Plasmonics-Based Alignment Ruler for 3D Circuit Technology

by

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Abstract

Metallic nanostructures can be engineered to manipulate light into a certain and unique fashion. One such example of these structures is the so-called plasmonic structures, which allows the coupling of an incident radiation with the surface electrons on the metal surface of the plasmonic nanostructure. This coupling has been utilized in a wide area of applications including structural coloring, which can be used in display, imaging, sensing and security applications. One such important area that can utilize these structures is the three-dimensional integrated circuit technology (3D ICs). 3D ICs technology is about the vertical stacking and integration of various technologies that can include electronics, biological systems, chemistry analysis, energy, etc. to form one complete autonomous system. Integrating these technologies altogether involve several steps, one of which is alignment to accuracies at the micro and nanoscale. Wafer-to-Wafer and Wafer-to-chip alignment is an inherited concept from the CMOS and MEMs technologies. However, using the plasmonic structures and their spectral responses to achieve the alignment in 3D IC technology is a very new concept. In this research, an optical technique for this alignment by incorporating nano-optical technology, known as ‘alignment ruler’, is proposed, implemented, and tested.

Keywords: plasmon ruler; alignment; plasmonics; 3D Integrated Circuits; plasmonic nanostructures, plasmon coupling
Dedication

To the free mind …
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First of all, I would like to express my deepest gratitude and acknowledgements to Prof. Bozena Kaminska for giving me the opportunity to work under her supervision. She was very encouraging throughout my journey and her efforts are really appreciated. She would continue to serve as a role model for my future endeavour. Second of all, I would like to extend the same to Dr. Hao Jiang without whom this research would not have been possible. He provided tremendous technical guidance and many important personal advices to advance the research and become better in the personal aspect too. Next, I would like to express my sincere thanks to Prof. Kaminska’s PhD candidate, Mahssa Abdolahi for helping me out in the experiments conducted in 4Dlabs. Her opinion and advice were of a value during this research and are much appreciated. I would like also to extend the thanks to Dr. Jaspir Patel for the technical advice provided as well. Next, I would like to acknowledge 4DLabs and LASIR facilities staff for their hours to train guide and assist me throughout the experiments. Then, I would like to express my greatest thanks to my wife, kids, parents and the extended family for their great emotional support I needed during my studies. Finally, I would like to express my thanks to the government of Oman and my employer, Occidental, for granting me the opportunity to continue my master studies in Canada.
Table of Contents

Approval ........................................................................................................... ii
Abstract ............................................................................................................ iii
Dedication .......................................................................................................... iv
Acknowledgements ........................................................................................... v
Table of Contents .............................................................................................. vi
List of Figures .................................................................................................... vii
List of Tables ..................................................................................................... viii
List of Acronyms ............................................................................................... ix

Chapter 1. Introduction .................................................................................... 1
  1.1. Three Dimensional Integrated Circuits (3D ICs) .................................. 1
  1.2. 3D ICs Approaches: .............................................................................. 3
        1.2.1. 3D packaging technology: .......................................................... 3
              Packaging-based 3D integration .................................................... 3
              Die-to-die 3D integration ............................................................... 3
              Die-to-wafer 3D integration ......................................................... 4
        1.2.2. Monolithic, wafer level, back-end-of-the-line (BEOL) compatible 3D
techology: ................................................................................................ 4
  1.3. Plasmonics ............................................................................................... 5
  1.4. Motivation and Objectives ..................................................................... 6
  1.5. Thesis Outline ......................................................................................... 7

Chapter 2. Literature Review .......................................................................... 8
  2.1. Plasmonics and Nanostructures ............................................................ 8
        2.1.1. Introduction ................................................................................ 8
        2.1.2. Light and Matter Interaction .................................................... 11
        2.1.3. Surface Plasmon Resonance (SPR) ......................................... 12
        2.1.4. Plasmonic physics: delocalized and localized surface plasmons: 13
        2.1.5. Plasmonic colors: structural colors and extraordinary transmission
theory (EOT) ......................................................................................... 18
        2.1.6. Nano-Media: an application of plasmonic colors .................... 21
        2.1.7. Plasmonics coupling: ................................................................. 24
        2.1.8. Plasmon Rulers: an application of plasmonics coupling .......... 26
  2.2. Alignment in 3D Integrated Circuit Technology .................................... 31
        2.2.1. Alignment Methods .................................................................. 33
              Transparent substrate: ................................................................. 33
              Through-wafer hole: ................................................................. 34
              IR transmission microscopy: ...................................................... 34
              Alignment using digital images: ............................................... 35
              SmartView alignment: ............................................................... 35
              3DAAlign method: ................................................................. 36
        2.2.2. Alignment Characterization: ...................................................... 37
  2.3. Nanofabrication for plasmonics ............................................................... 37
        2.3.1 Introduction................................................................................. 37
2.3.2. Electron Beam Lithography (EBL) ...................................................... 38
2.3.3 Focused Ion-Beam (FIB) ................................................................. 38
2.3.4 Laser Interference Lithography (LIL) .............................................. 38
2.3.5 Laser Writing ................................................................................... 39
2.4. Near-Infrared (NIR) Spectroscopy ..................................................... 43

Chapter 3. Concept of Plasmonic Ruler Used for Alignment in 3D
Integrated Circuits ..................................................................................... 47
3.1. Design of an alignment ruler ............................................................... 47
3.2. Simulation of alignment ruler .............................................................. 50
3.3. Simulation Results .............................................................................. 51
   3.3.1 Single Alignment Ruler Simulations .............................................. 52
   3.3.2 Interdigitated Simulations ............................................................. 55
   3.3.3 Planarized Simulations ................................................................. 61

Chapter 4. Experimental work .................................................................... 65
4.1. Fabrication ........................................................................................... 65
   4.1.1. Laser Exposures: ......................................................................... 67
   4.1.2. Metal Etching: ............................................................................ 77
4.2. Characterization and Optical Testing .................................................. 82
   4.2.1. Test 1: Transmission via two physically separated devices with IPA
          as a separator .................................................................................. 84
   4.2.2. Test 2: Transmission via fabricated two layers with 200 nm PMMA
          in between .................................................................................... 85
   4.2.3. Test 3: Transmission via fabricated two layers with 20 nm PMMA in
          between ....................................................................................... 87

Chapter 5. Conclusion and Future Work ...................................................... 90
5.1. Conclusion .......................................................................................... 90
5.2. Future Work ....................................................................................... 90

References ................................................................................................. 92
List of Tables

Table 3.1. Single alignment ruler optimized parameters
Table 3.2. Grating thickness optimization for the Single Ruler
Table 3.3. Summary of interdigitated simulations results for Al-based gratings
Table 4.1 Shipley resist spinning parameters
Table 4.2. Summary of laser exposures results of exposed gratings 100-300 nm
Table 4.3. Summary of reactive ion etching parameters for Al metal
Table 4.4. Selected patterns and laser power for optimizing the final ruler gratings
List of Figures

Figure 1.1. 3D ICs Integration
Figure 1.2. Wire and flip-chip bonding in packaging-based 3D integration
Figure 1.3. Die-to-die 3D integration with TSVs
Figure 1.4. Die-to-wafer 3D integration
Figure 1.5. BEOL 3D integration
Figure 2.1 Examples of metallic nanostructures under electron microscopy
Figure 2.2 Examples of optical properties obtained from nanostructures
Figure 2.3 Light wave vectors relationship
Figure 2.4 Surface Plasmon Polariton excitement by grating coupling
Figure 2.5 Scattering spectra for (a) different shapes of single silver nanoparticles (b) individual gold nanoparticles (top) and their corresponding spectra (bottom) (c) field localization in chain of closely spaced gold nanoparticles.
Figure 2.6. Extraordinary transmission through an array of circular holes in a silver film
Figure 2.7. Structural colors in subwavelength hole arrays
Figure 2.8. The concept of nano-media
Figure 2.9. The pixelated nano-substrate of the nano-media
Figure 2.10. Plasmonic coupling for two closely spaced nanoparticles
Figure 2.11. An example of nonlinear Plasmonic Ruler
Figure 2.12. Backward scattered intensity with respect to symmetry in the nonlinear Plasmonic Ruler
Figure 2.13. A molecular plasmon ruler demonstration and characterization
Figure 2.14. Plasmonic Ruler based on Silver Nano-blocks
Figure 2.15. Resonant wavelength mapping with respect to the lateral displacement
Figure 2.16. Resonant wavelength mapping with respect to the vertical displacement
Figure 2.17. 3D IC example
Figure 2.18. Examples of early adoption of semi 3D integration
Figure 2.19. Alignment process using a transparent substrate
Figure 2.20. Through-wafer hole alignment
Figure 2.21. Alignment with IR transmission microscopy
Figure 2.22. Alignment using digital images
Figure 2.23. Smartview Alignment
Figure 2.24. 3DAAlign method
Figure 2.25. Electron Beam Lithography (EBL) process
Figure 2.26. Example photoresist patterning using LIL technique with sub-100 pitching
Figure 2.27. Temperature profile of a laser spot
Figure 2.28. Laser Direct Writer System Schematic
Figure 2.29. The electromagnetic spectrum
Figure 2.30. The basic configuration of NIR spectroscopy
Figure 2.31. Schematic of typical FT-NIR spectrophotometer
Figure 2.32. An example of absorbance spectra measured using FT-NIR spectrophotometer
Figure 3.1. Metallic Diffraction Grating
Figure 3.2. Concept of using plasmon ruler for alignment
Figure 3.3. Metallic Subwavelength Gratings (PSS) acting as an alignment ruler
Figure 3.4. Simulated Single Plasmon Ruler
Figure 3.5. Simulation methodology
Figure 3.6. Transmission profiles for copper, gold, and aluminum gratings based on optimized parameters shown in table 3.1
Figure 3.7. Design used for the Interdigitized simulations for alignment ruler
Figure 3.8. Interdigitized simulations process for alignment ruler
Figure 3.9. Transmission efficiencies for Al-based ruler with pitching of 1200 nm, grating thickness of 150 nm
Figure 3.10. Non-planarization (a) vs. planarization simulation (b)
Figure 3.11. Planarization simulation (a) dz = 0 nm, (b) dz = 10 nm, (c) dz = 20 nm, (d) dz = 30 nm, (e) dz = 40 nm, (f) dz = 50 nm
Figure 4.1. Heidelberg uPG 101 Laser Writer
Figure 4.2. Single Alignment Ruler Fabrication Process
Figure 4.3. Clewin software and gratings design
Figure 4.4. Gratings with pitches 1000, 1100, 1200 nms at 18mW-10% laser power
Figure 4.5. Gratings with pitches 1000, 1100, 1200 nms at laser powers of (a) 18mW-20% (b) 18mW-30%
Figure 4.6. Gratings with pitches 1000, 1100, 1200 nms at laser powers of (a) 18mW-40% (b) 18mW-50%
Figure 4.7. Gratings with pitches 1000, 1100, 1200 nms at laser powers of 18mW-100%
Figure 4.8. SEM images of gratings with pitches of 1200 nm exposed with 20%-30 of 18 mW laser power in increments of 2% for line gratings
Figure 4.9. SEM images showing descumming process effects on gratings with pitches of 1200 nm and designed widths of 150 nm exposed with various laser powers

Figure 4.10. Outline of reactive ion etching

Figure 4.11. Etching types

Figure 4.12 SEM images of gratings after etching and photoresist stripping.

Figure 4.13 SEM images of optimized gratings for the alignment ruler

Figure 4.14 Design of two layers ruler for optical testing

Figure 4.15 Transmission spectra via two physically separated rulers. IPA is applied in between the layers to observe the transmission changes over time.

Figure 4.16 Experimental transmission spectra via two physically in-separated rulers with 200 nm PMMA layer in between.

