tip. For a linearly polarized incident plane wave with substrate illumination, Sundaranurthy was able to obtain a factor of enhancement of 1654 at 856nm for 16nm gap. This study was important because Sundaranurthy was able to show the current distribution along the antenna surface and the current behaviour at the gap. The numerical analysis showed that there is a strong displacement current flowing through the gap which is highly uniform and continuous with the displacement current on the antenna’s surface figure 2.3-2. This displacement current is maximized as we get closer to the tip consequently the Electric field enhancement is maximized at the tip. One major problem with Sundaranurthy device was the imperfect fabrication of the nano antenna as shown in figure 2.3-3, especially the sharpness of the bowtie’s edges.
In 2009 McMahon et.al used the finite element method to compute the electric field intensity enhancement at a gap between two gold dimers with a diameter of 90nm [52]. For a gap of 5nm, 1nm, 0.5nm and 0.25 nm he was able to get 2, 3, 3 and 5 orders of magnitude respectively with a resonance wavelength of 550nm, 600nm, 700nm and 900nm respectively. In 2010 McMahon et.al investigated the field enhancement due to cylindrical nano wires and bowtie antennas where he was the first to use nonlocal dielectric constants [53]. Using finite difference time domain (FDTD) analysis he investigated the localized field enhancement at a gap of 5nm, 2nm, 1nm and 0.5nm. The output of his numerical analysis for the bowtie using local dielectric function is summarized in the table 2.3-1. McMahon showed that taking non-local dielectric constant into consideration, will result in the decline of the near field intensity enhancement by one order of magnitude compared to using local dielectric functions.
<table>
<thead>
<tr>
<th>Gap(nm)</th>
<th>Resonance wave length(nm)</th>
<th>Normalized field enhancement (orders of magnitude)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Local</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>520</td>
<td>4</td>
</tr>
<tr>
<td>1</td>
<td>545</td>
<td>4</td>
</tr>
<tr>
<td>0.5</td>
<td>570</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 2.3-1: Near field intensity enhancement local dielectric constant.

It is worth noting that these very small sizes of the gap are not realizable by the state of the art fabrication techniques. In early 2012 Hongzhi Chen et al. [54] of Michigan state University tried to increase the frequency of operation to IR regime. Chen fabricated a bowtie nano antenna for a carbon nano tube photo detector, where the antenna worked as a plasmonic length that focuses light into the photo detector. The arm length was 200nm and a gap of 30nm separated the antenna. The 60° bowtie resulted in a relative intensity enhancement of 220 times at 0.77 µm. The final report about optimized nano structures for better enhancement and localization at the hot spot came out in August 2012 by Thorsten Feichtner [55] of University of Würzburg, Germany. Feichtner used the evolutionary algorithm along with FDTD numerical analysis to find the optimized nano structure for greater field enhancement. He proposed that the hybridization of a split ring and a two wire antenna can merge the fundamental magnetic resonance of the first with the fundamental electric resonance of the second. For a 647nm Gaussian beam elimination the
structure resulted in relative enhancement of 3500 at the middle of a 10 nm gap as shown in the figure 2.3-4.

![Figure 2.3-4: Geometry and dimensions of split ring antenna and near field intensity distribution [55].](image)

Most of the reported nano antennas are based on detecting the field enhancement in the gap by several techniques. All the attempts to get an accurate measurement for the localized field in the gap failed. Simply because the insertion of any probe will significantly disturb the dynamics.

### 2.4 28.3 THZ ANTENNAS

K.B.Crozier of university of stanford in 2003 was the first to investigate the effect of the nano antenna geometry on the field enhancement [56]. Since nano antennas are resonant structures, antenna geometry dramatically affects coupling between free space propagating waves and surface waves propagating at the antenna’s surface. Crozier investigated the effect of the tip angle and the tip radius of curvature of a 1.56µm bowtie antenna with 60nm thickness. He was able to obtain relative intensity of 6200 for a linearly polarized plane wave with 10.375µm of wavelength. Croazier not only performed FDTD numerical
simulation but he also fabricated nano antenna array with 3µm spacing between every bowtie element Using Electron beam lithography. In 2011 Michele Gallo et al. proposed a solar energy converter design using four square spiral array made of gold over a low cost substrate with realtive permittivity of 4.6 [9]. The spiral antennas were designed to channel the induced surface waves at 10.6µm to the feed gap which was connected to a 50Ω microstrip line for collecting the localized energy. Figure 2.4-1 shows the output current from the antenna array as a response of a circularly polarized plane wave at 28.3 THz with amplitude of 239 V/m.

Table 2.4-1: Elemental square spiral antenna and rectified current due to 4 element array [9].

2.5 SUMMARY OF OPTICAL NANO ANTENNAS

<table>
<thead>
<tr>
<th>Reference</th>
<th>Resonance wavelength (nm)</th>
<th>Gap size(nm)</th>
<th>Relative intensity enhancement (orders of magnitude)</th>
<th>Antenna structure</th>
<th>Total Antenna Dimension (nm²)</th>
<th>Applications</th>
<th>Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001 [50]</td>
<td>329</td>
<td>No gap</td>
<td>5</td>
<td>Irregular triangle</td>
<td>nano-particles shapes, no antenna</td>
<td>Near field microscopy, theoretical paper</td>
<td>Theoretical paper</td>
</tr>
<tr>
<td>Year</td>
<td>Width</td>
<td>Height</td>
<td>Resonance</td>
<td>Type</td>
<td>Numerical Method</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-------</td>
<td>--------</td>
<td>-----------</td>
<td>------</td>
<td>------------------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>2005 [51]</td>
<td>856</td>
<td>16</td>
<td>4</td>
<td>Bowtie</td>
<td>192 x 88</td>
<td>General, random λ choice</td>
<td>FDTD simulations matching a reference</td>
</tr>
<tr>
<td>2008 [57]</td>
<td>820</td>
<td>30</td>
<td>2</td>
<td>Bowtie, Dipole</td>
<td>~230x100</td>
<td>General, random λ choice</td>
<td>Green’s tensor method simulations</td>
</tr>
<tr>
<td>2009 [52]</td>
<td>900</td>
<td>0.25</td>
<td>5</td>
<td>Dimer</td>
<td>90-nm Au nanoparticle dimers</td>
<td>Surface-enhanced Raman spectroscopy (SERS)</td>
<td>Finite element calculations</td>
</tr>
<tr>
<td>2010 [53]</td>
<td>570</td>
<td>0.5</td>
<td>5 for local, 4 non-local</td>
<td>Bowtie</td>
<td>87x50</td>
<td>General, random λ choice</td>
<td>Study &amp; simulations only</td>
</tr>
<tr>
<td>2011 [58]</td>
<td>~785</td>
<td>3 -- 16</td>
<td>8 -- 6</td>
<td>Dimer array</td>
<td>205x80</td>
<td>Surface enhanced Raman scattering (SERS)</td>
<td>Benzenethiol Raman spectrum</td>
</tr>
<tr>
<td>2012 [54]</td>
<td>830</td>
<td>30</td>
<td>2</td>
<td>Bowtie</td>
<td>~400x100</td>
<td>CNT photo-detectors</td>
<td>IR laser shined, elec. Signal meas</td>
</tr>
</tbody>
</table>

**Table 2.5-1: Comparison between previously reported optical antennas.**

### 2.6 MIM DIODE

For rectification purposes, available electronics cannot track a THz signal. Thus, the only way for THz rectification is through tunnelling effect where electrons can go through a thin layer of oxide by tunnelling phenomena. This quantum mechanical effect cannot happen
through insulators that are thicker than few tens of angstroms since tunnelling probability falls off exponentially with the barrier thickness. Sommerfeld and Bethe [59] were pioneers in studying the tunnelling effect theoretically. They found equations that describe tunnelling current density across a rectangular barrier for the case of very high and very low voltage. Holm [60] completed the picture by treating the intermediate case, never the less both of them used the WBK approximation to derive the pertinent theory. The use of WBK approximation made the validity of the previous analysis questionable. In 1961, Fisher and Giaever [61] were able to fabricate the first tunnelling diode with 5nm of aluminium oxide sandwiched between two aluminium electrodes. Fisher was able to experimentally measure the variation of the junction’s current and resistance with the applied voltage and oxide thickness respectively. In 1963, Simmons [62] introduced a single theory to treat any barrier of arbitrary shape and corrected the errors that were made before. The application of Simmon’s equation to a rectangular barrier, which is the case of interest for this thesis, will result in the following equations for the case of low and intermediate bias voltage:

Low voltage case:

\[ J = \frac{3(2m\phi)^{1/2}}{2\pi s}(\frac{e}{h})^2 V \exp \left( -\frac{4\pi s}{h} \right) (2m\phi_o)^{1/2} \]  \hspace{1cm} (2.1)

Intermediate voltage case:

\[ J = \frac{e}{2\pi h s} \left\{ \left( \phi - \frac{ev}{2} \right) \exp \left( -\frac{4\pi s}{h} \right) \left( 2m \right)^{1/2} \left( \phi - \frac{ev}{2} \right) - \left( \phi + \frac{ev}{2} \right) \exp \left( -\frac{4\pi s}{h} \right) \left( 2m \right)^{1/2} \left( \phi + \frac{ev}{2} \right) \right\} \]  \hspace{1cm} (2.2)

Where \( m \) is the mass of electron, \( e \) is the electron’s charge, \( h \) is Planck’s constant, \( S \) is the barrier’s thickness, \( V \) is the bias voltage, \( \phi_o \) is the height of the rectangular barrier, and \( J \) is
the tunnelling current density. Two major observations can be drawn based on these equations. First, tunnelling current density drops exponentially with the increase of the oxide’s thickness. Second, there has to be work function difference and Fermi level gradient between the two electrodes in order for electrons to tunnel.

The application of this tunneling concept started in 1960s when point contact MIM diode was used for microwave detection and millimetre wave frequency mixing [61]. Point contact MIM consists of a sharp metallic tip in contact with a metal plane with insulator or air gap in between as shown in figure 2.6-1. The point contact metallic wire was usually made of tungsten and acts as an antenna to couple light via its very sharp tip to the oxide layer for rectification [13-15].

![Figure 2.6-1: Sharp tip tungsten wire with point contact.](image)

The problem with whisker or even tungsten wire was the reproducibility of MIM diode, in addition to mechanical fragility of the fabricated diodes. Point contact diodes were used for millimetre waves until 1968 when Hocker of MIT [63] extended the frequency of operation to 337µm. The problems of the point contact diodes such as the difficulty of obtaining reproducible result were fixed in 1974 by Gustafson and Bachner [64, 65] by the introduction of a planar metal-oxide-metal junction formed by two crossed thin film metallic strips as shown in figure 2.6-2. The new planar MIM provided mechanical strength, process reproducibility and the ability to integrate the MIM diode to other devices.
In this research we investigate the integration of such planar MIM diode to a THz nano antenna.

According to Kale [66] the rectified voltage from the junction depends on the nonlinear change of the current with the applied voltage and is given by:

\[
V_{\text{rect}} = - \frac{1}{4} \frac{I'(V_{\text{bias}})}{I'(V_{\text{bias}})} V_{\text{ac}}^2
\]

From equation 2.3 we introduce the sensitivity of the diode which is the main evaluation for the diode performance:

\[
S = \frac{I''(V_{\text{bias}})}{I'(V_{\text{bias}})}
\]

The sensitivity of the MIM diode is a very important factor in the design of antenna coupled diode, since it represents the conversion efficiency of the diode from AC to DC. As a result, finding ways to improve the sensitivity of the diode is a field of research on its own. Design consideration of MIM diode will be discussed in details in chapter 4. In 1997 C.Fumeaux [67] introduced the smallest thin film MIM diode. Fumeaux integrated nano antennas
(bowtie, planar dipole, and a spiral) to Ni-NiO-Ni diode as shown in figure 2.6-3. Using EBL, Fumeaux achieved 110nm x 110nm as an area of contact which resulted in a very high rectification speed. The MIM is then connected to gold electric leads as shown in figure 2.6-4 for testing purposes. The Maximum $\frac{d^2I}{d^2V_{bias}}$ he obtained was between -40 to 40mA/V$^2$. A major drawback of this design is the overlap of the lead arms and their connection to the antenna tip which will channel the excited surface plasmons to travel in the bias leads instead of being localized at the MIM diode. In addition this way of fabricating rectennas avoids taking advantage of rod lightening effect, since the sharp pointed tip of the antenna is removed. In order to overcome these problems, overlapped bowtie was used in this project with bias leads far away from the feed point.

