

DESIGN OF ALL-SILICON PHOTONIC AND PLASMONIC PERFECT ABSORBERS AND THEIR APPLICATIONS

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We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.



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ABSTRACT

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Majority of the optoelectronic devices works either in infrared regime or in visible spectrum. Among these, perfect absorbers attracted great attention due to their high applicability in solar cells and high performance photodetectors as well as special applications such as surface enhanced sensing. However, high material costs and elaborate nano-fabrication procedures to build perfect absorbers are prohibitive issues that researchers or processors have to deal with. In this work, all-Silicon (Si) practical low-cost photonic and plasmonic perfect absorbers are investigated by theoretical modeling and the designed devices are fabricated by utilizing standard CMOS technology. In order to model the optical response of Si, the effect of charge carrier mobility on the dielectric is analyzed. We showed that high performance devices that can perform better than the state of the art are possible without requiring high cost materials and elaborate fabrication techniques. Photonic perfect absorbers that have promising band properties in infrared are designed and fabricated. Experimental results support theoretical predictions. We used computational approach to investigate the effect of temperature.

Keywords: Photonics, Silicon, Perfect absorbers.

ÖZET

TÜMÜ SİLİSYUM FOTONİK VE PLAZMONİK MÜKEMMEL IŞIK SOĞURUCULARININ TASARIMI VE UYGULAMALARI

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Optoelektronik aygıtların büyük çoğunluğu kızılötesi veya görünür bölgede çalışması için planlanmıştır. Bu aygıtlarda özellikle de mükemmel emiciler çok çalışılmaktadır. Mükemmel emiciler güneş hücrelerinde, yüksek verimli fotodedektörlerde ve yüzey yardımı ile artırılmış hassasiyetli algılayıcılar için çok önemlidir. Ancak, iyi emici yüzeyler elde etmek için pahalı nanofabrikasyon yöntemlerine ve egzotik malzemelere ihtiyaç bulunmaktadır. Bu tez çalışmasında, tümü Silisyuma dayalı düşük maliyetli fotonik ve plazmonik mükemmel emiciler teorik modelleme ve sayısal benzetim yöntemi ile tasarlanmıştır. Mikro/nanofabrikasyon yöntemleri ile standart CMOS üretim teknolojisi kullanılarak üretilmiştir. Silisyumun optik modellenmesi için, yük taşıyıcıların mobilite değerlerinin dielektrik özelliklerine etkisi incelenmiştir. Silisyum gibi düşük maliyetli malzeme ve yaygın üretim yöntemleri kullanılarak, literatürdeki örnekleri ile kıyaslanabilir veya daha üstün tasarımlar elde edilmiştir. Kızılötesi bölgede mükemmel emici özelliklere sahip fotonik yapılar gösterilmiştir ve elde edilen deneysel sonuçlar ile desteklenmiştir. Sıcaklığın etkisi sayısal olarak benzetim yöntemi ile incelenmiştir.

Anahtar sözcükler: Fotonik, Silisyum, mükemmel ışık soğurucuları.

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Contents

1	Introduction	1
1.1	Photonics and Plasmonics	1
1.2	Silicon	2
1.3	Simulation	3
1.4	Perfect Absorbers	4
1.5	Experiments	4
1.6	Thesis Overview	5
2	Background and Theory	7
2.1	Drude Model	7
2.2	Induction of Optical Constants	8
2.3	Modeling of Mobility	11
2.4	Plasmonic Parameters	11
3	Practical Photonic Perfect Absorbers: Theoretical Modeling and	

Experimental Demonstration	13
3.1 Introduction	13
3.2 Simulation	14
3.3 Results	14
3.3.1 Simulation Results	14
3.3.2 Experimental Results	15
3.4 Conclusion	20
4 Design of All-Silicon Plasmonic Perfect Absorbers	22
4.1 Introduction	22
4.2 Results and Discussion	23
4.3 Conclusion	27
5 Effect of Temperature on Optical Response of Perfect Absorbers	29
5.1 Introduction	29
5.2 Device Structure	30
5.3 Simulation	30
5.4 Results and Discussion	31
5.5 Conclusion	33
6 Conclusion and Future Directions	35