Figure 4.17 Simulated transmission spectra via two physically in-separated rulers with 200 nm PMMA layer in between.

Figure 4.18 Experimental transmission spectra via two physically in-separated rulers with 20 nm PMMA layer in between.

Figure 4.19 Simulated transmission spectra via two physically in-separated rulers with 20 nm PMMA layer in between.
# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>3D ICs</td>
<td>Three Dimensional Integrated Circuits</td>
</tr>
<tr>
<td>RCWA</td>
<td>Rigours Coupled Wave Analysis</td>
</tr>
<tr>
<td>ICs</td>
<td>Integrated Circuits</td>
</tr>
<tr>
<td>TSV</td>
<td>Through Silicon Via</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal-Oxide Semiconductor</td>
</tr>
<tr>
<td>SPP</td>
<td>Surface Plasmon Polariton</td>
</tr>
<tr>
<td>SPR</td>
<td>Surface Plasmon Resonance</td>
</tr>
<tr>
<td>LSPR</td>
<td>Local Surface Plasmon Resonance</td>
</tr>
<tr>
<td>FDTD</td>
<td>Fine Difference Time Domain</td>
</tr>
<tr>
<td>DDA</td>
<td>Discrete-Dipole Approximation</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared Radiation</td>
</tr>
<tr>
<td>NIR</td>
<td>Near-Infrared Radiation</td>
</tr>
<tr>
<td>EBL</td>
<td>Electron Beam Lithography</td>
</tr>
<tr>
<td>FIB</td>
<td>Focused Ion Beam</td>
</tr>
<tr>
<td>EOT</td>
<td>Extra Ordinary Transmission</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive Ion Etching</td>
</tr>
<tr>
<td>NHA</td>
<td>Nano-Hole Array</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>FT</td>
<td>Fourier Transform</td>
</tr>
<tr>
<td>NIR</td>
<td>Near-Infrared</td>
</tr>
<tr>
<td>FT NIR</td>
<td>Fourier Transform Near-Infrared</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitted Diode</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive Ion Etching</td>
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<tr>
<td>Al</td>
<td>Aluminum</td>
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<tr>
<td>PR</td>
<td>Photoresist</td>
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Chapter 1.

Introduction

1.1. Three Dimensional Integrated Circuits (3D ICs)

Higher performance demands, lower power requirements, and smaller device sizes were key factors in driving the integrated circuit industry in the past decades. Devices scaling was fully governed by Moore’s law during these times. Later on, nanotechnology came into the picture. Device scaling predicted by Moore’s law along with the advancements in nanofabrication and nanocharacterization enabled an industrial revolution in electronics and computing to achieve enhanced performance along with reliability and reduced cost. However, even with nanotechnology advancements and due to the physical limitations in scaling down and deviations from the law of physics (Quantum effects), a better alternative is needed to improve device density. One such technology that have been developed is the three dimensional Integrated circuits (3D IC). 3D IC technology comes into play to resolve several known challenges of the physical limitations of the existing CMOS technology and to provide other opportunities. Improved performance, functionality, density and integration are benefits automatically realized from the 3D technology. 3D integration is about vertically stacking and connecting different functional components to form a complete system. 3D technology can also support the production of heterogeneous systems (i.e. integrating a variety of technologies) that not only include electronics but even chemical, and biological systems, microfluidics, energy systems and so many others, see figure 1.1.
Figure 1.1. 3D ICs Integration

3D technology was not properly defined from the beginning. Several technologies adopted the simplest forms of the 3D ICs. In fact, memory chips were among the first to employ such concept by staking DRAM dies in a package with each chip shifted a certain distance to allow wire bonding across the chips.

Other approaches were implemented eventually. For example, Through Silicon VIA (TSV) is another technique to allow chip-stacking by making connection through metal (commonly copper) plugs passing through the Silicon substrate. TSV allows shorter interconnect distances, improving device speed and reducing power consumptions. TSV can also perform wafer-level stacking when compared to wire-bonding which only allows chip-level stacking [35].

Generally, 3D IC integration includes four main processes: alignment, bonding, thinning, and interconnection [6]. Several approaches to 3D integration are reported in the literature [29-31]. However, all these approaches along with the four main processes of integration have different challenges and represents significant opportunities for research and development. Alignment is one of the areas of research interest that can
help increase device densities and provide higher accuracy density stacking processes allowing more functionalities, better performance and smaller form factor.

1.2. 3D ICs Approaches:

1.2.1. 3D packaging technology:

*Packaging-based 3D integration*

Packaging-based 3D integration is possible by either wire or flip-chip bonding, see figure 1.4. As can been see in the figure, wires are used to interconnect the multiple layers.

![Figure 1.2. Wire and flip-chip bonding in packaging-based 3D integration](image)

Packaging-based 3D integration can be realized by system-in-package (SiP), where thinned chips are stacked and interconnected by wire bonding (top of figure 1.4). Further, these SiPs can also be stacked with a flip-chip bonding method to achieve package-on-package (PoP) (bottom of figure 1.4). Today’s cell phones use at least one of these packaging systems.

*Die-to-die 3D integration*

In die-to-die integration, a thinned die is placed on top of another die and a through-silicon-via (TSV) interconnection is used to integrate, see figure 1.5.
Laser drilling and deep reactive ion etching with copper fills can be used to form the TSV interconnection in this integration.

**Die-to-wafer 3D integration**

A die can be integrated with a wafer as shown in figure 1.6 by using interchip electrical interconnections. During the die bonding process, these interconnections can be formed by post-bond via formation or solder bonding.

**1.2.2. Monolithic, wafer level, back-end-of-the-line (BEOL) compatible 3D technology:**

3D integration is enabled by wafer alignment, bonding, thinning and inter-wafer interconnections as shown in Figure 1.7.
In a nutshell, 3D integration is an important technology to overcome the physical limitations of the CMOS technology, improve power efficiency, provide better performance and above all, provide complete integration of different technologies. However, 3D technology has its own set of challenges especially during the implementation phase. For example, alignment is a critical part of 3D integration and there is a high demand to provide an accurate method to perform the alignment to provide correct system integration (i.e. better device density). Other technologies such as plasmonics come into play to resolve some of these challenges.

1.3. Plasmonics

Plasmonics offers an opportunity for 3D IC technology. It could simplify the integration and packaging processes in 3D ICs. Plasmonics is a multidisciplinary field in nanotechnology dealing with the extraordinary properties of surface plasmons for technological applications [39]. This field is built upon the resonant interaction of the light with free electrons of metals. These free electrons couple efficiently with the incoming light to form surface plasmons resonance and polaritons. Historically, the Romans used metal particles in coloured glasses, which was an application of light and matter interaction. The negative dielectric permittivity of metals at the optical frequencies enhances the electromagnetic field around these metallic particles. After the discovery of full-light absorption and surface-enhanced Raman spectroscopy in 1970s, metallic nanostructures became a great research interest especially with the later breakthroughs in nanofabrication and electromagnetic modelling [46]. The fundamentals of Plasmonics
are associated with the Surface Plasmon Polaritons (SPPs) founded by the coupling between light and surface electron oscillation in conductive materials. Different systems can be used to couple light to SPPs such as launching SPPs at the metal-dielectric interface via a prism. However, this technique does not allow any localization or SPP beam shape control, which lead to use local scatterers instead such as particles and holes. An array of holes in a metal film or the single slits source are common example to obtain a collimated or converging SPP beam [40]. Surface Plasmons were first reported by Rufus Ritchie in 1950s. And since the 1970s, the confinement of subwavelength electromagnetic fields and their enhancement have been widely applied in the field of the spectroscopy. Advances in nanofabrication, characterization and simulation techniques allowed the exploration of the various electromagnetic modes in the nanoscale which lead to plasmonic optical devices fabrication [39]. These modes are not constrained by the optical diffraction limits, hence allowing the fabrication of devices in the nanoscale [40].

1.4. Motivation and Objectives

Alignment is a key process in the 3D IC integration and there have been many techniques developed for CMOS and MEMs technologies; however, all these techniques have alignment accuracy down to 250 nm only [6]. An alignment ruler based on plasmonics (transmission mode) presents an opportunity to contribute to the alignment process in 3D ICs with alignment tolerances that is much less than the current commercial tools. Prior to this research, several attempts have been made to fabricate plasmon rulers to do distance measurements in nanoscale using nanoparticles in microbiology applications [19-22]. 3D ICs could benefit from these plasmon rulers as well such as in areas of electronic designs, precise variation analysis, authentication processes, and many others. In this research, a newly designed plasmon ruler is used to guide the alignment process in 3D ICs or any other technologies that require alignments. This alignment ruler is based on very simple nanostructures and aims to use these structures with very low-cost microfabrication techniques to provide better alignment accuracies. This novelty of this method lies on the fact that is plasmonics-based which
provides accurate alignments when compared to the other mechanical or light-based methods.

1.5. Thesis Outline

This thesis includes four sections: literature review, design and simulation, fabrication work and optical testing. These sections are distributed into five chapters.

Chapter 1 introduces 3D ICs and the alignment process in the 3D ICs technologies and integrations. It also introduces the fundamentals of plasmonics upon which an alignment ruler is designed in this research.

Chapter 2 presents a literature review in nanostructures in general with a focus on metallic diffraction gratings whose optical properties are exploited to design plasmon rulers. An introduction to the current commercial alignment processes in the 3D ICs integration is also presented here. Laser writing and direct laser writing are also presented here as these tools can be used to fabricate an economically attractive alignment ruler for 3D Integrated circuits.

Chapter 3 focuses on the design and technical simulation of the designed alignment ruler using RSOFT software, which is based on Rigours Coupled Wave Analysis (RCWA) of Maxwell’s equations solutions.

Chapter 4 presents the experimental work carried out to fabricate the alignment ruler along with the characterization methods used to verify the processes and test the functionality of the fabrication in general and the ruler in particular (optical testing).

Chapter 5 presents a summary of the thesis and the recommended future work.
Chapter 2.

Literature Review

2.1. Plasmonics and Nanostructures

2.1.1. Introduction

 Metallic nanostructures are physical structures that have at least one dimension in the scale of 1-100 nm and are made of a metal such as gold, silver, and copper. These structures hold remarkable physical and chemical properties that are possible to tune based on the size and shape of the composing materials resulting in new properties. The large surface area to volume ratio is one of the driving factors in the new properties. Surface Plasmon Resonance (SPR) which is the oscillation of free conductive electrons in the metallic nanostructures is a source of some of the optical properties. This phenomenon can result in light absorption, scattering, or enhanced local electromagnetic field which in turn is used in different applications such as sensing, imaging, photothermal therapy, and solar energy harvesting. For example, Local Surface Plasmon Resonance (LSPR) is very sensitive to refractive index of the surrounding media making it suitable for bio-sensing applications by detecting the wave spectrum shifts. Furthermore, the frequency and intensity of LSPR can be finely tuned by the shape, size, and metal composition, making it more suitable for other kind of applications [2]. The ability of exploiting the plasmonics nanostructures to efficiently convert energy between the free-space photons and the confined plasmon is yet another application that allows manipulating light and thereby generate structural colors [5]. Generally, metallic nanostructures can be classified based on their dimensions into 0D (all three dimensions are nanoscale) such as particles and atoms, 1D (two dimensions are nanoscale) such as nanowires and nanorods, 2D (one dimension only is nanoscale) such as thin films (nanoplates, nanosheets), and 3D such as polyhedral [4-5].
Figure 2.1 Examples of metallic nanostructures under electron microscopy: (a) 0D Pd spherical nanoparticles (b) 1D Au nanorods (c) 2D Pd nanosheets (d) 3D Pd nanocubes. Adapted with permission from [4]

Varying the size and shape of nanostructures and nanoparticles can greatly change their properties, which are different from the properties of the bulk material. These changes affect, for example, the optical, catalytic, and magnetic properties of the structures.