Design and fabrication of MIM diode for infrared applications are not famous and very small steps of progress were taken. In 2010 however, Mario Dagenais et al. [68] introduced the idea of a symmetric MIM diode using poly silicon instead of metal. He fabricated polysilicon/SiO2/polysilicon planar tunnelling diode integrated to a bowtie antenna of 60°
flare angle as shown in figure 2.6-5. Dagenais used boiling water oxidation process to obtain 7nm layer of native oxide. The problem with Dagenais was with the bad fabrication of the bowtie arm which is obvious in figure 2.6-5-a. Dagenais obtained diode sensitivity between -4 to 8 figure 2.6-5-b. For energy harvesting applications, zero bias sensitivity and zero bias diode impedance is a very critical design consideration. Zero bias response can be achieved using asymmetric diodes with two different metals with two different work functions. This will result in Fermi level gradient at zero bias which will lead to electron tunnelling.

![Figure 2.6-5: Planar antenna coupled diode and diode sensitivity [68].](image)

In order to increase the diode response Dagenais used asymmetric diode along with Geometric field enhancement technique (GFE). GFE represents MIM diode with a simple overlap structure of a pointed metal over a planar one as shown in figure 2.6-6. Dagenais used polysilicon bowtie over Ti/Au platform. This asymmetric diode showed better response with sensitivity between -14 to 10.
2.7 SUMMARY OF PREVIOUSLY PUBLISHED MIM

<table>
<thead>
<tr>
<th>Reference</th>
<th>Type of MIM</th>
<th>Maximum Sensitivity ((\text{V}^{-1}))</th>
<th>Zero bias Sensitivity ((\text{V}^{-1}))</th>
<th>Zero bias resistance (ohm)</th>
<th>Oxide thickness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoofring 1989 [69]</td>
<td>Thin film Ni-NiO-Au (0.64(\mu)m(^2))</td>
<td>5.5</td>
<td>2.8</td>
<td>--</td>
<td>2.2</td>
</tr>
<tr>
<td>I. Wilke, et.al 1994[70]</td>
<td>Ni-NiO-Ni, (0.0576 (\mu)m(^2))</td>
<td>1.6</td>
<td>--</td>
<td>100</td>
<td>4</td>
</tr>
<tr>
<td>M. Abdel-Rahman et al. 2004 [71]</td>
<td>Thin film Ni-NiO-Ni (0.075 (\mu)m(^2) and 0.0014 (\mu)m(^2))</td>
<td>2.75 and 1.65 respectively</td>
<td>--</td>
<td>180</td>
<td>3.5</td>
</tr>
<tr>
<td>Esfandiari 2005 [72]</td>
<td>Thin film Ni-NiO-Pt (0.0025(\mu)m(^2))</td>
<td>-13</td>
<td>-3</td>
<td>--</td>
<td>2</td>
</tr>
<tr>
<td>S.Krishnan et al. 2008 [73]</td>
<td>Thin film Ni-NiO-cr/Au (1 (\mu)m(^2))</td>
<td>5</td>
<td>1</td>
<td>500K</td>
<td>3</td>
</tr>
</tbody>
</table>
2.8 10.6μm ANTENNA INTEGRATED DIODE

In 1978 Sanchez introduced a model of an antenna integrated to MIM diode [77] as shown in figure 2.8-1.

![Figure 2.8-1: Equivalent circuit model for antenna integrated rectifier [77].](image)

The antenna is represented by an AC voltage source and an internal resistance of $R_A$ whereas the diode is represented as a nonlinear resistance $R_D$, in parallel with a very small capacitance representing the small contact area between the antenna and the MIM diode. The results of this paper are very important and will be explained in details in Chapter 4 as we will use these results in the design of the THz diode.
Hobbs, on the other hand presented the total conversion efficiency of an antenna coupled MIM diode [78]:

\[ \eta = \eta_a \eta_s \eta_c \eta_j \]  

(2.5)

\( \eta_a \) is efficiency of coupling Free propagating Electromagnetic waves to the antenna. This is maximised at the antenna resonance wavelength. \( \eta_s \) is the propagation efficiency and it represents the ability of the antenna of delivering the received energy to the diode. \( \eta_s \) is reduced due to the losses of the antenna material (in THz frequencies this efficiency is usually low since noble metals are highly lossy at these frequencies). As a result, the antenna’s material needs to be carefully selected to increase \( \eta_s \) at the targeted wavelength. \( \eta_j \) is the diode conversion efficiency from AC to DC. \( \eta_c \) is the coupling efficiency between the diode and the receiving antenna. Since antenna’s modes are different from diode’s modes, \( \eta_c \) is used to measure the coupling between these different modes. Reducing the diode’s input impedance is vital to increase \( \eta_c \). The coupling efficiency is a major challenge in THz rectenna design since the diode’s resistance is usually 3 orders of magnitude greater than the antenna impedance. Based on [77, 79] coupling efficiency is given by:

\[ \eta_c = \frac{4(R_AR_D/(R_A + R_D)^2)}{1 + \omega(R_AR_D/(R_A + R_D)C_D)^2} \]  

(2.6)

The performance of an infrared rectenna is quantified by the detectivity \( D \)[66]:

\[ D = \sqrt{A} \sqrt{B} i_n^{-1} R_t \eta_a \eta_s \eta_c \eta_j \]  

(2.7)
A is the diode area \( (cm^2) \). B is the electrical bandwidth (Hz). \( R_i \) is the current responsivity (A/W) and it represents the ratio between the output DC current from the diode to the optical AC signal to the antenna. \( i_n \) is the noise current (A).

The maximum 10.6µm rectenna responsivity was reported in 2011 by Zhu et al. [80]. Zhu used a graphene diode with an Au bowtie overlapped over a planar Au base. The maximum responsivity was 0.8 A/W at 0.4V and the zero bias responsivity was 0.35 A/W.

With all the mentioned research to improve rectenna devices, there are major drawbacks in the literature. In contrast to the published approach, instead of creating a gap between the antenna arms, one of the ideas that we propose is to create very small overlap at the tips of the antenna with a thin oxide layer in between. This approach is expected to take full advantage of rod-lighting effect since the antenna’s sharp tip is maintained. Moreover, the presence of the sharp tip over the MIM diode is expected to localize the enhanced field right over the diode, leaving the passage through the insulating junction as the only path of propagation thereby increasing the rectified output voltage. This approach can also compensate for the mismatch between the nano antenna and the diode as the coupled power between them is fairly increased.
3. THEORY AND DESIGN OF PLASMONIC NANO ANTENNAS

3.1 ANSOFT HFSS

The very fine features of optical antennas make numerical analysis very demanding. In addition to the nano sizes of rectennas, material losses and strong dispersion of metals, at IR and visible frequencies, place a lot of challenges for numerical simulations and computing resources. Thus, choosing software to simulate nano antennas was very critical in the beginning, especially when separation between structures is very small and in the range of a few nano meters. Hoffmann made a very important study where he designed a very challenging problem and compared the ability of different time and frequency domain based software of handling this problem [81]. The problem was to find the localized field between two spheres of 40 nm in radius and 1 nm gap between them. The extremely small gap between the two spheres resulted in 6 orders of magnitude near field enhancement; however the point of designing a very small gap was to test the ability of different software in obtaining accurate results, such as Comsol, HFSS, CST microwave studio. Hoffmann compared the results of these software in 550 to 670 nm band to a semi-analytic MMP code which he considered as a reference because of its accuracy and small time of convergence. This piece of research showed that Ansoft HFSS [82] has the greatest ability among the previously mentioned software to handle nano structures. HFSS is based on Finite Element Method (FEM), it divides any volume into tetrahedral elements then exactly solves the point form Maxwell’s equations at
each node, consequently to obtain the electric field values at any point inside each element it simply performs elemental interpolation. HFSS gives the user the ability to choose the order of basis functions. Zero order basis functions for example assume linear variation inside each element, whereas second order basis functions consider parabolic variations which in turn give more accurate results but on the expense of computational resources such as simulation time. One disadvantage of FEM is that it needs relatively large matrices to solve a certain system of equations where the numbers of equations are equal to the number of unknowns. These unknowns are electric field values at the tetrahedral element vertices. Also nanostructures require a very fine mesh, in other words very small tetrahedral elements, which adds to the complexity of the computations. Figure 3.1-1 shows a description of Hoffman’s problem, the target was to compute the near field at the center of 1nm gap between two metallic spheres made of gold due to a linearly polarized incident plane wave. To simulate an infinite medium and prevent reflections perfectly matched layers or radiation boundaries can be used. In reality this is done by anechoic antenna measurement chamber, these conditions can be simulated in HFSS by inserting the structure into a box with side walls assigned as Perfectly Matched Layer (PML) or Absorbing Boundary Conditions (ABC) at least a quarter wavelength far from the antenna.
In order to reduce simulation time and memory one can use appropriate boundary conditions to simulate a reduced problem which is equivalent to the original one. Electric symmetry around the XZ plane and magnetic symmetry around the XY plane can be easily noticed; as a result, assigning XZ plane as a Perfect Electric Conductor (PEC), and XY as a Perfect Magnetic Conductor (PMC) results in an equivalent problem which is one fourth of the original. Figure 3.1-1 shows this equivalent problem which is based on image theory and can in principle decrease running time and memory required by four times. Another point of concern regarding this problem is the optical properties of gold. Nobel metals are highly dispersive in IR and visible frequency range, thus deep investigation of the frequency dependent relative permittivity of gold was done and will be explained in details in the subsection named Optical Properties of Metals. Reference [83] was used to obtain the real and imaginary part of the dielectric constant which was imported afterwards to HFSS. It is obvious from figure 3.1-2 that gold is very lossy between 300 to 500 nm since the value of the imaginary part of the dielectric constant is high compared to its real part. It is also worth noting that the value of the real part is always negative.
In order to make sure that we are using HFSS correctly we replicated Hofmann’s results and very positive agreement was achieved. Figure 3.1-3 shows near field intensity at the center of the gap versus the wave length of the incident plane wave. The graph compares results at different surface meshing values. Smaller surface mesh gives more accurate results in terms of higher peak and obvious red shift of the resonance wavelength. For 0.02 0.01 and 0.08 nm surface meshing HFSS gives very accurate results compared to MMP reference code.
Figure 3.1-4 shows the agreement of our simulation with Hofmann's, the slight difference in results might be because of the difference in center frequency and HFSS version.

3.2 OPTICAL PROPERTIES OF METALS

In this section we demonstrate a theoretical analysis about dispersive dielectric constant of metal or free electrons which determines the response of the medium to an incident electromagnetic wave the analysis in this section is based on [84].