List of Figures

- 2.1 The schematic view of the absorber which is formed using a cavity layer of thickness d_2 sandwiched between a film of thickness d_1 and a semi-infinite opaque layer of thickness d_3 . t_1 , t_2 and t_3 are transmission coefficients, r_1 , r_2 and r_3 are reflection coefficients at the corresponding film boundaries, respectively. In addition, these boundaries have corresponding angles of reflection and transmission, Φ_1 , Φ_2 and Φ_3 , used to calculate transmittance and reflectance. In our case, $\Phi_1 = \Phi_2 = \Phi_3 = 0$ 9
- 3.1 Zero-reflection-dips for 5 different designs. With altered perfect absorber designs we observe zero/near-zero reflection which is actually perfect absorption since transmission is zero. Perfect absorption is achieved in the IR region. For designs 1-5, center wavelengths of absorption are 12.6 μm , 13.9 μm , 9.8 μm , 17.3 μm , 22 μm , respectively. For designs 1-5, the parameters (d_1 , d_2 , carrier concentration of Si device layer) are (5000 nm, 5000 nm, 10^{17} cm^{-3}), (5000 nm, 3000 nm, 10^{18} cm^{-3}), (4000 nm, 600 nm, 10^{17} cm^{-3}), (3000 nm, 4500 nm, 10^{17} cm^{-3}), (1500 nm, 3500 nm, 10^{18} cm^{-3}), respectively. 16

- 3.2 Multiple-band reflection dips for 4 different designs. We achieved multiple-band near-perfect absorbers in the IR region. For designs 6-9, center wavelengths of absorption are 10.7 μm , 22.4 μm , 6.2 μm , 4.1 μm , respectively. We achieved absorption bandwidths greater than 2 μm where reflection is below 10 %. For designs 6-9, design parameters (d_1 , d_2 , carrier concentration of Si device layer) are (2500 nm, 4000 nm, 10^{17} cm^{-3}), (1000 nm, 5000 nm, 10^{17} cm^{-3}), (100 nm, 1500 nm, 10^{20} cm^{-3}), (100 nm, 100 nm, 10^{17} cm^{-3}), respectively. 17
- 3.3 Wide-band reflection dips for 3 different designs. We obtain wide-band zero-reflection, which is essentially wideband perfect absorption since transmission is zero. Wideband dips can be seen for various ranges of infrared spectrum. For design 10-12, d_1 , d_2 and carrier concentration of n-Si at the top are 1000 nm, 100 nm, 10^{19} cm^{-3} ; 600 nm, 1500 nm, 10^{19} cm^{-3} and 60 nm, 600 nm, 10^{20} cm^{-3} , respectively. The carrier concentration of Si at the bottom is 10^{20} cm^{-3} . Center wavelengths of design 10-12 are 13.6 μm , 16.7 μm and 5.4 μm , respectively. Bandwidths of absorption less than 10 % of design 10-12 are 2.6 μm , 3.5 μm and 2.7 μm , respectively. . . 18
- 3.4 Cross-sectional SEM image and AFM scanned surface of thinned SOI wafer, respectively. In (a), from one of the RIE etched chips, we show that the final thickness of the device layer Si can be reduced to desired thickness values for each chip. In (b), the AFM image of the surface of the thinned SOI wafer is shown. Also, in (b) the image shows that surface roughness of the final Si surface is kept as smooth as possible using the SF_6 based RIE recipe. . . . 19
- 3.5 The theoretical and experimental reflection dips for a design whose effective device layer thickness is 6.8 μm . We observed an evident consistency between the theoretical and experimental optical responses of the design in IR wavelength spectrum, which is measured using FTIR. 20

4.1	(a) Scanning Electron Microscope image of 2D plasmonic absorber structure. (b) Schematic illustration of 2D grating structures. . .	24
4.2	(a, b) Measured and calculated reflection spectra, respectively, for samples with periodicity $P = 8 \mu\text{m}$ and $P = 9 \mu\text{m}$	25
4.3	Reflection spectrum for three different incidence angles for plasmonic absorber structures with $P = 9 \mu\text{m}$ and $P = 12 \mu\text{m}$. a - b: experimental and calculated reflection spectra for $P = 12 \mu\text{m}$, respectively. c - d :experimental and calculated reflection spectra for $P = 9 \mu\text{m}$, respectively.	26
4.4	Blue arrows show the molecular resonance points of the acetone. Red arrows show the plasmonic resonances of silicon gratings under air and acetone. Spectral shift from air ($n = 1$) to acetone ($n = 1.36$) can be observed clearly.	28
5.1	Percentage reflection vs. wavelength change (a) as the thickness of Silicon layer at the top changes from 1 to 5 μm when thickness of SiO_2 layer is 1 μm , (b) as the thickness of SiO_2 cavity layer changes from 1 to 5 μm when thickness of Silicon film at the top is 1 μm . Temperature is 300 K, doping concentration of the Silicon film and Silicon substrate are 10^{19} cm^{-3} and 10^{20} cm^{-3} respectively. 32	
5.2	Refractive index vs. wavelength change as the doping concentration of Si varies from 10^{20} cm^{-3} to 10^{17} cm^{-3}	33
5.3	Percentage reflection vs. wavelength graphs for temperatures of 300 K, 400 K and 500 K. For (a) $d_1 = 200 \text{ nm}$, $d_2 = 600 \text{ nm}$ doping concentration of silicon film and substrate 10^{18} cm^{-3} and 10^{20} cm^{-3} respectively (b) $d_1 = 600 \text{ nm}$, $d_2 = 2000 \text{ nm}$ doping concentration of silicon film and substrate 10^{19} cm^{-3} and 10^{20} cm^{-3} respectively. 34	