Color and transparency (hence wavelengths) are examples of optical properties that can be exhibited by nanostructures and nanoparticles. The interaction of light with the material controls the observed color (or wavelength). Typically, an observer would only see the reflected colors but not the absorbed ones. Generally, the incident light on a material can be transmitted, absorbed and/or reflected. At the nanoscale and when the structure is comparable in size to the incident wavelength, a new behavior, scattering (diffraction) of light is exhibited. This scattered light can contribute to either the reflected or transmitted light but not the absorbed. The scattering purely depends on the size, shape and refractive index of the structure, and the refractive index of the surrounding media. For nanostructures and nanomaterials, color can be generated by interference, scattering, surface plasmon, and quantum fluorescence. When light is incident on a metal surface, some of the light waves propagate on the surface-giving rise to the surface plasmon [8]. When these structures are fabricated properly to exhibit surface plasmons, they can be called Plasmonic structures. Plasmonic nanostructures with light absorption can be used for example to generate heat photothermally and also with light scattering from the reflected photons to amplify the local electromagnetic field. All the metal nanostructure are capable of generating local surface plasmon resonance but for each it can occur under different wavelength. For metals such as gold, silver, and copper it can occur under visible light. The position of the local surface plasmon resonance peak
is directly impacted by the size and shape of the structures. This position change is taken advantage of for applications such as bio-sensing [1]. Figure 2.2. shows an example of the brilliant optical properties that can be obtained tuning the metallic nanostructures and their surface plasmon resonance [4].

![Figure 2.2 Examples of optical properties obtained from nanostructures: (a) nanorods, (b) nanoshells, (c) nanocages. Adapted with permission from [4]](image)

Catalytic and magnetic properties are also emerging from the size and shape changes of the nanostructures and nanoparticles. Bulk gold for example is known to be very chemically inert; however, at sizes of 3-4nm, gold nanoparticles become very catalytic. Additionally, changing the size and shape of the ferromagnetic metals to the nanoscale results in a phenomenon called superparamagnetism, which is a temperature dependent property [9]. These properties and many others are exploited in fields such as structural colors, imaging, displaying and many others.

Advances in micro/nano fabrication and characterization have allowed fabricating reflection and transmission gratings in the nanometer scale and with controlled reflection and transmission profiles by simply controlling the geometrical parameters and the material used. The optical behaviours of these structures are exploited in different areas such as sensing, telecommunications, and structural coloring. Today, commercial spectrophotometers can be used to measure the transmission and reflection spectrum of such gratings [13].
2.1.2. Light and Matter Interaction

Several theories were developed about light especially in the late seventieth century starting from the corpuscular theory which treats light as a steam of particles (Newton). Later, additional theories followed about light as a wave (Grimaldi and Huygens), and light as an electromagnetic wave (Maxwell and Schrodinger) [26,56]. Understanding these theories has allowed scientists to manipulate light and produce useful applications in areas such as optics, holography, photonics, and telecommunications [26]. The modern theories today settle on treating light as both a wave and a particle (photon) [56]. Not only understanding what light is but, further, understanding light and matter interaction has been a very important concept since the existence of humanity. In fact, this understanding kept evolving until we are today able to manipulate light in a very tiny scale down to the atomic level. Generally, light can be absorbed (A), reflected (R), or transmitted (T) when interacting with matter [33]. These three quantities can be related [34] by this simple equation:

\[ R + T + A = 1 \]  

For today's many applications and to understand light-matter interaction, light can be modeled in three forms: ray, wave, and/or particle. The ray model is the simplest among these forms and is always used for simplicity especially in optics. The wave model is used to understand the interaction of light with matter with sizes comparable to or smaller than the light wavelengths. The particle model is used to explain the interaction of light with individual atoms of the matter [33].

In general, light is described as an electromagnetic wave where \( \mathbf{E} \) and \( \mathbf{H} \) are the electric and magnetic vectors that are perpendicular to each other and both being perpendicular to the propagation direction, \( \mathbf{k} \) (the wave vector) [34]. A light wave can be simply represented by the following equation:

\[ \psi = A \cos(kt - \omega \tau) \]  

Where \( k = \frac{2\pi}{\lambda} \) and called the wave number. \( \omega \) is the angular frequency of the light wave. \( A \) is the amplitude of the light wave propagating in space, \( z \), and time, \( t \). \( \lambda \) is the...
wavelength [56]. Another vector called the Poynting vector describing the energy flux density can also be used with the following relationship:

\[ S = E \times H \]  

1.3

Figure 2.3 Light wave vectors relationship, Adapted with permission from [34]

This light-matter interaction leads to the discovery of many important optical phenomena such as the surface plasmon resonance which is a result of light interaction with metallic features at the nanoscale.

2.1.3. Surface Plasmon Resonance (SPR)

Nano-optics is an emerging field driven by the rapid advancement in nanotechnology that includes nanoscience, nanofabrication and nanocharacterization. It is the science of controlling optical fields at scales shorter than the wavelength of the radiation and includes the near-field enhancement of the electromagnetic fields, light manipulation, light matter interaction, and non-linear phenomena. The surface plasmon phenomena fall into this new field. Surface Plasmon Resonance (SPR) was first physically observed by Wood in 1902 when he noticed a pattern of dark and bright bands (anomalies) in the reflected light from a mirror with gratings on its surface due to the incidence of p-polarized light (magnetic field is parallel to the grating grooves). Rayleigh then Fano presented a physical interpretation of the phenomena but Otto and Kretschmann only later offered a better physics understanding in 1968. Upon this understanding, they were
able to excite surface plasmons using special configurations. In a simple experiment, if a polarized light is incident on a prism then passing the light into a thin metal film such as gold, the light reflects off the metal film which is behaving like a mirror. Changing the incident light angle on this system, the intensity of the reflected light dips (decreases). At this dip, surface plasmons are excited causing a resonance resulting from the interaction between the photons of the p-polarized light (incident) and the free electrons of the metal film. The angle at which the dip or the maximum loss of reflected light occurs is called the resonance angle or surface plasmon angle. This angle depends on the characteristics of the system such as the refractive indices of the media on both sides of the media and the metal film [45].

This concept is very important in bio-sensing by monitoring the refractive index near the vicinity of the metal surface. The refractive index around the metal film changes when a mass of e.g. proteins accumulates on it. This refractive change translates into a spectral shift of the SPR as depicted in figure 1.10 [45]. In the late 1990s, TM polarized light resonances were discovered in the near infrared and visible range [13]. Initially, it was thought that the subwavelength apertures had very low light transmission efficiency. However, in the late 1990s, it was proven using holes (in nanoscale) in a 2D metallic structures that an Extraordinary Light Transmission (EOT) up to ten times larger than the diameters of these holes can occur. Surface plasmon polaritons (SPPs) in the metallic interfaces is attributed to some of this enhanced transmission. Due to this effect, Incident light can excite the electromagnetic modes of the periodic gratings allowing transmissions that are very close to 100% [11].

2.1.4. Plasmonic physics: delocalized and localized surface plasmons:

There are two types of surface plasmons. Surface plasmon polariton (SPP) are the confined electromagnetic waves propagating at the interface of the metal and the dielectric due to the coupling of the incident electromagnetic fields (light) and the metal’s electron plasma (surface) [48]. It is a conversion from the photons in the free-space to the confined plasmons in the metal surface at a subwavelength scale [52]. These waves
are still governed by the traditional macroscopic version of the famous Maxwell’s equations:

\[\nabla \cdot D = \rho_{\text{ext}} \quad 2.1\]

\[\nabla \cdot B = 0 \quad 2.2\]

\[\nabla \times E = -\frac{\partial B}{\partial t} \quad 2.3\]

\[\nabla \times H = J_{\text{ext}} + \frac{\partial D}{\partial t} \quad 2.4\]

D is the dielectric displacement, E is the electric field, H is the magnetic field, B is the magnetic induction. \(\rho_{\text{ext}}\) and \(J_{\text{ext}}\) are the external charge and the current densities, respectively \([48]\).

Metals have dispersive properties depending on the electromagnetic wave they are interacting with. Meaning, metals are highly reflective up to the infrared (IR) range; they permit electromagnetic wave penetration at the near-infrared (NIR) and visible range; and in the ultraviolet range, they behave like dielectrics. All these dispersive properties are captured by a complex dielectric function, \(\varepsilon(\omega)\) which is a complex number expressed as follows:

\[\varepsilon(\omega) = \varepsilon' + i\varepsilon'' \quad 2.5\]

\(\varepsilon'\) and \(\varepsilon''\) are dielectric constants. i is a complex number. For metals, \(\varepsilon' < 0\) (real part) and \(\varepsilon''\) (imaginary part) describes the absorption. This dielectric function determines the response or the optical properties (scattering, extinction, transmission, absorption, etc.) of the metal to the incident electromagnetic waves \([53]\). Surface plasmons are a kind of this interaction when they couple with the incident light.
Several methods exist to cause this coupling (surface plasmon excitement by incident light) such as: charge particle impact, prism coupling, grating coupling, highly focused optical beams, and near-field methods. For example, grating coupling aims to resolve the wave vector mismatch between the incident light and oscillating waves on the metal to excite the surface plasmons on the metal surface [48]. The wave dispersion in free space and the dispersion of the surface plasmon are matched by giving the free-space
dispersion wave a push. Figure 2.4 depicts one technique to do so: (a) the phase matching of the incident light to SPPs using grating coupling method (b) example patterned metal surface under SEM (c) phase-matching is translated into peak wavelength transmission (at 815 nm) due to SPP excitation.

Local surface plasmon (LSP) are similar in definition to the SPP except that they are not propagating, hence the name local. LSP can be excited by direct light illumination unlike SPP which require phase-matching condition for excitation. LSP resonance can be observed in a scattering mode in the interaction of the metal nanoparticles with the incident electromagnetic wave (the particle having diameters much smaller than the incident wave). Figure 2.7 shows (a) the scattering spectrum of a single silver nanoparticle with different shapes and (b) the optical dark field and SEM images of single gold nanoparticles (top) and their corresponding scattering spectrum (bottom) [48]. In figure 2.5, and in a single metallic nanoparticle, the localized plasmon resonance can be shifted by just changing the particle size and shape. Additionally, shifting can also be observed when having a group of nanoparticles in close proximity to each other due to the electromagnetic interaction between the localized mode. For ordered and closely spaced particles, the near-field interactions dominate with a dependence on the interparticle distance causing light confinement (strong field localization) in the gaps between the adjacent nanoparticles (figure 2.5 c). The confinement is due to the suppression of scattering in the far-field by the excitation of localized surface plasmon in each single particle [48].
Figure 2.5. Scattering spectra for (a) different shapes of single silver nanoparticles (b) individual gold nanoparticles (top) and their corresponding spectra (bottom) (c) field localization in chain of closely spaced gold nanoparticles. Adapted with permission from [48]
2.1.5. **Plasmonic colors: structural colors and extraordinary transmission theory (EOT)**

Structural colors originate from the complex interaction between light and the physical nanostructures [51]. In these structures, colors are purely generated by controlling the physical dimensions of the nanofeatures (i.e. pure physical origin) unlike pigments and dyes (i.e. material origin). Structural colors are advantageous over the pigment and dye-based coloration method for their reduced pixel area, sub-wavelength resolution, non-material dependency, and capability of extreme bright colors and stability [50, 52]. These colors can be generated by optical processes such as thin-layer interference, diffraction grating, light scattering, photonic crystals, etc. [51]. Based on plasmonic nanostructures, structural colors require highly sophisticated fabrication techniques such as e-beam lithography (EBL) and focused ion beam (FIB) which are time consuming and expensive [50]. These tools aim to exploit the geometrics of the nanostructures and thus manipulate light properties which include wavelength selection and hence color generation [52]. The wave selection in structural coloration can be achieved in two ways: reflection and transmission. Regardless of the mode, structural coloration in patterned metallic nanostructures is attributed to the excitation of surface plasmons.