3.2.1 DRUDE MODEL

Gold is very dispersive at high frequencies such as visible and infrared regimes, which is why frequency dependent optical or electronic properties had to be deeply investigated. From the chemical composition of metals it is known that they consist of fixed positive ions and free electrons, where the positive ions exert no restraining force on the negative charge carriers. Since the number of the two oppositely charged particles is the same, metals are considered to be plasma. According to Mark Fox [84], plasma is defined as a
neutral gas of charged particles. In order to get a deep understanding of metals response to an incident electromagnetic wave, we will start with the Drude-Lorentz model. In 1990 Paul Drude introduced a model to explain the transport properties of electrons in materials. Drude assumed that, in case of dielectrics, the microscopic behavior of electrons can be treated as a classical mechanical problem as shown in figure 3.2-1. Drude assumed that an electron is a body of mass m attached to a fixed core, representing the nucleus, via a spring that models attraction forces done by the nucleus on the electron. He also ignored all types of electron-electron interaction as well as electron-ion interaction. However, he considered that the only possible interaction is the collision between an electron and ion which happens with a fixed probability at every time interval $\tau$. This assumption is explained by figure 3.2-2, where an electron losses it’s momentum in a time interval $\tau$ and then it speeds up again. The reader might think that the presence of free electrons in metals can be thought of as a current, this is physically impossible because electrons travel randomly in opposite directions and the overall velocity is zero. Theoretical analysis in this section is inspired from Mark Fox [84].
In order to obtain a mathematical formula by which we can calculate the value of the dielectric constant of different types of metals at any frequency, we begin with studying the oscillation of a bounded electron due to the incidence of an alternating electric field. The equation of motion according to Newton’s law is as follows.

\[ m \ddot{x}(t) + m \gamma \dot{x}(t) + m \omega_o x(t) = -eE(t) \quad (3.1) \]

The first term represents the acceleration of the electron; the second term represents friction or damping with positive ions where \( \gamma \) is called the damping rate or damping frequency. Also \( \frac{1}{\gamma} \) is the momentum scattering time which is the time interval between each two collisions \( \gamma = \frac{1}{\gamma} \). The third term represents the attraction force between positive ions and negative electrons where \( \omega_o \) is the spring’s resonance frequency, while the fourth term is the driving force due to an external field that results in electron displacement of \( x \) meters from its equilibrium position. Assuming Time Harmonic Light wave as the primer action, then the displacement \( x(t) \) which is the material response will also be time harmonic following the causing effect.

\[ E(t) = E_o e^{i\omega t} \quad (3.2) \]

\[ x(t) = x_o e^{i\omega t} \quad (3.3) \]

\( E_o \) and \( \omega \) are the light’s amplitude and angular frequency respectively. Substituting eqn. 3.2 and 3.3 in 3.1:

\[ x_o = -eE_o / m / (\omega_o^2 - \omega^2 - i\gamma \omega) \quad (3.4) \]
Eqn. 3.4 represents dielectric medium. In order to switch to free carriers or metals case we need to remove positive ions restoring force on electrons in other words remove $\omega_o$.

$$x(t) = eE(t)/m(\omega^2 + i\gamma\omega) \quad (3.5)$$

If we define $p(t)$ as the polarization of the electron gas, $e$ as the electron’s charge and $N$ as the number of electrons per unit volume then we have:

$$p(t) = -Nex \quad (3.6)$$

$$D = \varepsilon_o E + p = \varepsilon_o \varepsilon_r E \quad (3.7)$$

Where $D$ is the electric flux density, $\varepsilon_o$ is free space permittivity, $\varepsilon_r$ is the metal relative permittivity. Considering eqn. 3.6 and 3.7 along with 3.5 and solving for $\varepsilon_r$ we get

$$\varepsilon_r(\omega) = 1 - Ne^2/\varepsilon_o m(\omega^2 + i\gamma\omega) \quad (3.8)$$

In most cases we deal with lightly damped systems where collisions between positive ions and electrons can be neglected. We will see later that this is an acceptable assumption and does not change the value of the relative permittivity.

$$\omega_p^2 = Ne^2/\varepsilon_o m \quad (3.9)$$

$\omega_p$ is defined as the plasma frequency and it corresponds to the electron cloud’s natural frequency. $m$ is the electron’s mass.

$$\varepsilon_r(\omega) = 1 - \omega_p^2/\omega^2 \quad (3.10)$$

Eqn. 3.10 is of great importance as it allows us to calculate the value of the relative permittivity of any metal at any frequency.
### 3.2.2 COMPLEX REFRACTIVE INDEX

From eqn. 3.8 we can decompose $\varepsilon_r$ into a real part $\varepsilon_1$ and an imaginary part $\varepsilon_2$, where

$$\varepsilon_1 = 1 - \frac{\gamma^2 \omega p^2}{1 + \gamma^2 \omega^2} \quad (3.11)$$

$$\varepsilon_2 = \frac{\gamma^2 \omega p^2}{\omega(1 + \gamma^2 \omega^2)} \quad (3.12)$$

Defining complex refractive index of a material as

$$n_c = \sqrt{\varepsilon_r} \quad (3.13)$$

$$n_c(\omega) = n(\omega) + i k(\omega) \quad (3.14)$$

$$n = \frac{(\varepsilon_1 + (\varepsilon_1^2 + \varepsilon_2^2)^{1/2})^{1/2}}{\sqrt{2}} \quad (3.15)$$

$$k = \frac{(-\varepsilon_1 + (\varepsilon_1^2 + \varepsilon_2^2)^{1/2})^{1/2}}{\sqrt{2}} \quad (3.16)$$

For a generic electric field in the phasor form:

$$\overrightarrow{E}(r, t) = \overrightarrow{E}_o e^{\omega t/c_o} e^{i\omega n_c z} e^{-i\omega t} \quad (3.17)$$

Where $r$ is the position vector, $\omega$ is the angular frequency of the incident field, $c_o$ is the speed of light in free space, $n_c$ is the complex refractive index of the material. From eqn.3.14 we can write 3.17 as

$$\overrightarrow{E}(r, t) = \overrightarrow{E}_o e^{-i\omega k z} e^{i\omega n_c z} e^{-i\omega t} \quad (3.18)$$
According to Beer’s law we can define the attenuation coefficient $\alpha (\omega) = 2\omega k / c$. If we put eqn.3.17 in the instantaneous form we get:

$$\vec{E}(r,t) = \vec{E}_0 e^{-0.5\alpha^2} \cos(-\omega t + (\omega n/c_0)\vec{K} \cdot \vec{r})$$

(3.19)

$\vec{K}$ is propagation direction. Now it is obvious that $n$ which is the real part of the complex refractive index is what determines the speed of light inside the material, thus defining the phase velocity as

$$v_{ph} = c_0 / n(\omega)$$

(3.20)

Thus $n$ is called refractive index. Since $k$ is responsible for attenuation in the medium, it is called extinction coefficient.

### 3.2.3 METAL REFLECTIVITY AND FREE CARRIERS CONDUCTIVITY

Reflectivity of metals depends on both refractive index and extinction coefficient and is given by:

$$R = \left| \frac{n_c - 1}{n_c + 1} \right|^2 = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}$$

(3.21)

It is important to know that $n_c$ can be pure real or pure imaginary. Eqn.3.10 leads us to two different regions. First, when $\omega < \omega_p$, $\varepsilon_r(\omega)$ is negative, thus eqn. 3.13 shows that $n_c$ will be pure imaginary leading to 100% reflectivity according to eqn. 3.21. The opposite scenario will happen if the frequency is greater than or equal to the plasma frequency as the reflectivity of metals drops to zero.
Figure 3.2-3: Lightly damped metal reflectivity as a function of frequency [84].

Eqn. 3.1 can be written as follows:

\[ m \frac{dv}{dt} + myv = -eE \]  \hspace{1cm} (3.22)

Where \( v(t) \) is the electron’s speed and is given by

\[ v(t) = v_0 e^{-i\omega t} \]  \hspace{1cm} (3.23)

Substituting in 3.22 and using \( y = \frac{1}{\tau} \) we get

\[ v(t) = -e\tau \frac{E(t)}{m(1-i\omega \tau)} \]  \hspace{1cm} (3.24)

The application of an electric field will drift all electrons into the opposite direction of the applied field which will result in the flow of an alternating current \( j \).

\[ j = -Nev = \sigma E \]  \hspace{1cm} (3.25)

Solving 3.24 and 3.25 to obtain the frequency dependent conductivity

\[ \sigma(\omega) = \frac{Ne^2 \tau}{m(1-i\omega \tau)} \]  \hspace{1cm} (3.26)
Eqn. 3.26 gives the reader the ability to obtain the value of metal’s conductivity at any frequency. It is worth noting that for very low frequencies ($\omega \ll \gamma$) metal’s conductivity becomes independent on frequency and is given by

$$\sigma_o = \frac{N_e^2 e}{m}$$  \hspace{1cm} (3.27)

This Dc conductivity is usually used in millimeter or microwave regimes; however for visible or infrared frequencies eqn. 3.26 is used. All in all, the properties of any metal can be obtained only by knowing two variables: First, plasma frequency which depends on the number of valence electrons and atoms density, Secondly, DC conductivity which can be measured experimentally. The following Table lists the plasma frequency and the number of valence electrons per unit volume for some famous metals. Furthermore; metals are very shiny and reflective for any frequency less than the plasma frequency. Consequently, Metals behave as Perfect electric conductor with very small skin depth for microwave and millimeter waves, whereas it is very lossy and has high penetration in IR and visible regime. Finally, metals act as a lossy dielectric for ultra violet frequencies.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Valence electrons</th>
<th>Electronic density ($10^{28} \text{ m}^{-3}$)</th>
<th>Plasma frequency ($10^{15} \text{ Hz}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>1</td>
<td>4.7</td>
<td>1.95</td>
</tr>
<tr>
<td>Na</td>
<td>1</td>
<td>2.65</td>
<td>1.46</td>
</tr>
<tr>
<td>K</td>
<td>1</td>
<td>1.4</td>
<td>1.06</td>
</tr>
<tr>
<td>Rb</td>
<td>1</td>
<td>1.15</td>
<td>0.96</td>
</tr>
<tr>
<td>Cs</td>
<td>1</td>
<td>0.91</td>
<td>0.86</td>
</tr>
<tr>
<td>Cu</td>
<td>1</td>
<td>8.47</td>
<td>2.61</td>
</tr>
<tr>
<td>Ag</td>
<td>1</td>
<td>5.86</td>
<td>2.17</td>
</tr>
<tr>
<td>Au</td>
<td>1</td>
<td>5.9</td>
<td>2.18</td>
</tr>
<tr>
<td>Be</td>
<td>2</td>
<td>24.7</td>
<td>4.46</td>
</tr>
<tr>
<td>Mg</td>
<td>2</td>
<td>8.61</td>
<td>2.63</td>
</tr>
<tr>
<td>Ca</td>
<td>2</td>
<td>4.61</td>
<td>1.93</td>
</tr>
<tr>
<td>Al</td>
<td>3</td>
<td>18.1</td>
<td>3.82</td>
</tr>
</tbody>
</table>

Table 3.2-1: plasma frequency for some famous metals.
3.2.4 DRUDE MODEL DEFICIENCIES

As mentioned before Drude neglected all interactions that happen between electrons and atoms not only that but also by the time Drude developed his model scientists did not have any quantum mechanical insight. Figure 3.2-4 compares the reflectivity of aluminum calculated using Drude model for lightly damped and undamped system to aluminum measured reflectivity. An interesting observation is that the experimental data shows less reflectivity than what was expected by the Drude model, especially at 1.5eV where there is a significant decrease in reflectivity by almost 20%. The reason for that is the interband transition, figure 3.2-5 shows aluminum band diagram where all energy levels below the Fermi level are full and all those above the Fermi level are empty.

Parallel bands exist at W and K points of the brillouin zone, at these two points the momentum is conserved and there is no need for a phonon to assist transition of electron from valence to conduction band. From the energy band diagram it can be seen that this transition is equal to 1.5eV and is the reason behind the dip in reflectivity. For nano antennas analysis, it is usually better to measure the optical properties of metals using an
ellipsometer. If the measurement setup does not exist then one can find plenty of trustable references. Handbook of Optical Constants of Solids by Edward J. Palik is the most used [85].