Ebbesen et.al demonstrated that in a perforated periodic subwavelength hole arrays in a thick metallic film, light transmission is several orders higher than what was originally predicted by Beth’s theory [52]. At first, it was thought that it is very easy to generate subwavelength light sources by just drilling a circular subwavelength hole in a thick metallic screen and illuminate the screen from one side. Some of the light gets transmitted through the hole. However, the basic laws of electromagnetics suggest that the transmitted light intensity is very weak [45]. Ebbesen et. al found that the excited surface plasmon waves propagates through the subwavelength hole arrays giving rise to high transmission on the other side of the holes at certain wavelengths. Figure 2.6 shows the zero-order transmission spectrum in a square lattice with 150 nm holes standing within 200 nm thick silver film and having a pitch of 900 nm.
Figure 2.6. Extraordinary transmission through an array of circular holes in a silver film. Adapted with permission from [25]

In this spectrum, there is a transmission peak at 326 nm and a set of peaks appearing with gradual increase at longer wavelengths exceeding the pitch value $a_0$. The pitch is found to determine the position of the peaks and the position of the maxima scales with this pitch value independent of the metal used, hole diameter, or film thickness. The width of the peaks is determined by the aspect ratio (film thickness to hole diameter) [25]. The sharp peak in the ultraviolet region in figure 2.8 is only particular to the very thin films (bulk metal plasmon) [46, 48]. Additionally, the film thickness increase decreases the intensity of the transmission. The spectrum also changes significantly with the type of the lattice [25]. In a square-lattice subwavelength hole arrays, the transmission peak wavelength is approximated to be (incident light is assumed to be normal on the hole arrays)

$$
\lambda_{max} \approx \frac{p}{\sqrt{i^2 + j^2}} \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}}
$$

2.7
P is a constant related to the square lattice, i and j are scattering orders related to the hole arrays, \( \varepsilon_m \) and \( \varepsilon_d \) are the permittivity of the metal and the dielectric medium.

The holes and their associated scattering loss and the Fano-type interaction are not taken into consideration in the above equation. These factors when taking into account causes a red-shift in the resonance leading to slightly lowering the transmission peak wavelength. In any case, the transmitted wavelength is dependent on the lattice constant which means the transmitted color can be selected by adjusting this constant.

For example, figure 2.7 a, b, c depicts the lowest order transmission peak (when i and j are zero) in a square lattice hole arrays. The hole arrays are standing on a 300 nm-thick
silver film and when the lattice constant changes from 300 to 550 nm, the maximum peak wavelength varies from 436 nm to 627 nm (figure 2.7 b). Changing the lattice to triangular improves the color transmission. Figure 2.7 d and e shows the triangular and square lattice hole arrays and the color improvements (reduced color cross-talk and purer color) realized when switching to triangular lattice. The numbers on the right are the lattice constants. The maximum peak wavelength in a triangular lattice becomes [52]:

\[ \lambda_{\text{max}} = \frac{P}{\sqrt{\frac{2}{(i^2 + ij + j^2)}}} \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \] 2.8

2.1.6. Nano-Media: an application of plasmonic colors

Nano-media is a novel idea based on plasmonic to imprint and display brilliant color images along with information storage. This technology constitutes of a pre-pixelated nanostructure carrying the primary colors: red (R), green (G), and blue (B) and is called a universal stamp. The imprinting process aims to activate the pixels as per the desired image to print or display using an intensity control layer. Pixels in nanomedia can be activated by photolithography [insert reference], photographic exposure using an emulsion layer [insert reference], and inkjet printing [insert reference]. Figure 2.8 represents the concept of nano-media and how it works. Nano-media includes a substrate, a pixelated nanostructure (nano-substrate) and an intensity control layer (ICL) on top (figure 2.8a). The nano-substrate includes subpixels of RGB colors for the image and IR pixel for information storage (figure 2.8b). To produce an image, the ICL which tunes the subpixels intensity is patterned according to the input image. In other words, ICL acts as either transparent on top of some subpixels or blockage on some others (figure 2.8c) [54].
Figure 2.8. The concept of nano-media: (a) Schematic of the nano-media (b) Top view of the layout of the subpixels on nano-substrate (c) Schematic of a color image displayed on nano-media. Copyright © 2014, IEEE [54]
In this concept, the pixelated nano-structure which determines the optical properties and the quality of the image is a nano-hole array (NHA) metallized with an aluminum film. Figure 2.9 shows a microscope image (a) and an SEM image (b) of this nano-structure.

![Microscope Image](image1.png)  ![SEM Image](image2.png)

**Figure 2.9.** The pixelated nano-substrate of the nano-media: (a) a microscope image (b) an SEM image. Copyright © 2014, IEEE [54]

Under reflection, the angle-dependent incident light interferes with the periodic nanoholes displaying various wavelength peaks for each subpixel. The NHA can also be engineered to display colors under transmission following the EOT theory (see section 2.1.4) [54].
2.1.7. Plasmonics coupling:

Very powerful field enhancements can be achieved via the near-field coupling between nanoparticles. The localized surface plasmon resonance of each single nanoparticle can interact via a Columbian force with the adjacent particles causing a shift from the resonance of the single particle to a new resonance. Figure 2.10 depicts the simplest case of plasmon coupling for a two closely spaced spherical particles (a). The coupled particles have an effective polarizability $\alpha_{eff}$ which is the collective polarizability of the individual particles $\alpha_1$ and $\alpha_2$ and is dependent on the distance between the dipoles $r$. Two dipole modes exist: longitudinally aligned dipoles, figure 2.12 a, and transversally aligned dipoles. The polarizability of each mode is given by:

\[
\alpha_{eff}^{long} = \frac{\alpha_1 + \alpha_2 + \frac{\alpha_1 \alpha_2}{\pi r^3}}{1 - \frac{\alpha_1 \alpha_2}{4 \pi^2 r^6}} \quad 2.9
\]

\[
\alpha_{eff}^{trans} = \frac{\alpha_1 + \alpha_2 - \frac{\alpha_1 \alpha_2}{2 \pi r^3}}{1 - \frac{\alpha_1 \alpha_2}{16 \pi^2 r^6}} \quad 2.10
\]

Decreasing the dipole separation $r$, the spectral response under the longitudinal coupling is red-shifted towards lower frequencies with a slight increase in the magnitude of the effective polarizability, see figure 2.10 b. This resonance shift is experimentally proven to be a function of the separation distance between the particles, see figure 2.10 c. when the particles are very close to each other, surface charges of each particle interact strongly forming large field enhancement at the gap between the particles which are called hot spots.
And the more the particles get closer, the more is the produced field enhancement. Figure 2.10 d shows the distribution of the near-field enhancement. Contrary, the spectral response under the transversal coupling is blue-shifted [46]. As can be seen, the strength of the plasmon coupling and the spectral shift of the LSPR is dependent on the inter-particle distance, so this plasmon coupling behaviour is used to design the so-called plasmon rulers for very accurate distance measurements in the nanoscale. The nanoparticles scatter light very strongly and the scattering spectra can be collected and translated into optical measurements of bimolecular distances [18].
2.1.8. **Plasmon Rulers: an application of plasmonics coupling**

Plasmonic nanostructures have very unique applications due to their optical properties owned to the surface plasmon resonances. These resonances are associated with the strong absorption, scattering, and beyond the diffraction limitation localization of light. These different modes are used to tailor the plasmonic nanostructures for their optical properties which are directly related to the distance between the structures. This relationship is used to design plasmon rulers to measure distances especially in the biological and chemical processes. Butet et. al designed and tested a nonlinear (3D) Plasmonic nanoruler based on the Fano resonances using nanorods: a gold nanorod on top of two parallel nanorods. Each rod is 100 nm long and 50 nm wide and the parallel rods are separated by 60 nm, figure 2.11.

![Figure 2.11. An example of nonlinear Plasmonic Ruler. Adapted with permission from [27]](image)

When this ruler is exited by an incident wave polarized in the x-direction and propagating in the z direction, the top nanorod responds with a dipolar plasmonic mode coupled with the incident wave, radiating light efficiently. The bottom rods respond with quadrupolar plasmonic modes where each rod supports an out of phase dipole moment causing no efficient radiation. The backward scattered intensity of this ruler is calculated and shown in figure 2.12.
In this ruler, the quadrupolar mode is exited by coupling with Fano resonances which dramatically improves the optical response of the ruler [27].

The plasmonic coupling between nanoparticles has also been utilized to design these plasmon rulers to measure distances in the nanoscale. Sonnichsen et. al described a molecular ruler based on the plasmon coupling using gold and silver nanoparticles [17]. These particles exhibit plasmon resonances in the visible range and used to monitor distances between single and multiple pairs of particles. The plasmon resonance wavelength of the gold and silver nanoparticles is affected by the surrounding medium. In figure 2.13 a top left image, the single silver nanoparticle exhibit blue color under resonance and when paired with another particle, top right image, the color becomes blue-green (i.e. resonance shift – see top image of figure 2.13 b). Likewise, in the same figure at the bottom, the individual gold particles exhibit green color and when paired they exhibit orange color. The bottom image of figure 2.13 b shows the resonance shift for this case. So basically, two particles get close to each other and their plasmon resonances couple causing a shift in their resonance compared with their individual resonance. This shift is called spectral shift as can be seen in figure 2.13 c and it is experimentally proven that this spectral shift is directly proportional to the particle separation distances. The particles are reported to have diameters of 40 nm to allow
sufficient light scattering. The particles are illuminated with unpolarized white light to cause the resonance and a microscope operating in the transmission mode collects the scattered light.

Figure 2.13. A molecular plasmon ruler demonstration and characterization: (a) the single and multiple silver and gold nanoparticles under dark-field microscope in transmission mode, (b) the scattering spectra of the single and multiple silver and gold nanoparticles, (c) the spectral shift between gold particle pair. Adapted with permission from [17]
Another plasmonic ruler that is based on silver metal blocks is also reported by Lee et. al. This ruler is also based on the plasmonic coupling between two metal Nano-blocks coming close to each other. The plasmon resonance is dependent on the geometries of the blocks such as the gap distance and lateral distances of the blocks. See figure 2.14. A strong electric field along the z-direction confined between the two blocks is a result of the plasmonic coupling. Two modes are used to track distances along x and y directions where each mode is reported to have different optical properties with resonant wavelength of 838 nm and 1041 nm. One mode is concentrated in the up and down side and the other is on both sides. When the blocks move along x or y directions, the effective cross-section size from the structure decreases with a decrease in the resonant wavelength. Spectral shifts are reported as the blocks moves along the x and y directions which in turn are translated in distance measurements. wavelengths. [3].

![Figure 2.14. Plasmonic Ruler based on Silver Nano-blocks.](image)

**Figure 2.14. Plasmonic Ruler based on Silver Nano-blocks. Copyright © 2015, IEEE [3]**

![Figure 2.15. Resonant wavelength mapping with respect to the lateral displacement for (a) mode 1 and (b) mode 2.](image)

**Figure 2.15. Resonant wavelength mapping with respect to the lateral displacement for (a) mode 1 and (b) mode 2. Copyright © 2015, IEEE [3]**
Figure 2.15 demonstrate the lateral displacements of the two modes with respect to the resonant. The vertical shifts which is equivalent to the gap thickness are linked to another resonant mode. If the gap is increased from 10 nm to 14 nm, the resonance is blue-shifted from 838 nm to 769 nm and if decreased to 6 nm, a red-shift occurs to 986 nm [28]. Figure 2.16 summarizes the results for the vertical shifts where thickness is the gap between the two Nano-blocks.