3.3 NANO ANTENNAS IN VISIBLE REGIME

We extended Hoffmann’s study to analyze different shapes of nano antennas, in order to create one that will give the greatest field localization and enhancement, which is the main point for our application. We compared the performance of sphere, rod, torus and a bowtie. The same optical properties (figure 3.1-2) and boundary conditions were used. Figure 3.3-1 shows the simulations results which were done at 0.05nm surface meshing. The bowtie shaped dipole showed great performance compared to other antennas. The rod was 20 nm in thickness, 30nm in width and 80nm in length. It also showed weak results with enhancement of only three orders of magnitude. This can be explained by the absence of a sharp tip which is the main reason behind Field enhancement. Bowtie was 80nm in height and 20nm in thickness with a tip of 60° and it showed the best performance. The torus had an inner radius of 21nm and outer radius of 42nm, the Sphere was 80nm in diameter and the gap size for all simulations was 1nm. Incident plain wave propagating normal to the antenna axis with 1v/m electric field polarized parallel to the antenna axis.
It is worth noting that we not only seek high peak but also wider bandwidth in order to make use of broader spectrum. Thus the Area under Curve (AUC) would be a more accurate quantity to judge the performance of the antenna. Consequently, we calculated the AUC for the three antennas. Torus gave 0.0235, Sphere gave 0.0379 and Bowtie gave 0.0573. The physical reason behind bowtie great performance will be discussed in greater detail in the following section. For the sake of study we analyzed the performance of a square loop nano antenna of 1 nm gap as shown in figure 3.3-2. Spiral nano antenna performance was magnificent, with 6 orders of magnitude enhancement. This can be explained by the huge aperture area given to the spiral. Bowtie is still preferred for the spiral because of its ease in fabrication, integration and small size. It is worth noting that the area of the spiral is around four orders of magnitude higher than the bowtie.
3.4 TRAVELLING SURFACE PLASMON POLARITONS

3.4.1 INTRODUCTION FOR SURFACE PLASMONS

Metals are made of fixed positive ions that are not free to move and a moving electron cloud where the electrons are in continuous random motion. Figure 3.4-1 explains the formation of surface oscillations in metals.

Figure 3.4-1: Electrons oscillations and Formation of surface plasmons.

Figure 3.4-1(a) shows the electrons in dynamic equilibrium, because of their continuous motion, spots with high electron concentration will be created as shown in 3.4-1(b). For
example, two electrons will be very close in space and as a result these two electrons will repel and overshoot their original place and different spots of high electron density will be created as shown in figure 3.4-1(c). This process will result in continuous charge oscillations. There are two types of these oscillations: first, surface charge oscillations which are the focus of this study and will be explained in details, secondly, bulk oscillation or bulk plasmons which are not of any interest because they can only be excited at one frequency which is the plasma frequency of a certain metal. Figure 3.4-2 shows the electric filed lines due to surface plasmons.

![Diagram of surface charge oscillations and electric field lines](image)

_Figure 3.4-2: surface charge oscillations and the electric field lines distribution._

Our goal in the following analysis is to understand the behavior of the electric field and its interaction with these surface oscillations and if there is a way to couple the incident field to surface plasmons or surface oscillations.

### 3.4.2 MAXWELL’S EQUATIONS SOLUTION FOR SURFACE PLASMONS

According to Mark Fox [84] surface plasmons are quantized energy electromagnetic waves that are spatially localized to interface between plasma and dielectric.
Following this definition and assuming time harmonic electromagnetic wave, electric and magnetic field can be written as follow for TM case (this analysis follows the analysis by Stefan Maier [86]):

- **Fields in dielectric:**

  \[
  \varepsilon(x, z, t)^d = \left[ E_x^d, 0, E_z^d \right] e^{-i \omega t} e^{i k_x^d x} e^{-k_z^d z} \quad (3.28-a) \\
  H(x, z, t)^d = \left[ 0, H_y^d, 0 \right] e^{-i \omega t} e^{i k_x^d x} e^{-k_z^d z} \quad (3.28-b)
  \]

  \(\omega\) is the angular frequency of the alternating field, \(k_x^d\) is the spatial frequency in the x-direction in the dielectric, \(k_z^d\) is the decaying constant in the positive z-direction in the dielectric.

- **Fields in metal:**

  \[
  \varepsilon(x, z, t)^m = \left[ E_x^m, 0, E_z^m \right] e^{-i \omega t} e^{i k_x^m x} e^{k_z^m z} \quad (3.28-c) \\
  H(x, z, t)^m = \left[ 0, H_y^m, 0 \right] e^{-i \omega t} e^{i k_x^m x} e^{k_z^m z} \quad (3.28-d)
  \]

  \(\omega\) is the angular frequency of the alternating field, \(k_x^m\) is the spatial frequency in the x-direction in the metal, \(k_z^m\) is the decaying constant in the negative z-direction in the metal.
These equations satisfy the mathematical solution of Maxwell’s differential equations as well as surface plasmons’ physical behavior, since they describe evanescent behavior along positive and negative z and only propagation along the interface in the x-direction. Maxwell’s equations describe a boundary value problem where the satisfaction of the differential operator is necessary but not sufficient for the complete solution. Continuity of the tangential electric and magnetic fields as well as the continuity of the normal component of the displacement vector at the interface should be satisfied.

At the interface where $z=0$:

$$E_d^x e^{ik_d^x x} = E_m^x e^{ik_m^x x} \quad (3.29)$$

For this condition to be satisfied at every point along the interface the following two conditions have to be satisfied:

$$E_d^x = E_m^x \quad (3.30)$$

$$k_d^x = k_m^x \quad (3.31)$$

Equation 3.31 is usually known as momentum conservation. To satisfy the normal components continuity:

$$H_d^y = H_m^y \quad (3.32)$$

$$\varepsilon_d E_d^x = \varepsilon_m E_m^x \quad (3.33)$$

Using 3.30 till 3.33 in 3.28-a till 3.28-d:
\[
\varepsilon(x, z, t)^d = \left[ E_x, 0, E_z^d \right] e^{-i\omega t} e^{ik_x x} e^{-k_z^d z} \quad (3.34-a)
\]

\[
H(x, z, t)^d = \left[ 0, H_y, 0 \right] e^{-i\omega t} e^{ik_x x} e^{-k_z^d z} \quad (3.34-b)
\]

\[
\varepsilon(x, z, t)^m = \left[ E_x, 0, E^m_z \right] e^{-i\omega t} e^{ik_x x} e^{k^m_z z} \quad (3.34-c)
\]

\[
H(x, z, t)^m = \left[ 0, H_y, 0 \right] e^{-i\omega t} e^{ik_x x} e^{k^m_z z} \quad (3.34-d)
\]

Equations 3.34-a till 3.34-d totally describe the field behavior in the metal and the dielectric. The value of the amplitude of the fields \( E_x, H_y, E_z^d \) and \( E^m_z \) are not of great importance because they depend on the initial conditions, however \( k_z^d, k^m_z \) and \( k_x \) are critical and very important to be determined in order to obtain a complete solution, because simply they describe the evolution of the electric and magnetic fields along the space. In order to determine these three unknowns, three independent equations are needed. Using Maxwell’s second equation:

\[
\nabla \times H = j_o \varepsilon_r \frac{\partial \varepsilon}{\partial t} \quad (3.35-a)
\]

Considering infinite medium in y-direction and TM case, 3.35-a can be written as:

\[
\left( \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right) \times \left( H_x, H_y, H_z \right) = j_o \varepsilon_r \frac{\partial \varepsilon}{\partial t} \left( \varepsilon_x, \varepsilon_y, \varepsilon_z \right) \quad (3.35-b)
\]

\[
\frac{\partial H_y}{\partial z} = - \frac{\partial \varepsilon_x}{\partial t} \quad (3.35-c)
\]

By applying 3.35-c to 3.34-a till 3.34-d we get:

\[
k_z^d H_y = -i \varepsilon_d \varepsilon_0 \omega E_x \quad (3.36)
\]
\[ k^m_z H_y = i\epsilon_m \varepsilon_0 \omega E_x \]  
(3.37)

3.36 and 3.37 can be written in one equation as

\[ \frac{k^d_z}{\epsilon_d} + \frac{k^m_z}{\epsilon_m} = 0 \]  
(3.38)

As mentioned before, the target of this analysis is to solve for the three unknowns \( k^d_z, k^m_z \), and \( k_x \) because these parameters are what determine the spatial evolution of the electromagnetic waves.

Maxwell’s equations are first order coupled differential equations. In other words, each equation contains both electric and magnetic field. These equations can be decoupled on the expense of increasing the order of the differential equation, resulting in what’s called Helmholtz wave equation:

\[ \nabla^2 \varepsilon = \frac{\varepsilon_d}{c^2} \frac{\partial^2 \varepsilon}{\partial t^2} \]  
(3.39)

For 3.34-a and 3.34-c to be a proper modeling of the electric field inside both media, they should satisfy 3.39. By substituting them in 3.39 we get:

\[ k_x^2 - (k_x^d)^2 = \frac{\varepsilon_d \omega^2}{c^2} \]  
(3.40)

\[ k_x^2 - (k_x^m)^2 = \frac{\varepsilon_m \omega^2}{c^2} \]  
(3.41)

Solving 3.38, 3.40 and 3.41 for the three unknowns \( k^d_z, k^m_z \) and \( k_x \) we get:

\[ k_x = \frac{\omega}{c} \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \]  
(3.42)
\[ k^d_z = \frac{\omega}{c} \sqrt{-\varepsilon_d^2 \over \varepsilon_m + \varepsilon_d} \] (3.43)

\[ k^m_z = \frac{\omega}{c} \sqrt{-\varepsilon_m^2 \over \varepsilon_m + \varepsilon_d} \] (3.44)

\( \varepsilon_m \) is the dielectric function of the metal, \( \varepsilon_m = 1 - \omega_p^2 / \omega^2 \).

In order to get more insight about the interaction between light and surface plasmons we draw the dispersion relation 3.4-4:

\[ \omega = \frac{ck_x}{\sqrt{\varepsilon_d}} \]

Figure 3.4-4: dispersion relation of traveling surface plasmon. The curve was plotted for free space dielectric. Blue curve shows Surface plasmon polariton dispersion. Red line represents free space dispersion.

From graph 3.4-4 the red line represents free space dispersion relation, where the angular frequency of the wave is proportional to its spatial frequency with a constant rate of change which is equal to the phase or group velocity of light. However, for surface waves dispersion relation is not that simple. The first observation is that we have no solution for
frequencies between $\omega_{sp}$ and $\omega_p$. In other words, electromagnetic waves with angular frequency that is $\omega_{sp} < \omega < \omega_p$ cannot propagate as surface waves simply because there is no value for their wave vectors. The second observation is that the value of $k_x$ is constant at $\omega = \omega_{sp}$. Thus at very high values of the wave vector along x-direction the group velocity ($\frac{d\omega}{dk}$) is equal to zero. From eqn. 3.42, $k_x$ goes to infinity when $\varepsilon_m + \varepsilon_d$ goes to zero and $\omega = \omega_{sp}$

$$\varepsilon_m = 1 - \frac{\omega_p^2}{\omega^2}$$  \hspace{1cm} (3.45)

$$\varepsilon_d = 1 - \frac{\omega_p^2}{\omega_{sp}^2}$$  \hspace{1cm} (3.46)

$$\omega_{sp} = \frac{\omega_p}{\sqrt{1 + \varepsilon_d}}$$  \hspace{1cm} (3.47)

For our case the dielectric is free space and the metal is gold, so $\omega_p = 1369.7 \times 10^{12} \text{ r/s}$, $\omega_{sp} = \frac{\omega_p}{\sqrt{2}}$.

The interaction between light and surface plasmons is very strong. In order to couple incident electromagnetic power to travelling surface waves, their wave vectors have to be the same in order to conserve momentum and satisfy boundary conditions. This region extends from 0 to 0.3$f_p$(65.4 THz) as shown in figure 3.4-4. In this project we target frequencies between 20 to 60 THz, thus we can guarantee coupling of incident light to surface waves and excite surface plasmon polariton which is one reason behind electromagnetic energy enhancement in nano antennas. For frequencies higher than 0.3$f_p$ at which we have momentum mismatch we can still couple electromagnetic energy by the use of gratings or prisms. Even though there is a solution for frequencies higher than
plasma frequency, this region is not very attractive to work with because of high losses in metal. As mentioned before metals act as lossy dielectrics in UV region.

## 3.5 LIGHT INTERACTION WITH SUB WAVELENGTH PARTICLES

![Figure 3.5-1: Linearly polarized electric field incident on a nano sphere with dielectric function ε immersed in a medium. with a dielectric constant ε_m](image)

For detailed analysis of this topic the reader is encouraged to read classical electromagnetic books like classical electrodynamics by Jackson [87]. Since the wave length is much longer than the particle size, we can assume that there is no change of the field value around the particle; as a result we can analyze the problem as electrostatic one.

\[ \nabla^2 \Phi = 0 \quad (3.48) \]

\[ E = -\nabla \Phi \quad (3.49) \]

Due to azimuthal symmetry the general solution is:

\[ \Phi(r, \theta) = \sum_{l=1}^{\infty} \left( A_l r^l + B_l r^{-(l+1)} \right) P_l(\cos \theta) \quad (3.50) \]

Where \( p_l(x) \) is known as Legendre Polynomial of order \( l \) and \( \theta \) is the angle between the position vector \( r \) at point P and the z-axis (Fig. 3.5-1):
\[ P_n(x) = 2^n \sum_{k=0}^{n} x^k \left( \frac{n+k+1}{2^n} \right) \]  
(3.51)

We first start with decomposing the problem into two regions; one of them is inside the sphere, while the other is outside the sphere. For the field to be finite inside the sphere:

\[ \Phi_{\text{in}}(r, \theta) = \sum_{l=1}^{\infty} (A_l r^l) P_l \cos \theta \]  
(3.52)

\[ \Phi_{\text{out}}(r, \theta) = \sum_{l=1}^{\infty} (B_l r^l + C_l r^{-(l+1)}) P_l \cos \theta \]  
(3.53)

At infinity and for static problem the electric filed value will be \( E_o \) and \( \Phi_{\text{out}} = -E_o z \), also at infinity the second term between brackets becomes zero, thus:

\[ \Phi_{\text{out}}(r, \theta) = \sum_{l=1}^{\infty} (B_l r^l) P_l \cos \theta \]  
(3.54)

Since \( P_1(x) = x \), \( B_l = E_o \) when \( l = 1 \) and \( B_l = 0 \) otherwise. In order to satisfy the boundary conditions at \( r = a \):

\[ -\frac{1}{a} \frac{\partial \Phi_{\text{in}}}{\partial \theta} = -\frac{1}{a} \frac{\partial \Phi_{\text{out}}}{\partial \theta} \]  
(3.53)

Eqn. 3.53 satisfies the Continuity of tangential E-field components

\[ -\varepsilon_o \varepsilon \frac{\partial \Phi_{\text{in}}}{\partial r} = -\varepsilon_o \varepsilon_m \frac{\partial \Phi_{\text{out}}}{\partial r} \]  
(3.54)

Eqn. 3.54 satisfies the equality of normal components of the displacement vector
With straight forward algebra one can find:

\[ \Phi_{in} = -\frac{3\varepsilon_m}{\varepsilon + 2\varepsilon_m} E_o r \cos \theta \]  
\[ \Phi_{out} = -E_o r \cos \theta + \frac{\varepsilon - \varepsilon_m}{\varepsilon + 2\varepsilon_m} E_o a^3 \cos \theta \frac{\cos \theta}{r^3} \] (3.55) (3.56)

Defining \( p \) as:

\[ P = 4\pi \varepsilon_o \varepsilon_m a^3 \frac{\varepsilon - \varepsilon_m}{\varepsilon + 2\varepsilon_m} E_o \] (3.57)

Using the definition of \( P \) in 3.56 we get:

\[ \Phi_{out} = -E_o r \cos \theta + \frac{p_r}{4\pi \varepsilon_o \varepsilon_m r^3} \] (3.58)

\[ \alpha = 4\pi a^3 \frac{\varepsilon - \varepsilon_m}{\varepsilon + 2\varepsilon_m} \] (3.59)

Where \( \alpha \) is called the polarizability factor, from 3.57:

\[ P = \varepsilon_o \varepsilon_m \alpha E_o \] (3.58)

Using the nabla operator on 3.55 and 3.58 we get the fields expressions:

\[ E_{in} = \frac{3\varepsilon_m}{\varepsilon + 2\varepsilon_m} E_o \] (3.59)

\[ E_{out} = E_o + \frac{3n(nP) - p}{4\pi \varepsilon_o \varepsilon_m} \frac{1}{r^3} \] (3.60)

In order to obtain field enhancement outside the sphere we need to maximize \( E_{out} \) (i.e maximize \( P \)). Polarizability factor \( \alpha \) is maximum when \( |\varepsilon + 2\varepsilon_m| \) is minimum.
Figure 3.5-2 shows that $\alpha$ is a resonance factor, in other words it shoots up at certain frequencies, thus the electric field outside is significantly enhanced at this frequency.

3.6 LIGHT CONCENTRATION AT NANO TIPS

There are two main reasons behind light accumulation at nano tips. The first one is the famous lightning rod effect; to protect buildings from being struck by lightning and catching on fire, a long metallic rod with a tapered end is attached to the roof of the building. This tapered end will accumulate charges around it and the lightning will strike this end, which in turn is connected to the ground to discharge. This can be interpreted by Maxwell’s equations as follows:

$$\mathbf{V} \times \mathbf{H} = \mathbf{D} + \mathbf{J}$$  \hspace{1cm} (3.61)

$$\mathbf{V} \cdot \mathbf{V} \times \mathbf{H} = \mathbf{V} \cdot \mathbf{D} + \mathbf{V} \cdot \mathbf{J}$$  \hspace{1cm} (3.62)

$$\mathbf{V} \cdot \mathbf{D} = -\mathbf{V} \cdot \mathbf{J}$$  \hspace{1cm} (3.63)
\[ \nabla \cdot J = -\partial_t (\nabla \cdot D) \quad (3.64) \]
\[ \partial_t (\rho) = -\nabla \cdot J \quad (3.65) \]

Equation 3.65 shows that the divergence of the current density is directly proportional with the rate of change of the charges at a point. In order to observe the validity of this analysis we plotted the current distribution for one of the bowtie simulation. Figure 3.6-1 shows that the divergence of the surface current at the corners of the bowtie nano antenna is much greater than any point at the middle thus the accumulation of charges increase which results in the enhancement of the normal component of the displacement or electric field vector.

![Figure 3.6-1: Simulated surface current vector distribution for bowtie nano antenna.](image)

Second, according to Stockman [88] the group and phase velocity of surface waves decrease with propagation and go to zero at the tip of a tapered cone as shown in figure 3.6-2, Thus electromagnetic energy accumulates at the end.
Figure 3.6-2: (a) phase and group velocity are zero at the tip of a cone. (b) Electric field enhancement along propagation direction z [88].

3.7 NANO ANTENNAS APPLICATIONS

Nano antennas have numerous numbers of applications. Near field optical microscopy: localized near field will allow nano scale features in biological and solid state systems to be illuminated i.e. spatial resolution better than the diffraction limit. New sensors that are capable of detecting a single molecule of a chemical or biological agent. In optoelectronics it can be used as ordered arrays of closely spaced metal nanoparticles which enable the guiding of electromagnetic energy in sub wavelength-sized devices. Nano antennas integrated diodes for energy harvesting (rectenna) which is the main study of this thesis.

3.8 NANO ANTENNAS PARAMETERS INVESTIGATION

Unlike microwave antennas theory, nano antenna theory is not well established. In order to get a hold of the parameters that affects nano antennas performance in terms of resonance frequency and field enhancement we did a parametric analysis to investigate the effect of gap size, apex angle, antenna dimensions, polarization and angle of incidence.
3.8.1 GAP SIZE

Figure 3.8-1 shows the simulation results of a bowtie dipole with a base of 2µm and arm length of 2µm with a gap that varies from 10nm to 100nm with 10nm step. Incident wave propagating perpendicular to the antenna axis with linearly polarized field of intensity of 1v/m.

![Graph showing near field intensity calculated at the gap center for different gap sizes.]

It was obvious from the simulation results that the gap size has significant effect on field intensity. As gap size increases, electric field intensity dramatically decreases and resonance frequency slightly blue shifts. This can be explained by the evanescent nature of the induced surface waves. The further the observation point from the bowtie tip is, the lower the field intensity that can be detected. To conclude, it is better to design nano
antennas with very small gaps in order to get more field enhancement, however nano fabrica-
tion techniques are still the greatest obstacle.

### 3.8.2 TIP ANGLE

In order to detect the effect of the apex on the antenna performance we fixed the length of the nano antenna at 2μm and the gap at 10nm and we ran simulations for 20°, 40°, 80°, 100°, 140°. Figure 3.8-2 shows that field enhancement increases as we go from 20° to 80° and then it decreases again. The optimum angle will not be fixed for different antenna dimensions. To sum up, tip angle has to be optimized for different designs and different substrates.

![Figure 3.8-2: Near field intensity variation with tip angle.](image)

### 3.8.3 ANTENNA LENGTH

In microwave regime the condition for resonance is usually that the electrical length is an integer multiple of half wavelength. On the other hand that is not the case with nano antennas. Figure 3.8-3 shows simulation results for a bowtie with 80° tip angle and 10 nm
gap. The arm length was varied between from 1μm to 4μm. As the arm length increases, aperture area and field intensity increases as well. However, at the same time, dissipation in each arm increases. The optimum bowtie length will not be fixed for different antenna dimensions. In short, bowtie length has to be optimized for different designs, substrates, and resonance wavelength.

![Near field intensity variation with antenna length.](image)

**Figure 3.8-3**: Near field intensity variation with antenna length.

### 3.8.4 FIELD POLARIZATION AND ANGLE OF INCIDENCE

In antenna theory, reception is most effective when the polarization of the incident field is similar to the polarization of the receiving antenna in transmission mode. Simulation showed that the same rule applies for nano antennas. In order to validate that rule we simulated all possible space locations of the propagation direction and electric filed polarization in 3-D. Where the polar angle θ varies from 0° to 90° with 18° step and at each angle the azimuthal angle φ varies from 0° to 180° with 18° step.
According to simulation results in figure 3.8-4, maximum electric field enhancement (five orders of magnitude) will happen at $\theta=0^\circ$ & $\phi=0^\circ$, i.e. Wave Vector is perpendicular to antenna’s surface and E-field is Polarized parallel to antenna’s axis. The induced field is zero when the incident field polarization is perpendicular to the plain containing the antenna, this result applies for any nano antenna design.

### 3.9 28THz (10.6 μm) NANO ANTENNA DESIGN

For energy harvesting applications the antenna should be broad band and resonate at 10.6μm, which is the peak of the infrared emissions. For a normal dipole the impedance and radiation properties of the antenna are frequency sensitive, slight variation of the incident wave frequency or fabrication inaccuracy can give rise to parasitic inductances or capacitances. Also narrow bandwidth of dipole antennas with narrow dipoles pushed us to look for a broadband antenna that can be fabricated with high precision using electron-beam lithography. The solution for that would be the bowtie antenna which can be
considered as a tapered dipole antenna. In addition to its easy design, the impedance of an infinite dipole is frequency independent and depends only on the flare angle as given as follows [89]:

\[
Z_{\text{ant}} = \frac{\eta_0}{2} \sqrt{\frac{1}{\epsilon_{\text{eff}} K(\cos(\varphi/2))} K(\sin(\varphi/2))}
\] (3.66)

\(K(x)\) is the complete elliptic integral of the first kind [90], \(K(x) = \int_0^\pi \frac{d\theta}{\sqrt{1-x^2\sin^2\theta}}\). \(\eta_0\) is the free space characteristic impedance, \(\epsilon_{\text{eff}}\) is the effective dielectric function that the 28 THz wave see when incident on an antenna on substrate.