![Figure 2.16. Resonant wavelength mapping with respect to the vertical displacement. Copyright © 2013, IEEE [28]](image)

As can be seen, the plasmonic nanostructures can be exploited for their optical properties to design plasmon rulers for distance measurements that are important in the biological and chemical processes. In this research, the same behaviours of spectral shifts from the plasmonic coupling are used but not to measure distances rather to perform very accurate alignments needed for the 3D IC technology.
2.2. Alignment in 3D Integrated Circuit Technology

Relying on Moore’s law, complementary metal-oxide-semiconductor (CMOS) scaling based on this law is expected to slow down in the next generation of the IC technology [10]. Three-dimensional integrated circuit technology (3D ICs) is driven by the fact that Moore’s law prediction has come to near the physical limits in the integrated circuitry. This technology offers an opportunity to further extends Moore’s law and provides more capabilities to meet the high technology demands especially in electronics, computing, and mobility. 3D ICs technology can be defined as the packaging of the heterogeneous devices using copper-filled through silicon vias (TSV) to allow multiple layers of devices (vertical integration) with vertical interconnections [1] [2], figure 2.17.

![Figure 2.17. 3D IC example. Copyright © 2006, IEEE [2]](image)

Research activities worldwide are currently focusing on this technology with memory and mobile devices already seeing some adoption [10]. Figure 2.18. Shows some of the early examples of 3D integration [1].

3D ICs extends to not only improving performance but also to include improved functionality, reduced power, density and integration. 3D IC integration include four main processes: alignment, bonding, thinning and interconnection [6].
Figure 2.18. Examples of early adoption of semi 3D integration (a) cross-section view of Apple iPhone 5 motherboard, (b) cross-section view of SanDisk MicroSD card, (c) cross-section view of Sony IMX135 image sensor. Copyright © 2014, IEEE [1]
When it comes to high densities, devices can be stacked, which adds a third dimension compared to the 2D traditional circuits. The vertical interconnections (TSV) between the stacked layers becomes a critical factor in the 3D IC integration processes. As a result, the stacking between the layers requires extreme alignment capabilities.

Generally, there are two methods to perform wafer-scale integration of 3D circuits: bottom-up and top-down. In the bottom-up, the layering does not need any stacking since the first layer is completely fabricated first and then followed by the fabrication of the next sequential layers until the whole buildout is completed. In the top-down, separate layers are fabricated in parallel and then stacked to form the 3D circuit. A challenge for this method is the accurate alignment requirements for proper stacking. 3D IC technology requires high submicron alignment accuracy and the current methods are only at about 1-micron accuracy and some of these methods require a glass substrate (through-wafer alignment strategy). Further, the alignment accuracy is degraded when the wavelength-dependent signal attenuates through silicon [2]. Additionally, bonding and thinning processes that are performed next in the 3D circuit technology causes further misalignments because theses processes directly impact the flatness of the fully processed wafers in each layer of the 3D circuit [6].

2.2.1. Alignment Methods

Alignment processes were studied and developed originally for 2D lithography (mask-wafer alignment) and then for MEMs technology. Later, alignment has also become an important process in the 3D IC integration, wafer-level packaging and microfluidics. The current commercial tools provide alignment accuracy down to approximately 250 nm. These tools are based on alignment marks created on the wafers to be aligned and use microscopy tools to assist with the alignment process. In general, these alignment techniques can be achieved using one of the following methods [6]:

**Transparent substrate:**

In this method, figure 2.19, an optical microscope is used to view the alignment marks on the wafers through e.g. a glass substrate and while moving the wafer stages, the
alignment marks are set to overlap to achieve the alignment. The accuracy of this method is reported to be approximately 5 ums.

![Figure 2.19. Alignment process using a transparent substrate. Copyright © 2011, IEEE [6]](image)

**Through-wafer hole:**

In one of the wafers, a hole is etched and used to locate the alignment mark on the second wafer, figure 2.20. A challenge for this method is the difficulty in achieving accurate position and dimensions for the via hole during fabrication and thus this method can hardly achieve a micrometer-level alignment.

![Figure 2.20. though-wafer hole alignment. Copyright © 2011, IEEE [6]](image)

**IR transmission microscopy:**

Silicon is known to be transparent to IR and so an IR source is used and placed on the opposite side of the optical microscope, figure 2.21. This method can provide an accuracy that is about 1 um. The major disadvantage of this method is the nontransparency of the metals on the silicon layer.
Alignment using digital images:

Alignment marks are placed on the front side of the first wafer and the back side of the second wafer. The microscope captures a digital image of the alignment marks of the top wafer. The second wafer is moved between the microscope and the first wafer. The alignment marks in the second wafer are tracked and aligned with the stored image, figure 2.22. The tolerance of this method is about 5 ums.

SmartView alignment:

In this method, two pairs of microscope are used, one pair on top (right side and left side) and one at the bottom (right side and left side). The wafers to be aligned are placed in between the pairs of the microscopes in a face to face fashion. The wafer stages are moved horizontally and vertically and the four microscopes are used to do the alignment, figure 2.23. This method can achieve an accuracy down to 0.25 um.
3DAlign method:

This method also uses two microscopes sets where one set views directly down to the front side of a wafer and another set views the bottom side of the second wafer through a special mirror. When the two images from the wafers are overlaid and aligned, a submicrometric misalignment tolerance can be achieved, figure 2.24.
2.2.2. Alignment Characterization:

Alignment characterization is another challenge in the 3D IC integration. Alignment accuracy can be inspected before and after bonding. However, the inspection before bonding is limited to the in-focus checkup and the inspection after bonding is limited due to the invisibility of the alignment marks after bonding. Practically, there are three methods that are currently used in 3D integration: optical, IR, and cross-sectional inspections. Optical methods are limited to the transparent wafers to allow viewing the alignment marks. IR inspection extends the capability to the nontransparent wafers; however, the IR signal can be attenuated by the thickness of the silicon wafer or the other metals available on the wafer. The advantage of the optical and IR characterization is that these methods are non-destructive. On the other hand, the cross-sectional inspection provides the best accurate characterization but is limited to development and research since this method is destructive [6].

2.3. Nanofabrication for plasmonics

2.3.1 Introduction

Recent developments in the nanofabrication techniques such as Electron Beam Lithography (EBL) enabled light manipulation control in nanostructures. These techniques can be either physical or chemical or a mix of these two. They are also associated with lithographic processes in which a pattern is defined by a writing tool or self-assembly. Using a writing tool can be either a direct or indirect process depending whether a mask is used or not. Traditional lithography using masks and optical techniques are limited due to the diffraction limitations. For feature sizes smaller than the wavelength, the mask is no longer a limitation but the numerical aperture and the wavelength are the limitations. Decreasing the wavelength, increasing the numerical aperture (immersion lithography), and near-field lithography are possibilities to fabricate beyond the diffraction limitations. However, each of these possibilities brings their challenges. For example, decreasing the wavelength is not straightforward and requires sophisticated and expensive equipment [46]. Several other technologies emerged to
fabricate structures in the plasmonic modes such as Electron Beam Lithography (EBL), Focused Ion-Beam (FIB), Laser Interference Lithography (LIL), etc.

2.3.2. Electron Beam Lithography (EBL)

Accelerated electrons have very small wavelengths thus eliminating the diffraction limitations of optical techniques that are using light instead. These electrons can be used to expose electron-sensitive resists to fabricate features at very small nanoscale [46]. Figure 2.25 represents a typical EBL process to fabricate nanostructures. After the resist is deposited on a substrate, an electron beam is used to expose the resist creating the desired pattern, Figure 2.25 a. Next a development process is performed to remove away the exposed areas of the resist (positive resist), see figure 2.25 b. An etching process or lift-off process that includes a metallization step is performed at this stage, figure 2.25 c. At the end, the unwanted metal areas are removed by immersing the sample into a solvent to dissolve the remaining resist leaving the desired structure.

2.3.3 Focused Ion-Beam (FIB)

The FIB technique uses ions instead of electrons. The advantage over using electrons is that accelerated ions can have similar wavelength of accelerated electrons but with more mass allowing efficient momentum transfer and hence physical etching of the material. This technique has been extensively used to fabricate perforated metallic thin films. However, it is less popular than EBL because it requires dedicated equipment and may contaminate samples [46].

2.3.4 Laser Interference Lithography (LIL)

This technique is of low cost but can only in used in the process of fabricating periodic or quasiperiodic structures. Figure 2.27 shows an example patterning of photoresist having 70 nm widths.
Figure 2.25. Electron Beam Lithography (EBL) process: (a) EBL resist patterning using an electron beam (red) on a resist (yellow), (b) resist after development, (c) metal coating, (d) resist stripping. Adapted with permission from [46]

2.3.5 Laser Writing

Laser (Light Amplification by Stimulated Emission Radiation) is one of the greatest discoveries for which the laser is widely used in so many applications such as medicine, beauty, manufacturing industry and weapon systems. Higher power, less divergence angle, monochromaticity, shorter light pulse, and continuously tunable spectrum output are characteristics unique to laser that allowed its wide application usage [24].
Figure 2.26. Example photoresist patterning using LIL technique with sub-100 pitch. Adapted with permission from [46]

Specifically, the interaction of laser beams with material has been an important method in microfabrication since the 1980s. Direct laser writing is the process of adding, removing or modifying material from a substrate based on laser beam scanning point by point and without using a mask. The laser source and the optics are two important factors in determining the possible writable features by laser [23]. However, laser fabrication techniques are limited to the micrometer scales due to the optical diffraction limitations of the laser and researchers are working continuously to improve resolutions to the nanoscale. To describe the limitations, Resolution (R), depth of focus (DOF), incident light wavelength (λ), numerical aperture (NA) are the most important parameters to consider which are related as follows:

\[ R = k_1 \frac{\lambda}{NA} = k_1 \frac{\lambda}{n \sin \theta} \quad 2.11 \]

\[ DOF = k_2 \frac{\lambda}{(NA)^2} = k_2 \frac{\lambda}{(n \sin \theta)^2} \quad 2.12 \]

Where \( k_1 \) and \( k_2 \) are related to the exposure process and the properties of the photoresist, \( n \) is the index of refraction of light transferring medium (air or liquid) and \( \theta \) is the half-angular aperture of the objective lens. Hence to improve the resolution, one can
use shorter wavelength, higher numerical aperture and optimized exposure process and properties of the photoresist. However, shortening the wavelength (infinitely) require sophisticated tools and expensive equipment which may not be attainable. In addition, longer wavelengths may be desired for higher DOF to avoid focus errors and achieve the desired writing depths. The photoresist is also another important factor to obtain better resolutions with laser writing; however, contamination and edge bend cannot be neglected during the application of the photoresist onto the substrate. It is also important to develop or select the appropriate photoresist according to the laser system wavelength. When the laser beam hits the photoresist, complex physical and chemical changes result in because the laser energy profile is of a Gaussian shape, the temperature of the laser beam at the center is higher than around the center – see figure 2.28. This causes different responses on the photoresist layer and so selecting a suitable laser power that matches the thermal thresholds of the photoresist improves the resolution of the laser writing [23].

Laser direct writing (LDW) is a microfabrication technique in which the laser beam interacts with an acceptor material, which is the organic photoresist. Several advantages are realized for LDW, which includes low cost, high processing rate, high precision and simplicity especially for periodic structures [24].

![Temperature profile of a laser spot](image)

**Figure 2.27. Temperature profile of a laser spot. Adapted with permission from [24]**
A typical laser direct writer system contains three main parts: laser moderation part to control the power and pulse of the laser beam, focusing detection part to keep the beam focused on the desired position, and the scanning stage on which the sample is placed. A computer software is used to monitor and control the laser writing process which include inputting the desired writing parameters and designs. Figure 2.29 depicts a typical schematic of a direct laser writer.

![Diagram of a direct laser writer system](image)

**Figure 2.28. Laser Direct Writer System Schematic. Adapted with permission from [24]**

After the photoresist is exposed by the laser beam whose wavelength is fixed, its properties are modified at the exposed areas only to allow the designed patterns to remain after development. If the photoresist is positive, the exposed areas are washed away during development. If the photoresist is negative, the opposite is true [24]. Refer to chapter 4 for additional details.
2.4. Near-Infrared (NIR) Spectroscopy

Near-infrared (NIR) spectroscopy dates back to when Herschel studied the NIR energy in 1800s leading to the discovery of the infrared (IR) region in the electromagnetic spectrum, the second spectrum discovered after the visible spectrum (the NIR ranges between 700 nm and 2500 nm) [55]. Figure 2.30 depicts the complete electromagnetic spectrum [56].

![Electromagnetic Spectrum](image)

**Figure 2.29. The electromagnetic spectrum. Adapted with permission from [56]**

The basic concept of absorption spectroscopy is to measure how well a sample can absorbs light at certain wavelengths by shining a monochromatic light beam with a certain wavelength and measure how much of the beam is absorbed then repeating for other wavelengths. NIR spectroscopy is based on the absorption of the NIR radiation and its physical origin is attributed to the molecular vibrations in the matter. The NIR radiation interacts with the matter and causes molecules when absorbed or radiated to change their rotational and vibrational movements based on these molecules’ structures. These movements have unique frequency characteristics representing the composition of the material in chemical analysis or material characterization (size, thickness,
roughness, etc.) in other analysis. However, NIR spectroscopy is not limited to these analyses and can extend to a wide range of applications in astronomy, agriculture, medicine, etc. [55]. The frequency characteristics associated with the molecular movements can be described as spectral signatures capturing transmitted, absorbed or reflected radiation. Depending on the sample, the measurements can be performed in reflection or transmission. A basic NIR spectrometer includes a source, a dispersive element and a detector. The source is used to generate the NIR energy and could be of halogen bulbs or LEDs. The dispersive element which could be a prism or a diffraction grating allows to capture the intensity of different wavelengths. The detector captures the signal after its altercation with the sample and depends on the desired wavelength to be detected: silicon-based, Pbs, and InGaAs. Figure 2.31 shows the basic components of NIR spectrophotometer under the transmission and reflectance modes [55].

![Diagram of NIR spectrophotometer](image)

**Figure 2.30. The basic configuration of NIR spectroscopy. Adapted with permission from [55]**

Several commercial NIR spectrometers are available in the market and each uses a specific technique to measure the desired spectral responses. One common spectrometer known for high precision and accuracy is Fourier-transform NIR spectrophotometer (FT NIR) [57]. The dispersive element in the FT NIR is a Michelson interferometer which divides the collimated beam light into two paths using a beamsplitter, one of the split beams is sent through a sample, and then recombining the
beams to create an interference. Hence, this interference contains some information about the sample being studied [58]. Further, FT NIR employs Fourier transform which is mathematical function representing a signal based on the constituent frequencies. Computer power that became readily available later allowed the FTIR spectroscopy to dominate the IR identification process. The FT-NIR spectrophotometer uses a single beam containing multiple frequencies and measures how much of the beam is absorbed by the sample and then repeating the process with another set of frequencies for several times. The data is then collected by a computer which calculates the absorption at each wavelength. Figure 2.32 shows a typical diagram of an FT-NIR spectrophotometer.

![Figure 2.31. Schematic of typical FT-NIR spectrophotometer. Adapted with permission from [55]](image)

The source, typically 5-50 W halogen bulbs, provides the NIR signal to be used. The NIR signal is then collimated and directed into interferometer for modulation. Typically, the interferometer consists of two plane mirrors perpendicular to each other, the first moves along its axis and the second is a beamsplitter, layered coatings placed on a substrate. The beamsplitter partially reflects the NIR signal onto fixed mirrors and transmits the
remaining signal to the moving mirror controlled by a laser source. The reflected beams are then recombined at the beamsplitter and sent out to the detector. Based on the optical path difference or the retardation, the beams then interfere with each other. If the moving and fixed mirrors are each at equal distances form the beamsplitter, the retardation is zero and all the NIR signal from the source reaches the detector. Intensity variation as the moving mirror is translated holds spectral information retrieved by the FT function. Before the detector, the signal is delivered via the sample which selectively absorbs and reflects or transmits the remainder of the signal to the detector. The detector can be of one of several types depending on the degree of responsivity and defectivity for the application. An InGaAs detector can highly detects up to 1700 nm with fast/intermediate responsivity [55]. Compared to other techniques, FT NIR spectroscopy offers higher sensitivity where all the frequencies in FT are processed at the same time and where a large aperture can be used to collect light [57]. Finally, the absorbance (transmittance or reflectance) spectra is usually plotted against wave number (the reciprocal of the wavelength), see figure 2.33 [55].

![Absorbance spectra](image)

**Figure 2.32.** An example of absorbance spectra measured using FT NIR spectrophotometer. Adapted with permission from [55]
Chapter 3.

Concept of Plasmonic Ruler Used for Alignment in 3D Integrated Circuits

3.1. Design of an alignment ruler

Metallic diffraction gratings are one-dimensional periodic structures (1-D) with a very thin metal layer that is grooved in a repeated manner – see figure 3.1. This structure can be freestanding or lying on top of a substrate are even embedded within another material. These gratings have been studied for many years to exploit their behaviours for different applications starting from the submillimeter and radio wavelengths era. Such an example of these periodic gratings is depicted in figure 3.1 where Pd is the periodicity, w is the metal grating width, and t is the metal grating thickness. The spacing between the gratings can also be described as a.

![Figure 3.1. Metallic Diffraction Grating](image)

Pd = Grating periodicity  
t = Grating thickness  
w = Grating width
The transmission spectra in the metallic diffraction grating can be uniquely characterized. The grating periodicity determines the position of the peaks. The width of these peaks is dependent on the aspect ratio (grating thickness to depth), i.e. with lower aspect ratios, the peaks are broad and with aspect ratios approaching maximum (~1), a maximum sharpness results in [25].

Our alignment ruler is based on this simple plasmonic structure in which light is manipulated at the nano-scale. The incident light is coupled with the surface electrons on the metallic nanostructures. This coupling is exploited to engineer an application for alignment. The concept is that the spectral response of such structures can be tailored precisely to transmit or scatter the incident light. This information is then translated into an alignment data. Figure 3.2 depicts the concept. During a typical 3D IC process, plasmonic subwavelength structures (PSSs) are fabricated on the surfaces of the chips and the wafer to be aligned. A broadband collimated NIR light is sent from the back of the wafer. This light gets transmitted through the wafer, PSS pairs, and the chip. The transmitted light is then collected from the other side by a special camera with very high resolution. The placement of the camera is important as long the depth of focus is maintained to collect the transmitted light from within the range od this depth that is dependent on the optics of the camera. Each pair of PSS (one in the chip and one in the wafer) is excited by the near-infrared radiation (NIR). When two PSS are brought close to each other, the transmission intensities and the peaks captured by the camera are translated into an alignment data (as we will see later in the simulation and optical testing).
Figure 3.2 Concept of using plasmon ruler for alignment

NIR is used to excite and create the coupling since it is transparent in silicon used in the integrated circuits at its wavelength range to mitigate any affect of the IC contents on the collected transmission reading. NIR transmitted is then transmitted through the paired PSSs. Due to the coupling of NIR to surface plasmons on the PSS, extraordinary transmission whose peak wavelength dependent on the PSS geometrics is detected. The transmitted radiation is very sensitive to sub-nanometric shifts between the paired PSSs. Furthermore; the transmission is translated into alignment displacement and then used to guide the alignment process. The PSS can be a metallic subwavelength grating, see figure 3.3.
Figure 3.3 Plasmonic Subwavelength Structure (PSS) acting as an alignment ruler

Numerical simulations are used to find out the appropriate metal and geometrics of the PSS including: periodicity, and gratings' thickness and width.

3.2. Simulation of alignment ruler

Accurate modeling in plasmonics is very important to develop a better understanding before experimenting and exploring useful Plasmonic applications. However, it is not easy to compute the optical properties of the metallic nanostructures. Today’s tools are only capable of providing an approximate solution to Maxwell’s equations provided that these tools are either handling very small or asymmetric structures. Scattering problems for various metallic nanostructures can be studied with methods such as Finite Difference Time Domain (FDTD), the Discrete-Dipole Approximation (DDA), Rigours Couple Wave Analysis (RCWA) and many other tools [42, 44]. FDTD uses the time-domain form of Maxwell’s equation by discretizing the time and space of the particle or structure and the space around it to solve for the complex electromagnetic wave interaction [18]. It is based on a grid of spaced cells having sizes smaller than 1/20 the wavelength of the medium [43]. The idea is to fire an incident wave and perform an iterative computation of the electric and magnetic field vectors at a point
at a given instant of time using the previous time interval [44]. As such when hundreds of wavelengths are involved in two or three-dimensional nanostructures, high computational resources are required [43]. In the DDA method, each particle is represented by very small cubic elements each of which have dipole interactions with the incident and neighbouring elements induced electric fields. The solution of Maxwell’s equations in this case becomes algebraic for each coupled dipole, which has a dipole moment that is induced by the incident, and neighbouring fields [44]. The selection of the tool is highly dependent on the type of the structure to be simulated, computation power availability, and required accuracy.

The Rigorous Coupled Wave Analysis (RCWA) is one of the other methods to study the electromagnetic scattering resulting from the incident waves on nanostructures. This model is based on semi-analytical form of Maxwell’s equations. RCWA assumes a specific form of gratings to enable easy separation of space variables [38]. The gratings and the fields are expressed in a sum of spatial harmonics where in a uniform layer these harmonics correspond to the plane waves [49]. In other words, the method relies on the Fourier expansions of the space periodic part of the solution using Matrix forms of Maxwell’s equations [38]. RCWA algorithm calculates the sum of the electromagnetic fields over coupled waves using Fourier harmonics that are related to the coupled waves. In other words, Maxwell’s equations are solved in the Fourier domain in order to arrive at the diffraction efficiencies at the end [7]. RCWA is based on Floquet’s theorem in which periodic differential equations are solved and expanded to Floquet functions. In a multi-layer structure, the electromagnetic modes are calculated for each layer and propagated through the rest of the layers. Scattering matrices are used to match boundary conditions at the layers interfaces to provide a solution that is used as an electromagnetic radiation base for the next layer. This base is then projected by the radiation pattern to form Algebraic expressions of Maxwell’s equations that are solved numerically [49].

3.3. Simulation Results

Rsoft CAD is very capable software and has several modes to simulate optical properties of devices. FULLWAVE FDTD is a tool to simulate photonic structures to
study the propagating of light in these structures by employing the finite-difference-time-domain (FDTD) method. For our periodic structure, the DiffractMOD is employed. DiffractMOD is typically used to simulate diffractive optical elements, periodic nanostructures, and photonics bandgap structures. In this mode, the diffraction efficiency (absorption, transmission, and reflectance) and the field distribution can be calculated using an algorithm that is based on the Rigorous Coupled Wave Analysis (RCWA) and enhanced with the Model Transmission Line theory (MTL). RCWA is semi analytical method used in the computational electromagnetics that is to solve the scattering problems in the periodic structures. The method solves for Maxwell Equations in the periodic differential form. Typically, the device to be simulated using RCWA is divided into uniform layers in the z-direction. For each layer, the electromagnetic modes are calculated and then propagated to the other layers using the boundary conditions between the layers. Maxwell’s equations and the boundary conditions are expanded becoming infinitely large equations. Based on how accurate the solution needs to be, the higher order terms of these large equations can be cut off. The MTL calculates the sum of the electromagnetic fields but just over individual modes instead of the couple waves to improve the calculation results [7]. To design the alignment ruler, Rsoft CAD is used to perform two simulation types: single ruler where an alignment ruler is positioned in a single chip and interdigitated simulation where two alignment rulers are positioned into two different chips and interdigitated. The rulers’ optical responses in these cases are studied by simulation as follows. Tuning the grating periodicity for the peak position and the ratio of the grating width to thickness for the broadness or sharpness of the transmission profile, and the metal used, an optimized alignment ruler is designed.