### 3.9.1 ANTENNA ON SUBSTRATE

Due to symmetry, a planar antenna in air radiates equally on both sides. This symmetry can be broken by the presence of a substrate on one side, which in turn changes the phase velocity and current distribution on the antenna’s surface. According to [91] an on substrate antenna radiates most of its power to the substrate side. Due to reciprocity, an antenna on substrate couples more energy from the substrate side and the ratio between them is given by:

\[
p_{\text{sub}} = \left(\frac{\epsilon_{\text{sub}}}{\epsilon_{\text{air}}}\right)^{3/2} p_{\text{air}}
\] (3.67)

Where \(\epsilon_{\text{sub}}\) is the substrate’s relative permittivity, figure 3.9-1 [67] shows the evolution of the effective permittivity of a silicon substrate with frequency.
For 28.3 THz, the effective permittivity of a silicon substrate is 11.6 thus the electromagnetic power coupled to the antenna from the substrate side is 40 times that coupled from air side. In order to make use of this property, we used the following stack up shown in figure 3.9-2, along with high resistivity 375µm silicon substrate, in order to reduce substrate losses. 1.5µm silicon dioxide layer is added to both sides to act as an antireflective coating at 10.6µm. This matching section improves the transmission to the substrate by 80%. Gold back reflector of 200nm in thickness is used to insure full reflection and coupling to the antenna from the substrate side. 5nm chromium layer was put under the gold nano antenna for sticking purposes.
Francisco Gonzalez measured the optical properties of 75nm thin film gold evaporated on a silicon substrate at infrared frequencies (5-15 µm) [92]. The fitted equations for the experimental results are:

\[
n(f) = -0.5097680004322286 - \frac{3.0508946281044503 \times 10^{40}}{f^3} + \frac{8.694327295404505 \times 10^{27}}{f^2} + \frac{7.071831942548983 \times 10^{13}}{f} \tag{3.68}
\]

\[
k(f) = -0.8507140979084992 + \frac{3.494475566745883 \times 10^{39}}{f^3} - \frac{5.767704394113701 \times 10^{27}}{f^2} + 2.20946290239641 \times 10^{14} \frac{1}{f} \tag{3.69}
\]

Since \(\epsilon_r = n_c^2\), \(n_c\) is given by 3.14, thus:

\[
\epsilon_{real} = n^2 \cdot k^2 \tag{3.70}
\]

\[
\epsilon_{imaginary} = 2nk \tag{3.71}
\]

Using equations 3.68 and 3.69 along with 3.70 and 3.71 we get Gold optical properties as shown in figure 3.9-3.
3.9.2 NANO ANTENNA OPTIMIZATION FOR MAXIMUM FIELD ENHANCEMENT

Frequency dependent gold optical properties in figure 3.9-3 were imported to HFSS for exact simulation. For other materials HFSS library was used. 1v/m incident electric field polarized in a direction parallel to the antenna axis with surface meshing of 1 nm. Dimensions and the Thickness of the nano antenna were optimized to resonate around 10.6µm and give maximum electric field enhancement at the center of a 50nm gap.

Figure 3.9-4: Near field intensity for non-optimized (blue curve) and optimized (red curve) bowtie nano antenna.
Optimization process resulted in 2.3μm arm length (3/2 of the incident wavelength) and 90° flare angle with 100 nm of thickness. After these first results it was obvious that the optimization should be done for both antenna length and tip angle at the same time. The optimization for these two parameters resulted in relative intensity enhancement of 4 orders of magnitude. Optimized simulation results are shown in the below.

![Image](image.png)

**Figure 3.9-5**: Variation of near field intensity in a 50nm gap with both length and bow angle simultaneously at 28.3THz.

The highest values obtained for the 50nm gold bowtie is summarized in the table below.

<table>
<thead>
<tr>
<th>Near Field Intensity($V^2/m^2$)</th>
<th>Bow Angle</th>
<th>Arm Length(μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1433*10^4</td>
<td>50°</td>
<td>2.7</td>
</tr>
<tr>
<td>3.5341*10^4</td>
<td>20°</td>
<td>2.8</td>
</tr>
<tr>
<td>3.2347*10^4</td>
<td>20°</td>
<td>2.7</td>
</tr>
<tr>
<td>3.1489*10^4</td>
<td>30°</td>
<td>2.7</td>
</tr>
<tr>
<td>3.0785*10^4</td>
<td>70°</td>
<td>2.3</td>
</tr>
</tbody>
</table>

*Table 3.9-1*: Simulated near field intensity for different bowties of 50nm gap at 28.3 THz.

In order to see the variation and the increase of the localized near field intensity enhancement, we ran simulations for different gap sizes.
Figure 3.9-6: Optimized near field variation with different gaps.

Figure 3.9-6 shows the maximum localized field that can be obtained for our optimized antenna. Simulation shows that an intensity enhancement of 8 orders of magnitude can be obtained for 0.5 nm gap. This result is greater than any reported antenna by at least 2 orders of magnitude.
4. **ANTENNA INTEGRATED DIODE REALIZATION**

Quantum mechanical tunneling occurs when an electron penetrates a potential barrier instead of overcoming it. Electron tunneling is the only dynamics by which electric current can pass through an oxide sandwiched between two metals. Tunneling time is dependent on quantum transition probability per unit time making tunneling time very short and thus tunneling diodes are the most suitable for infrared detection.

### 4.1 TUNNEL DIODE

In 1958, Leo Esaki, a Japanese scientist [93] discovered a negative resistance behavior of a heavily doped semiconductor junction diode. Esaki used doping ratio of 1000 impurity atom to $10^7$ semiconductor atoms. Esaki's tunnel diode showed very unusual I-V characteristics, figure 4.1-1 [93], due to the high doping.

![Figure 4.1-1: I-V characteristic curve of a regular PN diode and tunnel diode. [93]](image-url)
In regular diodes the doping ratio is one impurity atom to every ten million semiconductor atom. The low doping value results in a wide depletion region and electron transport only if the applied voltage is high enough to overcome the potential barrier. In tunnel diode (pink curve) however it can be noticed that electrons pass the barrier and the current increases until it peaks at point 2 and reaches a value of $I_p$. This can be explained by electron tunneling through the very thin depletion region resulted from the high doping (one-millionth of an inch). There are four essential conditions for tunneling to occur from conduction band to valence band or vice versa [94]. First, barrier’s width is thin enough for finite tunneling probability. Second, existence of occupied energy states at the side from which electron tunnels. Third, existence of unoccupied energy states at the side electron tunnels to. Finally, conservation of electron’s momentum.

### 4.2 MIM DIODES

MIM tunneling diode is made of a thin oxide layer sandwiched between two electrodes made of either similar or different metals, where electrons can tunnel from one electrode to the other electrode. The MIM device is known by two other names, metal barrier metal (MBM) or metal oxide metal (MOM). The non-ohmic I-V characteristic of MIM can be asymmetric if the difference between the work functions of both metals is fairly large. MIM diodes can work as electromagnetic detectors especially for optical and infrared frequencies. Since the induced current on antenna’s surface has the same frequency as the incident optical radiation. No off the shelf electronic diode at present, can rectify the THz signal. On the contrary, MIM diodes can partially rectify THz signals due to the non-linearity in their I-V curve, in other words MIM has a nonlinear relation between the
current that passes through the oxide and the voltage developed across it. The voltage across the diode due to the passage of an Ac current with angular frequency $\omega$ takes the following form:

$$V = V_{dc} + V(\omega) + V(2\omega) + V(3\omega) + \cdots \quad (4.1)$$

Where the Dc voltage depends on the variation of the current across the diode with respect to the bias voltage [66]:

$$V_{\text{rect}} = -\frac{1}{4} \frac{f'(V_{\text{bias}})}{f'(V_{\text{bias}})} v_{ac}^2 \quad (4.2)$$

$v_{ac}$ is the amplitude of the Ac signal across the diode.

The first MIM optical detector was a point contact diode called cat-whisker, at which a metallic wire, usually tungsten, acts as an antenna to couple light via its very sharp tip to the oxide layer for rectification as shown in figure 4.2-1.

![Figure 4.2-1: Sharp tip tungsten wire with point contact.](image)

Point contact diodes were used in communications applications starting from few Giga hertz till 150 THz [95, 96]. Due to the instability and fragility of the point contact diode researchers started to use planar MIM which will be discussed in details in this chapter.
4.2.1 ADVANTAGES OF MIM TUNNELING DIODE

MIM diodes are characterized by their great performance when it comes to speed, operation in room temperature and ease of fabrication. The very short time required for tunneling process (in the range of pico-seconds)[97] makes tunneling diodes very fast which in turn makes them the most suitable for infrared and optical detection. The band gap of semiconductor materials that are being used for infrared and optical detection is comparable to KT at room temperature. Thermally excited electrons as a result can populate the conduction band of the semiconductor. In this case, the thermally generated current at room temperature will be greater than that generated by optical radiations. In contrast, the barrier energy of the tunneling diode is greater than the energy of thermally generated electrons at room temperature giving a chance for the tunneling current to dominate the dark current. Even though, the barrier’s thickness cannot exceed a few tens of angstroms for efficient tunneling, the process of fabrication is not difficult and does not require any complicated masks, a precise atomic layer deposition (ALD) process is enough.

4.2.2 LIMITATIONS OF MIM TUNNELING DIODE

Four major factors reduce MIM diodes performance. The most effective challenge is the efficient coupling of the antenna modes to the junction modes. In addition, the high resistance of the junction causes a huge mismatch between the antenna and the diode. Even though the fabrication process is easy, the precise growth of few nanometers of oxide can be a problem. Finally, the diode introduces considerable parasitic capacitance.
4.3 THEORTICAL MODEL OF MIM

In this section the theoretical analysis and design parameters of AID are presented. In the design section we will follow the rules that were deduced from the AID equivalent circuit model. MIM design has certain trade offs. For instance the increase in the oxide thickness increases the non-linearity in the I-V curve but decreases the tunneling current significantly. Furthermore, the decrease of the contact area decreases the capacitance (increase response time and cut off frequency) and also increase the diode’s resistance (increase antenna/diode mismatch). In this section we investigate each design parameter in detail.

4.3.1 EQUIVALENT CIRCUIT MODEL OF ANTENNA INTEGRATED DIODE

Figure 4.3-1 shows the equivalent circuit of an antenna integrated diode [77]. The antenna is represented by an AC voltage source and an internal impedance $R_A$. The diode is modeled as a nonlinear resistance $R_D$, where rectification occurs, and a parallel capacitance $C$, where $C = \varepsilon_0\varepsilon_d a/L$. $\varepsilon_0$ and $\varepsilon_d$ are the free space and oxide’s relative permittivities respectively, a and L are the diode contact area and oxide thickness respectively.
4.3.2 POWER COUPLING FROM ANTENNA TO DIODE

Sanchez showed that the max power delivered to the load $R_D$ is given by:

$$P_r = 2P \frac{1}{1+\sqrt{1+q^2}}$$  \hspace{1cm} (4.3)

$P$ is the incident power on the load by the antenna, $P_r$ is the delivered power to the load, $q = \omega c R_A$.

It is obvious from equation 4.1 that the delivered power $P_r$ is maximized when $q \ll 1$. In other words, power coupled to the diode from the antenna is maximized when the capacitance of the diode $c$ is minimized. If $q \ll 1$ all the power is delivered to the diode, from equation 4.1 $P_r = P$, and matching between antenna and diode is achieved.

4.3.3 RECTIFICATION

For the equivalent circuit in figure 4.3-1 the rectified voltage due to an incident power $P_{\text{inc}}$ can be expressed as:
\[ V_r = \frac{4\beta_i P_{\text{inc}} R_D^2}{1 + 2R_D R_A (1 + q^2) R_D z^2} \]  

(4.4)

\( \beta_i = \frac{i_r}{P_r} \) is defined as the current responsivity. The rectified power across the diode is then given by:

\[ P_{dc} = \frac{V_r^2}{R_D} \]  

(4.5)

With an optimum conversion efficiency of [77]:

\[ \eta_e = \frac{P_{dc}(\omega_0)}{P} \]  

(4.6)

\( x \) represents the ratio between \( R_D \) and \( R_A \), \( x_0 \) is the optimum ratio between the antenna internal impedance and the diode resistance that gives maximum conversion efficiency.

Figure 4.3-2: Conversion efficiency as a function of \( q (\omega c R_A) \). [77]
For frequencies in the roll off region ($\omega c R A \gg 1$) the conversion efficiency decreases as $q^{-3}$. From figure 4.3-2 it is obvious that $\omega c R A \ll 1$ at the frequency of interest. This is another main reason why the capacitance should be as small as possible, and this condition can be only achieved by decreasing the diode area since $c = \epsilon_0 \epsilon_d a / L$.

To quantify the maximum value of $c$ Sanchez introduced the cut off frequency of MIM diode. After this frequency the detection of the diode decreases by $f_c^{-3}$:

$$f_c = \frac{1}{2\pi R A c} \quad (4.7)$$

According to 4.7 the value of $c$ needs to be minimized for infrared operations. Furthermore, the rectification speed is proportional to $e^{-t/CRD}$ and thus to speed up the process the value of $c$ should be minimized by minimizing the overlap area.

To sum up, three main reasons in the design of MIM requires the minimization of the capacitance. First, according to equation 4.3 the minimization of $c$ will result in more delivered power to the diode. Second according to figure 4.3-2 the lower the value of $C$ the greater the conversion efficiency. Third, from equation 4.7 the diode capacitance should be small to increase the cut off frequency. Finally, Decreasing $c$ will speed up the process.

4.3.4 OXIDE THICKNESS

In order for tunneling to take place the two metals sandwiching the oxide should have different work functions. This can be done by either using two different metals with huge difference in work function or applying a bais voltage which in turn gives raise to difference in Fermi level by $qV_{Bias}$. Figure 4.3-3 [98] shows the change in the tunnel
resistance with the applied voltage for different thicknesses of the oxide. The work functions of both metals are 1 and 2 volts respectively. It is very obvious from figure 21 that a slight change in the oxide thickness results in a dramatical change in the value of the oxide resistance.

![Diagram](image)

**Figure 4.3-3: Variation of tunnel resistance with applied voltage for 3 oxide thicknesses [98].**

It is worth mentioning again that the resistance of the diode should be kept small in order not to lose the matching with the antenna’s internal impedance which is in the range of tenth of ohms.

\[
D = \exp\left(-2d \frac{\sqrt{2m(V - E)}}{(\hbar/2\pi)}\right) \quad (4.8)
\]

Equation 4.8 shows the transmission probability of the modified Schrödinger for an electron via a potential barrier of height V [99]. If d represents the barrier thickness then the probability of tunneling or the tunneling current value decreases exponentially by
increasing the oxide thickness \( d \). Tunneling probability of an electron via oxide of thickness 0.1, 1 and 10 nm are 0.68, 0.02 and \( 3 \times 10^{-17} \).

To conclude, the oxide thickness should be as small as possible in order to minimize the diode resistance and increase the tunneling probability, however decreasing the oxide thickness will increase the diode’s capacitance which will lead to lower cut of frequency and higher response time.

**4.4 FABRICATION PROCEDURES**

The fabrication of nano antenna integrated diode is complicated and goes through many stages. In this section we explain the fabrication steps that have been done in this project.

**4.4.1 WAFER CLEANING**

Wafer should be cleaned before the start of the process for removing any native oxide. We used high resistivity silicon wafer with relative permittivity of 11.7, bulk conductivity of 0.05 Siemens/m, and 375\( \mu \)m of thickness. The high resistivity wafer is used to improve the performance of the antenna by reducing the electric current that leaks from the antenna feed into the substrate. The cleaning operation is done by immersing the wafers in a Buffered Oxide Etch (BOE) for 5 minutes and then with three cycles of deionized water bath. Afterwards the wafer must be dried using Nitrogen \( (N_2) \) gun.
4.4.2 BACK REFLECTOR SPUTTERING

As mentioned in chapter 2, the wafer should be coated with gold layer from the back side with thickness of 4 times the skin depth at the operating frequency to ensure full reflection and guarantee substrate coupling. From equation 3.27 the value of \( \tau \) can be calculated as:

\[
\tau = \frac{Ne^2\sigma_0}{m} = 2.47 \times 10^{-14} \text{ sec} \tag{4.9}
\]

\( e = 1.6 \times 10^{-19} \text{ C}, m = 6.1 \times 10^{-31} \text{ kg}, N = 5.9 \times 10^{28} \text{ m}^{-3}, f_p = 2.18 \times 10^{15} \text{ Hz.} \)

For frequencies comparable to the damping frequency \( \gamma \) skin depth is given by:

\[
\delta = \frac{c}{\omega_p} \sqrt{\frac{2}{\tau f}} = 35.98 \text{ nm} \tag{4.10}
\]

The back reflector is 200 nm which is around 5 times of gold skin depth at 28.3 THz, and is enough to ensure total reflection from the back of the substrate. The back reflector was added using electron beam evaporator as shown in figure 4.4-1.

![Gold back reflector to ensure substrate coupling.](image-url)
4.4.3 PECVD FOR SILICON DIOXIDE GROWTH

Intrinsic impedance of Silicon is given by $120\pi/\sqrt{\varepsilon_r}$ and thus transmission from air to silicon is given by:

$$T = 1 - \frac{\sqrt{1 - \left(\varepsilon_{rси} / \varepsilon_r\right)}}{\sqrt{1 + \varepsilon_{rси} / \varepsilon_r}} = 45\%$$ (4.11)

Equation 4.11 shows that when an electromagnetic wave is incident on a silicon surface 55% is reflected back and 45% is transmitted, so around half of the power is lost.

In this project we show that 1.6µm silicon dioxide ($SiO_2$) will work as a matching section between air and silicon to improve the transmission. It is worth mentioning here that all the transmitted power will be reflected back by the gold back reflector to be coupled to the antenna from the substrate side.

According to Pozar [100] the input impedance seen by the EM waves incident from air to $SiO_2$ section over Silicon substrate is given by:

$$Z_{in} = Z_{SiO_2} \frac{Z_{Si} + jZ_{SiO_2} \tan(\beta l)}{Z_{SiO_2} + jZ_{Si} \tan(\beta l)}$$ (4.11)

$$\beta = 2\pi/\lambda, \quad \lambda = \frac{10.6}{\sqrt{\varepsilon_{rSiO_2}}} = \frac{10.6}{\sqrt{2.16}}$$ So the effective wavelength of light in $SiO_2$ is 7.2µm.

$$Z_{SiO_2} = 120\pi/\sqrt{\varepsilon_{rSiO_2}}, \quad Z_{Si} = 120\pi/\sqrt{\varepsilon_{rSi}}.$$ Substituting these values at equation 4.11 we get

$$Z_{in} = 1.7 \times \eta_0 \quad \text{and} \quad R = \frac{1.7 - 1}{1.7 + 1} = 25\%$$ this means that, adding 1.6µm of $SiO_2$ increases transmission from 45% to 75%. 

The $\text{SiO}_2$ antireflective coating can be added to the silicon wafer using several techniques such as sputtering, atomic layer deposition (ALD) or plasma enhanced chemical vapor deposition (PECVD). ALD produces the best uniformity of a thin film, however it is very slow. For this project we chose to work with PECVD because it produces good uniformity with high deposition rate and precise thickness.

![Image](image.png)

**Figure 4.4-2: SiO$_2$ Matching section over silicon wafer.**

PECVD process parameters are $\text{SiH}_4$ - 6sccm, $\text{N}_2\text{O}$ - 850sccm $\text{N}_2$ - 162.5sccm, Pressure - 1000mT, RF power - 20W, Table temperature - 300°C, Deposition rate : 66nm/min.

### 4.4.4 CUTTING, CLEANING AND ELECTRON RESIST SPIN COATING

In this step we cut and clean the wafer before we add the electron beam resist. After cutting the wafer into 1cmx1cm samples using a diamond scriber it should be immersed in acetone ($\text{CH}_3\text{COCH}_3$) for 5 minutes and shacked using ultra sonic bath, the same process is then repeated one time using isopropyl alcohol ($\text{CH}_3\text{CH}_2\text{CHOH}$) and anothera time using deionized water. The sample is then dried by $\text{N}_2$ gun and prebaked for 5 minutes at 120°C.
Figure 4.4-3 shows the variation of the thickness of the PMMA with the spin speed of the spin coater machine. For a good lift off process the ratio between the electron beam resist and the required metal thickness should be 5:1 respectively. In order to get 100nm of gold we use PMMA 950 A4 with a spin speed of 1000 rpm and 500 rpm/s ramp. After wards the sample is soft baked at 180°c for 10 minutes to dry the resist. In order to improve the liftoff process MMA/PMMA bilayer electron resist was used. MMA electron resist has lower resistivity than PMMA which facilitates the lift off process.

Figure 4.4-4: Sample stack up before lithography.
4.5 ELECTRON BEAM LITHOGRAPHY

Electron beam lithography (EBL) is a special technique of fabricating structures with nanometers dimensions. EBL consists of an electron beam that scans over a sample covered with a resist to these electrons. EBL has two main advantages; first, it has very high resolution in, second the ability of working with different materials and drawing complicated structures. However EBL is slow and expensive. In 1969 M.hatzakis [101] used the common polymer polymethyl methacrylate (PMMA), that works as electron resist. Since then PMMA is the most common electron resist used in EBL fabrication.

![Figure 4.5: EBL major components][102]

Figure 4.5-1 [102] shows the main components of an EBL system which is composed of three main parts. First, a column that forms and controls the beam. Second, a chamber underneath the beam that contains a stage where the sample can be mounted and can be
moved around for patterning. The vacuum system attached to the chamber is to maintain a certain pressure during the operation. The whole system is controlled by a computer that gives the user the ability to control the exposure beam, loading and unloading the sample, as well as aligning and focusing the electron beam. The column itself consists of many components. Two or more lenses to focus the beam, the lenses can be electrostatic or magnetic forces only to converge the beam. Three types of apertures exist inside the column. First, stray aperture to stop any stray electron. Second, blanking aperture to turn the beam on and off. Third, beam limiting aperture to control the beam aberration thus controlling resolution and beam current. The column also contains an alignment system to center the beam in the middle. Another very important component of the column is the stigmator which compensates for the imperfection in the construction and alignment of EBL column. Due to these imperfections the beam is not round but has a parabolic shape and the stigmator forces the beam back to its original shape [102]. Faraday cage located underneath the final beam limiting aperture and is used to measure the beam current and ensure the dose.

For nano antennas fabrication EBL machine had to be characterized using a dose matrix for the proposed stack up to determine the best dwell time and the beam current. First the sample is loaded to the machine; afterwards the beam current is adjusted to 500pA through Faraday cup. Finally pattern creation and execution are done.
4.5.1 NANO ANTENNAS FABRICATION

In this section fabrication of optimized nano antennas is discussed. Different stages of lithography are shown in the following graph.

![Diagram of nano antennas fabrication steps]

It can be seen from graph b that the MMA layer will be affected more by the scattered electrons which will result in better lift off process. Using this technique we were able to obtain nano antennas with sharp tips and 200nm spacing.
Unfortunately due to the absence of Near Field Scanning Optical Microscopy (NSOM), characterization of nano antennas via imaging near electric field was postponed for future work.

4.5.2 ANTENNA INTEGRATED DIODE FABRICATION

In order to integrate the nano diode to the nano antennas we propose a new design in this piece of research where we overlap the two antenna arms and put the MIM diode between them as shown in figure 4.5-5. The proposed design was based on the idea that field enhancement happens at the tip and thus it is better to place the tip right over the diode. Simulations show that the hot spot will be localized at the MIM diode with six orders of magnitude of relative electric field intensity enhancement as shown in figure 4.5-4. The overlap area should be as small as possible to decrease the diode capacitance. For measuring DC current, bias pads have to be connected to the nano antennas.
Fabrication of this overlapped antenna with bias pads is more challenging than normal dipole nano antennas that are usually investigated in the literature. The new design needs 3 layer alignment which is a challenging problem in EBL. We first fabricate the first antenna arm with bias pads using the same technique. Results are shown in figure 4.5-6.