3.3.1 Single Alignment Ruler Simulations

A standalone ruler is simulated here. Figure 3.4 shows the gratings of a single plasmon ruler that is based on gold metal along with the geometrical parameters to control (pitching, thickness, width) in the design. Copper and aluminum gratings are also considered for the simulation. The plasmon ruler is a Near Infrared based (NIR) and as such the design aims at obtaining transmission peaks located between 1000 and 1500 nm. Figure 3.5 summarizes the simulation mythology that is followed to simulate and optimize the simulations for this single ruler.
Based on the above methodology and to achieve a transmission peak of 1500 nm, table 3.1 summarizes the optimized parameters of a single plasmon ruler:
### Optimized Single Ruler Summary (Metal Gratings)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Periodicity</th>
<th>Grating Width</th>
<th>Grating Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>600 nm</td>
<td>500 nm</td>
<td>150 nm</td>
</tr>
</tbody>
</table>

**Table 3.1. Single alignment ruler optimized parameters**

With above parameters stated in table 3.1, figure 3.6 summarizes the transmission profiles for gratings that are based on copper, gold, and aluminum. From this figure, the three metals have similar transmission efficiency with minimal differences and with the transmission peak ranging from 1400 nm – 1700 nm.

![Transmission profiles for copper, gold, and aluminum gratings based on optimized parameters shown in table 3.1](image)

**Figure 3.6.** Transmission profiles for copper, gold, and aluminum gratings based on optimized parameters shown in table 3.1

Next, grating thickness is optimized to reduce the amount of metal used. Table 3.2 summarizes the simulation results after optimizing the thickness to \( t = 150 \) nm.

<table>
<thead>
<tr>
<th>Single Ruler (Pd=1200 nm, W=500 nm, t = 150 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Metal</strong></td>
</tr>
<tr>
<td>Peak (nm)</td>
</tr>
<tr>
<td>Transmission (%)</td>
</tr>
</tbody>
</table>
Table 3.2. Grating thickness optimization for the Single Ruler Based on Three Metals (Al, Au, Cu)

3.3.2 Interdigitated Simulations

For a typical alignment process, two rulers are placed on two different chips and used to guide the alignment process. This process is referred to as Interdigitated simulations. In the Interdigitated simulations, two alignment rulers are designed with the same geometries to simulate the vertical and horizontal shifts effect for alignment. Figure 3.7 depicts the design simulated in this section.

Figure 3.7. Design used for the Interdigitated simulations for alignment ruler (a) 3D view (b) cross-sectional view

The idea is that a one ruler is vertically shifted a certain distance (z-direction) and the transmission spectrum is calculated. The process is repeated for several values in the same direction. Then the same ruler is horizontally shifted a certain distance (x-direction) and the transmission profile is again calculated. Figure 3.8 depicts the basic idea of the interdigitited simulations, varying dz and dx values.
Figure 3.8. Interdigitated simulations process for alignment ruler

Figure 3.9 summarizes the effect of the vertical and horizontal shifts of the two rulers. The blue colored (marked with arrow) spectrum in the both figures shows the transmission when the two rulers are perfectly interdigitated and alignment is 100% (i.e. both dz and dx are zero). It can also be seen that from the figures in (a) and (b) that the transmission efficiency is very sensitive to any small vertical and horizontal shifts.

It is important to note that the periodicity of the aligned rulers (effective periodicity) becomes half of a single ruler since the two rulers are exactly the same (from 1200 nm for single to 600 nm for Interdigitated). Table 3.3 summarizes the Interdigitated simulations results for Aluminum gratings for various periodicities. In table 3.3, once the two alignment rulers are perfectly Interdigitated, the effective period reduces to half. For example, in the second raw where the periodicity simulated is 1200 nm, the effective period of the Interdigitated rulers is 600 nm.
Figure 3.9 Transmission efficiencies for Interdigitated Al-based ruler with effective pitching of 600 nm after interdigition, (a) vertical shifts - dz (b) horizontal shifts - dx
<table>
<thead>
<tr>
<th>Periodicity (nm)*</th>
<th>Grating Width (nm)</th>
<th>Grating Thickness (nm)</th>
<th>Peak Location (nm)</th>
<th>Peak Efficiency (%)</th>
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</thead>
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<td>Grating Thickness (nm)</td>
<td>Peak Location (nm)</td>
<td>Peak Efficiency (%)</td>
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<td>Peak Efficiency (%)</td>
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</tbody>
</table>

Table 3.3. Summary of Interdigitied simulations results for Al-based gratings
3.3.3 Planarized Simulations

All the above interdigitated simulations in the previous section assume that when the two rulers are interdigitated there is no filler material between them (figure 3.10 a). And this is the ideal situation while doing a real 3D IC integration process. However, because of the way the rulers are being experimentally tested by our prof of concept (fabricating all the layers of the Interdigitated rulers into a single device), where we introduced a filler material between the two rulers, a planarization step is required after fabricating the first layer of the ruler to build a uniform second layer (figure 3.10b). This slightly changes the simulation conditions when the two layers are being aligned and thus the simulations of the previous sections are repeated here.

Figure 3.10. Non-planarization (a) vs. planarization simulation (b)

So the concept remains the same except that now the separation (dz) between the two layers is increased. In figure 3.10b, and when using a filler material between the two chips, the gap between them (dz) is considered zero and this case is treated as a perfect alignment. Figure 3.11 summarizes the results of the simulation. In figure 3.11a, dz is fixed and set to zero whereas dx is increased from 0 nm to 600 nm. As dx increases, the transmission intensities increases and the peaks shift to the longer wavelengths. At a perfect alignment situation (i.e. dz =0, dx=0), a transmission peak is detected at 946 nm with 10% transmission peak. In figure 3.11b, dz is set to 10 nm and dx is carried again from 0 to 600 nm. The same observation, as dx increases, the transmission intensities increases and the peaks are shifted to the longer wavelengths. At dz=10 nm and dx = 0 nm, the closet to the perfect alignment situation, the peak is recorded at 931 nm with a 7% transmission. Figure 3.11 c,d,e follows the same observations as dz is increased,
20, 30, 40 and 50 nm. Comparing between the situations a-f in figure 3.11, the transmission intensities decrease when the chips are moving away from each other vertically (dz) and horizontally (dx). The transmission peaks are also moving to the shorter wavelength.

(a)

(b)
Figure 3.11. Planarization simulation (a) $dz = 0 \text{ nm}$, (b) $dz = 10 \text{ nm}$, (c) $dz = 20 \text{ nm}$, (d) $dz = 30 \text{ nm}$, (e) $dz = 40 \text{ nm}$, (f) $dz = 50 \text{ nm}$
Chapter 4.

Experimental work

4.1. Fabrication

The alignment ruler fabrication process takes place in the cleanroom and includes the following major steps:

1. **Substrate Preparation**: Substrate is cleaned with acetone and IPA. In this research, silicon and quartz substrates were experimented with.

2. **Metal Deposition**: A physical vapor deposition (PVD) process is used to deposit the metal of choice on the cleaned substrate. PVD is a process in which the material is vaporized from a solid or liquid source. The vaporized atoms or molecules are transported through vacuum or low-pressure plasma environment to the substrate for condensation and ultimately for deposition. This process is used to deposit metal films in the range of few nanometers to thousands of nanometers with rates ranging from 1 to 10 nanometers per seconds [58]. In this research, PVD is used to deposit Aluminum metal on the quartz substrate. PVD is also used to deposit gold onto silicon substrate.

3. **Photoresist Coating**: An adhesion promoter layer (HMDS) via priming was applied to the substrate afterwards to ensure the photoresist (Shipley S1805) adhesion to the metal layer. The photoresist was then spun using the following recipe:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Target Thickness</th>
<th>Ramp Up</th>
<th>Coating Parameters</th>
<th>Ramp Down</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Values</td>
<td>RPM</td>
<td>Duration (sec)</td>
<td>RPM</td>
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</tbody>
</table>

*Table 4.1 Shipley resist spinning parameters*
4. **Photoresist Patterning**: Heidelberg µPG 101 Laser Writer (figure 4.1) was used to pattern the Shipley resist with an optimized laser power to obtain the desired gratings for the ruler. Clewin software from PhoeniX Software was used to design the patterns (figure 4.3).

![Figure 4.1. Heidelberg µPG 101 Laser Writer](image)

5. **Metal Etching**: Gold was wet etched using TFA gold etchant. Aluminum was dry etched using BCL₃ and Cl₂ gases.

6. **Photoresist Stripping**: After etching, the photoresist is stripped by either immersion in acetone for 10 minutes or applying O₂ plasma for 10-15 minutes.

Figure 4.2 shows a schematic summary of the single ruler fabrication process.

![Figure 4.2 Single Alignment Ruler Fabrication Process: (a) metal deposition, (b) photoresist spinning, (c) photoresist patterning, (d) metal etching, (e) photoresist stripping](image)
After the above process was well-established, tons of experiments were performed to figure out the resolution of the laser writer, optimize the laser power to pattern the resist, hence the gratings, optimize the etching of these gratings, fabricate a single alignment ruler and fabricate coupled rulers for optical testing.

4.1.1. Laser Exposures:

The Heidelberg uPG 101 laser writer is equipped with a diode laser source having a wavelength of 375 nm and a maximum power of 18 mW. The laser writer which is a mask-less fabrication technique is used to perform the photolithography process (i.e. pattern the Shipley S1805 photoresist). The patterns are designed using Clewin software version 3.2.2 from PhoeniX Software, figure 4.3.

![Figure 4.3. Clewin software and gratings design](image-url)
To evaluate the resolution of the laser writer and optimize the possible structures, sets of patterns having periodicities ranging from 1000 nm to 1200 nm and widths from 100 nm to 300 nm are exposed under different laser powers ranging from 10% of 18 mW (1.8 mW) to 100% of 18 mW (18 mW) in increments of 10% (1.8, 3.6, 5.4, etc.). At 10% power exposure, there were no traces of 100 nm gratings for the three periodicities. The 200 nm gratings appeared only when the periodicity is at 1000 nm. However, it was observed that at the end of every four gratings, two lines get merged together. The 300 nm gratings appeared in all three periodicities; however, the overlapping of some of the gratings was still observed with the periodicities of 1000 and 1100 nms. This is a limitation on how the laser writer exposes the patterns. Figure 4.4 shows an SEM image of the patterns exposed at 18mW-10% power.