To overlap the second arm MMA and PMMA resist had to be spun over the sample and then the second arm pattern is exposed using EBL. Details are shown below.
The thin oxide layer was deposited using ALD to get precise thickness. In order to get few nanometers of oxide thickness we used 45 cycles at 300°C with 0.02 cycle length.

### 4.6 MIM DIODE RESULTS

![Figure 4.6-1: Measured MIM diode performance.](image)

![Figure 4.6-2: Damaged resist after ALD.](image)
Figure 4.6-1 shows the behavior of one of the 20 fabricated devices. The first plot shows the evolution of the current flowing through the junction with the bias voltage, the blue line on the same plot shows the fitted I-V characteristics to a first order polynomial. It is obvious from the polynomial fit the I-V relation is highly linear. This is evident in the di/dv curve where the values are very small. These devices showed no diode performance and almost zero sensitivity. This poor performance is due to the fabrication procedures that we followed. Since liftoff process occurred after ALD process, the electron beam resist had to be subjected to 300°C during oxide growth, which resulted in the destruction of the resist as shown in figure 4.6-2. Based on the previous results, two major modifications were implemented. First, ALD technique for oxide growth was avoided and sputtering is used instead. Second, Metals with different work functions were used to allow tunneling without the application of any external voltage as shown in next section.

### 4.7 NEW OPTIMIZED ASYMMETRIC RECTENNA DESIGN

In order to get a zero bias response metals with different work functions should be used. This will result in Fermi level gradient between both sides of the potential well which will allow electron tunneling without the need of the application of external potential energy. Due to the limited metal targets availability we decided to work with copper and gold that has work function of 4.7ev and 5.1ev respectively. Comparison between gold and copper optical properties [87] is shown in figure 4.7-1.
4.7.1 BIAS PADS EFFECT ON COPPER NANO ANTENNA

In this section we investigate the optimization of a copper nano antenna to enhance the maximum near field intensity. In addition, we study the effect of the bias pads (20µmx32µm) on the optimized antennas. To begin with, electric near field intensity due to 10 nm copper nano antennas was simulated for both cases, with and without bias pads. Optical properties of figure 4.7-1 were imported to HFSS and symmetry plains were used to reduce the computational domain as shown in figure 4.7-3.
Figure 4.7-2 shows the simulation results for copper nano antenna without pads with maximum near field intensity enhancement of six orders of magnitude. The main results of this graph are summarized in the table below. The integration on the other hand decreases enhancement by two orders of magnitude as reported in the last column of table 4.7-1.

<table>
<thead>
<tr>
<th>Near Field Intensity without pads</th>
<th>Flare Angle</th>
<th>Antenna arm Length in µm</th>
<th>Near field intensity with pads</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4*10^6</td>
<td>30°</td>
<td>3</td>
<td>1.065*10^4</td>
</tr>
<tr>
<td>1.1*10^6</td>
<td>30°</td>
<td>2.7</td>
<td>1.74*10^4</td>
</tr>
<tr>
<td>1.0*10^6</td>
<td>60°</td>
<td>2.7</td>
<td>4.7*10^4</td>
</tr>
</tbody>
</table>

Table 4.7-1: Optimized 10 nm gap bowtie antenna results. First column shows the maximum near field enhancement for three different dimensions. The fourth column shows the effect of the integration of bias pads on the value of the near field.
Figure 4.7-4 shows the optimized copper nano antenna radiation pattern. The antenna's reception or transmission pattern demonstrates azimuthal symmetry. Maximum reception can be achieved till polar angle of 30°. For energy harvesting applications nano antennas should be isotropic.

4.7.2 OVERLAPPED COPPER-GOLD NANO ANTENNA

In this section we compare simulation results for overlapped asymmetric copper-gold nano antennas with and without bias pads. Figure 4.7-5 shows the overlapped rectenna device without pads. The first arm is made of copper, whilst the second antenna arm is made of gold.
Figure 4.7-5: Simulated overlapped bowtie.

Figure 4.7-6: Near Field Intensity variation with both flare angle and bowtie length.

### Table 4.7-2: Maximum near field intensity for Copper-Gold nano antenna pattern.

<table>
<thead>
<tr>
<th>Near field intensity($V^2/m^2$)</th>
<th>Flare angle</th>
<th>Antenna arm Length in µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.04* $10^3$</td>
<td>20°</td>
<td>1.6</td>
</tr>
<tr>
<td>2.06* $10^3$</td>
<td>20°</td>
<td>1.9</td>
</tr>
<tr>
<td>1.647* $10^3$</td>
<td>30°</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Figure 4.7-6 and table 4.7-2 present the optimized antenna simulation results. Maximum near filed intensity enhancement of 3 orders of magnitude is obtained for bow angle of 20° and antenna length of 1.6µm. The major decline in the enhancement factor is due to the abrupt step resulted from fabrication as shown in figure 4.7-6, fabrication of an overlapped rectenna without the mentioned abrupt step will be discussed in future work.
Figure 4.7-8: Overlapped Copper-Gold antenna with bias pads.

Figure 4.7-9: Near Field Intensity variation with both flare angle and bowtie length for overlapped bowtie antenna including pads. Blue axis is the bowtie length.

<table>
<thead>
<tr>
<th>Near field intensity$(V^2/m^2)$</th>
<th>Flare angle</th>
<th>Antenna arm Length in $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>$20^\circ$</td>
<td>3</td>
</tr>
<tr>
<td>180</td>
<td>$30^\circ$</td>
<td>2.8</td>
</tr>
<tr>
<td>170</td>
<td>$30^\circ$</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Table 4.7-3: Maximum near field intensity for Copper-Gold nano antenna with bias pads.

Figure 4.7-9 shows the variation of the near field intensity with both bow angle and antenna length. Major optimized geometries are reported in table 4.7-3. Simulation results show that the incorporation of bias will reduce the near field intensity enhancement by one order of magnitude compared to the results obtained from the case that has no pads. A maximum enhancement of 280 times is obtained for bow angle of $20^\circ$ and antenna length of $3\mu m$. 
4.7.3 RECTENNA FABRICATION AND MEASURED RESULTS

The new rectenna device was made of Cu/CuO/Au. 0.7nm of oxide was sputtered using a CuO sputtering target. The arm length was 3μm and bow angle of 20°. Figure 4.7-10 shows SEM images for the fabricated rectenna device. Only two devices showed diode response, however the rest were open circuit.

Figure 4.7-10: Fabricated rectenna device.

Figure 4.7-11: MIM device 1 performance.
For both devices I-V curve was measured, then polynomial fit was used in order to calculate $dI/dV$ and $d^2I/dV^2$. The diode’s dynamic resistance can be calculated as $dV/dI$, device 1 and 2 show dynamic resistance of 35kΩ and 505Ω respectively at zero bias. The major diode parameter is the sensitivity which, as mentioned before, shows the diode’s ability of rectification. Device 1 and 2 show zero bias sensitivity of $1V^{-1}$ and $4V^{-1}$ respectively. The low diode resistance and its high sensitivity at zero bias nominate it to be used for optical testing. The difference in performance between both diodes, even though they went through the same fabrication process, is due mainly due to the non-uniformity of oxide growth resulted from the sputtering machine.
4.7.4 FABRICATION RECIPE

Electrode patterning was done by electron-beam lithography using a modified ZEISS scanning electron microscope (SEM) with a LaB6 cathode. The cathode was operated at an accelerating voltage of 30 kV. The exposure current was 11 pA. Raith Elphy Quantum software was used to manipulate the electron beam. A bilayer resist process was used. The bottom layer is a 350 nm of copolymer methyl methacrylate-methacrylic acid (MMA-MAA) baked for 10 min. on a hotplate at 180 °C. The top layer is 150 nm of 495-K polymethyl methacrylate (PMMA) baked for 10 min on a hotplate at 180 °C. The electrodes were exposed in a 100 µm × 100 µm write field at an area dose of 300 µC/cm² and 1 µs of dwell time. The resist was post exposure developed for 30 sec. in a 1:3 mixture of methylisobutylketone:isopropanol (MIBK:IPA). After patterning the first MIM electrode along with one bowtie antenna arm, a 5 nm thick film of Niobium (Nb) followed by a 95 nm thick film of gold (Au) were deposited using DC sputtering at 150 W of power at a chamber base pressure of 7 × 10⁻⁷ Torr and Argon (Ar) pressure of 3 mTorr. Immediately afterwards, 0.7 nm of CuO were deposited using RF sputtering at 150 W of power and Ar pressure of 3 mTorr. Liftoff was then performed removing all the excess metal and ending with one bowtie antenna arm and an Au electrode with a 0.7 nm layer of CuO on top of it. The second MIM diode electrode and the second bowtie antenna arm were then formed of a 100 nm thick copper (Cu) film that was deposited using DC sputtering at 150 W of power at a chamber base pressure of 7 × 10⁻⁷ Torr and Argon (Ar) pressure of 3 mTorr. The I-V characteristics, of the fabricated MIM diodes, were measured at room temperature using an HP B1500 semiconductor device analyzer with probe station setup.
5. SUMMARY

5.1 CONCLUSION

Nano antennas show great ability to enhance and localize light in sub wavelength volumes. Comparison between different nano antenna shapes showed that Bow-tie antenna has the greatest ability to enhance incident light, since it has sharp tip that makes use of rod-lightening effect. Optimized Bow-tie nano antenna presented in this work exhibits relative near field intensity enhancement of 8 orders of magnitude for 0.5 nm gap. This unique property nominates nano antennas for many applications such as near field optical microscopy. New sensors that are capable of detecting a single molecule of a chemical or biological agent. It can also be used for guiding electromagnetic energy in sub wavelength-sized devices. The main purpose of this thesis is to utilize nano antennas as an energy harvester in the infrared regime (28.3 THz) by integrating it to a THz diode. In order to insure coupling to the antenna at the frequency of resonance (28.3 THz), antenna surface modes’ dispersion relation was examined. Surface waves’ dispersion relation showed momentum matching between free propagating electromagnetic modes in space and localized surface plasmons modes at the antenna’s surface. This momentum matching is guaranteed up till 65.4 THz, in other words free space modes cannot naturally couple to antennas modes for frequencies higher than 65.4 THz. Frequency dependent optical properties show that noble metals are substantially dispersive. The high rectification speed of MIM diode
makes it the only suitable device for THz rectification. Even though the proposed overlap antenna integrated diode poses challenges to fabrication, it ensures light localization right above the rectifier; this technique overcomes the problem of antenna/diode mismatch in addition to MIM design tradeoffs. Fabricated MIM diode shows significant rectification ability at zero bias with sensitivity of $4 \, V^{-1}$ and low impedance of $500 \Omega$. The presented rectenna device was able to produce electrical current without the application of any eternal electrical source, which makes it the future of sustainable energy.

5.2 FUTURE WORK

With all the research work that was done regarding rectennas, there is, still a long way to go to make them a potential replacement for solar cells. In this section we present some of the ideas that need more investigation. To begin with, development of a comprehensive simulation test-bench for nano antennas in EM simulators is required in order to get a better understanding of nano antennas’ behavior. Experimenting different materials, recipes and fabrication techniques for nano antennas fabrication. Investigation of multi-layer and planar MIM structure and their comparison. Investigation of using carbon-nanotubes for rectification purpose and other types of antenna shapes that has higher input impedance. 3-way optimization of oxide thickness vs. contact area vs conductor material to achieve high sensitivity with low diode resistance at zero-bias. Investigate various methods of interconnecting multiple nano rectennas with minimal overhead and degradation of performance. Extracting, combining and delivering the rectifier output for meaningful usage. Rectenna implementation on flexible and low-cost substrates other than
silicon. Develop a characterization technique suitable for rectenna comparison with photovoltaics. Isolating the effect of measurement and testing structures on the captured fields and rectified outputs. Demonstrate end-to-end use of rectified output. Develop techniques to exclude effects of parasitic bond-pads. Finally, more optical characterization of the nano antenna materials using ellipsometer is needed.
BIBLIOGRAPHY