![Figure 4.4 Gratings with pitches 1000, 1100, 1200 nms at 18mW-10% laser power](image)

Better results were observed when the laser powers were increased to 20% and 30%. The 100-300nm gratings were observable, see figure 4.5 (a) and (b).
Figure 4.5 Gratings with pitches 1000, 1100, 1200 nms at laser powers of (a) 18mW-20%  (b) 18mW-30%

As the laser power increased, the 300 nm gratings started to deteriorate and disappear, see figure 4.6 (a) and (b).
Figure 4.6 Gratings with pitches 1000, 1100, 1200 nms at laser powers of (a) 18mW-40% (b) 18mW-50%

The grating distortion extended to the 200 nm gratings as the laser power increased and only 100 nm gratings stood out at 100% laser powers, see figure 4.6.
Figure 4.7 Gratings with pitches 1000, 1100, 1200 nms at laser powers of 18mW-100%

From the results obtained from figures 4.4, 4.5, 4.6, 4.7 it was observed that the ideal laser power exposure for our gratings is between 18mW-20% and 18mW-30% and that appropriate and possible grating periodicity is 1200 nm. Next experiments focused on these two parameters: the laser power range and grating periodicity of 1200 nm. A series of laser exposure starting from 20% of 18 mW to 30% were applied to patterns having pitches of 1200 nm with grating widths ranging from 100 nm to 300 nm in increments of 50 nm. The following figure shows the results obtained:

(a) Periodicity = 1200 nm, Exposed Grating = 100 nm
(b) Periodicity = 1200 nm, Exposed Grating = 150 nm
(c) Periodicity = 1200 nm, Exposed Grating = 200 nm
18 mW – 24%

18 mW – 26%

18 mW – 28%

18 mW – 30%

(d) Periodicity = 1200 nm, Exposed Grating = 250 nm

18 mW – 20%

18 mW – 22%
(e) Periodicity = 1200 nm, Exposed Grating = 300 nm
From figure 4.8 and table 4.2, it can be seen that as the exposed gratings width increases, the lines decrease (going from left to right in the table). Additionally, the exposed gratings widths decrease as the laser power increases. A descumming process in which O2 plasma is applied for 30-60 seconds (50 mTorr pressure and 100 W RF power) is suggested to remove the remains of the photoresist prior to etching for better uniformity of the gratings. Figure 4.9 shows the gratings after the suggested descumming process.
<table>
<thead>
<tr>
<th>Laser Power</th>
<th>Designed Vs. Fabricated (Grating Widths/nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Designed</td>
</tr>
<tr>
<td>100</td>
<td>550</td>
</tr>
<tr>
<td>20% - 18mW</td>
<td>420</td>
</tr>
<tr>
<td>22% - 18mW</td>
<td>434</td>
</tr>
<tr>
<td>24% - 18mW</td>
<td>377</td>
</tr>
<tr>
<td>26% - 18mW</td>
<td>284</td>
</tr>
<tr>
<td>28% - 18mW</td>
<td>200</td>
</tr>
</tbody>
</table>

Table 4.2. Summary of laser exposures results of exposed gratings 100-300 nm

4.1.2. **Metal Etching:**

After patterning the photoresist, reactive ion etching (RIE) is used to transfer the pattern to the Aluminum film. Cl₂-based gases are used for etching Aluminum. These gases are able to etch the Al film in high rates; however, Al tends to form an Al oxide film (Al₂O₃) when exposed to the atmosphere which hinders the etching of the metal. BCl₃ is usually mixed in to allow the removal of the oxide from the surface [59]. Figure 4.10 shows a system of RIE and the process of RIE for Silicon etching with CF₄ and SF₆ gas. The concept is the same for metal etching but with different gases.

The chamber is first pumped down to a high vacuum and then the etching gases are brought into the chamber. A plasma is then applied which dissociate the etching gases into reactive species of ions and radicals. These species are transferred to the substrate surface and react with etch target material, Al in our case. By-products then desorb from the substrate as a result. There are two types of etching: isotropic where there is undercut under the mask and anisotropic where there are vertical sidewalls and no undercut, figure 4.11 a and b.
Figure 4.9. SEM images showing descumming process effects on gratings with pitches of 1200 nm and designed widths of 150 nm exposed with various laser powers: (a) 18mW-20% (b) 18mW-22% (c) 18mW-24% (d) 18mW-26%, (e) 18mW-28% (f) 18mW-30%
During Al etching with Cl-based gases, the etching is expected to be isotropic; however, the supply of C and H atoms from the photoresist forms a sidewall protection on the film allowing anisotropic etching. Furthermore, reducing the reactor pressure allows ions to travel in a vertical manner allowing better anisotropy etching. [59]. Table 4.3 summarizes the RIE etching parameters. Based on the previous un-optimized etching process, table 4.4 shows the gratings and laser powers used to optimize the etching of the gratings. Following this table and the optimized etching recipe in table 4.3, figure 4.13. shows the SEM images of the optimized gratings.

![Figure 4.10. Outline of reactive ion etching. Adapted with permission from [59]](image)

![Figure 4.11. Etching types: (a) isotropic, (b) anisotropic. Adapted with permission from [59]](image)
From figure 4.12, it can be observed that the best pattern obtained are when the laser power is set to 18 mW-30% (5.4 mW) and the designed gratings are 100 nm (a-b). As such this structure and laser power are used to fabricate the final alignment ruler. Figure 4.13 shows the final optimized grating rulers for the alignment ruler. Per SEM the Al gratings have widths of approximately 530 nm hence a spacing of 670 nm (Pitching is at 1200 nm).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Pressure (mTorr)</th>
<th>Power (W)</th>
<th>Cl₂ (sccm)</th>
<th>BCl₃ (sccm)</th>
<th>Duration (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>30</td>
<td>100</td>
<td>10</td>
<td>35</td>
<td>1800</td>
</tr>
</tbody>
</table>

Table 4.3. Summary of reactive ion etching parameters for Al metal

<table>
<thead>
<tr>
<th>Design Width (nm)</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Power</td>
<td>18mW-30%</td>
<td>18mW-30%</td>
<td>18mW-26%</td>
<td>18mW-22%</td>
<td>18mW-20%</td>
</tr>
</tbody>
</table>

Table 4.4. Selected patterns and laser power for optimizing the final ruler gratings
Figure 4.12 SEM images of gratings after etching and photoresist stripping. Gratings exposed according to table 4.4 for each structure. Inset images shows the structure images under transmission mode via the optical microscope (a-b) 18 mW-30% for 100 nm gratings (c-d) 18 mW-30% for 150 nm gratings (e-f) 18mW-26% for 200 nm gratings.
4.2. Characterization and Optical Testing

To simulate and optically test the alignment process, two layers of the ruler are fabricated on top of each other. Each ruler fabrication process follows the same procedure developed in section 4.1. A silicon dioxide or PMMA layer acting as a space filler is applied between the two layers to simulate the spacing between the rulers during the alignment process (z-direction in simulation – see 3.3.2). Figure 4.13 shows the SEM images of the optimized gratings for the alignment ruler (a) overview of the gratings (b) vertical view with tilting (c) horizontal view with tilting (d) transmission view of the gratings under optical microscope.
two layers of the ruler as if in an alignment process. Figure 4.14 b shows the two layers fabricated on top of each
Figure 4.14 Two Layers fabrication, (a) design of two layers ruler for optical testing, a layer of a silicon dioxide (or PMMA) separates the two layers, (b) Two layers fabrication under SEM where the two layers are perfectly interdigitated and separated by ~ 20 nm, (c) Two layers fabrication under SEM where the two layers are shifted by ~ 400 nm and separated by ~ 20 nm.

other. The two layers are perfectly interdigitated (i.e. \( dx = 0 \) nm) and the two layers are separated by \( dz = 20 \) nm. Figure 4.14 c shows another two layers that are horizontally misaligned (\( dx = 400 \) nm) but with the same separation (i.e. \( dz = 20 \) nm). It is suggested to use e-beam for better results; which is also possible but this would increase the cost of the microfabrication as compared to the laser writer.

The sample is tested under an optical setup (NIR spectrophotometer – see section 2.4) to measure the transmission spectrum. This experimental spectrum is then compared with the simulated spectrum obtained in section 3.3.

4.2.1. Test 1: Transmission via two physically separated devices with IPA as a separator

In this test, two physically separate rulers are brought together. IPA is applied in between to facilitate adhesion and minimize the gap as much as possible. The transmission is then measured over time (0,15,30 minutes). Figure 4.15 depicts the measured transmission. Insignificant changes in the transmission are observed and this is reasoned due to the gap between the two layers is possibly larger than few hundreds of nanometers.
Figure 4.15 Transmission spectra via two physically separated rulers. IPA is applied in between the layers to observe the transmission changes over time.

4.2.2. Test 2: Transmission via fabricated two layers with 200 nm PMMA in between

This test differs significantly from the pervious test that the two layers are fabricated on top of each other (i.e. physically in-separable). A PMMA layer is applied between the two layers to ensure the first layer is planner before applying the second layer so that the second layer can be fabricated properly on the first layer. A 200 nm PMMA layer is applied for this test. Figure 4.16 shows the captured transmission for this case.
As the shift between the two layers decreases, the transmission also decreases which proves that the alignment is getting better when the two layers become close to each other. However, the peak captured in the simulation is not observed here because the peak is located outside of the used spectrometer detection range. This result shall be compared with simulation results depicted in figure 4.17.
It is observed that in both cases the experimental and simulated transmission spectra, as the horizontal (dx) increases the transmission increases. However, the amount of transmission is mismatched and can be explained due to the imperfect fabrication of the second layer. As can be seen in figure 4.14b, the second layer have gratings width of 200 nm whereas the designed gratings should be 500 nm. During fabricating the top layer, the surface conditions of the bottom layer impacted the laser exposure conditions that require uniform surfaces for uniform exposure. Beyond the laser exposure conditions, there are also some limitations on the spectrometer used. It can only detect transmissions related to wavelengths up to 1 um. In section 5.2, there are some suggestions on how to the outcome of the optical measurements by either improving or changing the fabrication process, or using a different mechanical system to detect vertical and horizontal shifts in the interdigitated ruler.

4.2.3. Test 3: Transmission via fabricated two layers with 20 nm PMMA in between

This case is similar to the previous test except that the PMMA layer is reduced to 20 nm thicknesses.
Figure 4.18 Experimental Transmission spectra via two physically in-separated rulers with 20 nm PMMA layer in between.

In figure 4.18, the transmission intensity again decreases as the horizontal shift decreases, which is the same observation from the previous test and this also matches the simulated transmission spectra in figure 4.19. Again, there is no observed peak in all the cases of the shifts, which is also due to the second layer imperfect fabrication and the spectrometer detection range limitation as well. It is also worth noting that the second layer uniformity plays another key factor in reducing the accuracy of the transmission spectrum when compared to the simulated transmission in figure 4.19.
Figure 4.19 Simulated Transmission spectra via two physically in-separated rulers with 20 nm PMMA layer in between.
Chapter 5.

Conclusion and Future Work

5.1. Conclusion

In this research, an alignment ruler was designed based on simulations. Then laser writing which is a low-cost and simple tool was used to fabricate grating structures that are used into an alignment ruler. The grating structures exploit the surface plasmon and Extraordinary Transmission theory to provide optical behaviours. This optical behaviour can be then translated into an alignment guide for the 3D ICs technology (an opportunity for better alignment accuracy) that needs a precise alignment process. The fabrication of the structure was further simplified by using a well-optimized reactive ion etching process which provided anisotropic profile for the gratings. Near-Infrared spectroscopy was then used to test and simulate an actual alignment process to verify the operability of the ruler.

5.2. Future Work

Further optimization to the fabrication process can be applied either by using different grating structures that provide better desired optical behaviour for alignment. A different exposure method other than laser writing can also be used to fabricate the desired gratings. In regard to optical testing, great improvement can be implemented to simplify and enhance the optical characterization and testing. First, a higher range of spectrometer is recommended to detect the transmission peaks which are the essence of the alignment ruler. Second, two separate rulers onto two separate devices can be used to rigorously measure the transmission spectrum versus the relative alignment error. This step requires designing and building an accurate mechanical control system.
with sub-nanometric accuracy in three dimensions. Such nanometric positioning systems are readily available in the market and can be employed to do the horizontal and vertical movements in the nanoscale. Second, a full spectroscopic alignment system can be actually designed and tested onto wafer-to-wafer or chip-to-wafer alignment to demonstrate a successful fabrication of some complex optical or electronic devices.
References


[21] Nanometric Rulers Based on Plasmon Coupling in Pairs of Gold Nanoparticles