Chapter 1

Introduction

1.1 Photonics and Plasmonics

Electronic devices operate on charge flow in matter or vacuum. Photonics is based on photon processes and is, in reality, a bond between electronics and optics. As semiconductors become dominant and powerful in optoelectronics, the strength of the tie between optics and electronics has improved. Although photonics is known as the science of generation, manipulation and detection of light via transmission, detection, amplification and modulation; photonic devices and systems are developed hugely and become widely used in industry and research, in parallel to the rise of semiconductors.

Plasmonics emerges when the interactions of light and matter are investigated in the scale of sub-wavelengths. Surface plasmons are oscillating charges associated with electronic wave at the surface. Surface must include immense amount of free charges so that charge polarization can be induced under light incidence and surface plasmons (SPs) can be excited. Surface plasmons enable to localize high amounts of light in a very narrow surface which allows to design and operate powerful resonant optical devices.

Plasmonics and Photonics enable to design of optical devices which are widely used in modern complementary-metal-oxide-semiconductor (CMOS) technology. SPs and photonic cavities have been used extensively to enhance the performance of miscellaneous optical and electronic devices such as photovoltaic devices [1, 2, 3], detectors [4, 5, 6, 7, 8], meta-materials [9, 10], sensing devices [11, 12], nano antennas [13, 14], modulators [15, 16], frequency selectors [17, 18, 19] and perfect absorbers [20, 21, 22, 23, 24, 25].

Perfect absorbers among these devices need careful investigation due to the fact that they can be used as light absorbing surfaces which can be tailored in many field of modern disciplines that are based on the transfer and conversion of data of optical signal into electrical signal.

1.2 Silicon

Metals are the materials that have mainly been used in plasmonic and photonic applications [26]. Metals can support surface plasmons which allow localization of fields. Metals can also be used as a photonic resonators which traps the light inside and allows the light to resonate inside. However, there are considerable bottlenecks associated with metals. High optical loss due to high amount of free electrons and the fabrication cost of metals have always been significant drawbacks of metal usage in the steps of device design and fabrication.

CMOS technology, today, is exceedingly dependent on Silicon(Si). Design tools and fabrication methods of Si improved incredibly. Thus, using Si instead of metals is a comprehensive solution for optical and electronic device design and fabrication that drew huge interest [27, 28, 29, 30]. Band gap energy of Si is 1.12 eV, which eliminates the interband transition in infrared wavelength region. ϵ is negative when the wavelength of operation is larger than the value that corresponds to plasma frequency which requires higher carrier concentration (N) of Si, greater than 10^{19} , to be able to design and operate the device in the near infrared regime. Moreover, solid solubility level of Si ($1.82 \times 10^{21} \text{ cm}^{-3}$) allows

higher doping levels of Si without introducing defects in contrast to Phosphorus (P). Thus, optical and material properties make Si an efficient plasmonic and photonic material for optical and electronic device design.

1.3 Simulation

Finite difference time domain (FDTD) method is used for simulation of our designs. FDTD is a simulation method that is used for solving Maxwell's time dependent curl equations which are the following equations:

$$\nabla \times E = -\partial B / \partial t \quad (1.1)$$

$$\nabla \times H = \partial E + \partial D / \partial t \quad (1.2)$$

In a defined frequency range, equations are solved in time domain by sending a short light pulse. Then, equations above are discretized using Yees FDTD algorithm [31]. FDTD solutions by Lumerical Inc. is used to design and simulate the perfect absorbers that is explained in detail in this thesis.

Simulation environment is usually bounded with perfectly matched layers (PML) in y direction. Periodic boundary is used to simulate infinite space in x directions. A plane wave light source is used to inject multi-frequency plane wave light, and different monitors are used to collect transmitted and reflected light. Absorption is induced via subtraction of transmission and reflection from incident light. Finally, to extract the steady state response of the structure, all processed light is Fourier transformed.

1.4 Perfect Absorbers

A perfect absorber structure ideally absorbs all incident radiation at the operating frequency by disabling reflection, transmission and scattering channels. It is not usually possible to absorb the incident light completely at all frequencies. However, for specific purposes, it may become possible for specific frequencies or for a regime of frequencies. For instance, many devices are designed to absorb light in infrared regime for practical purposes in research and industry today.

The field of perfect absorbers is a field that is at rise especially last decade. Many designs are suggested to operate as detectors, sensing devices, meta-materials, modulators, micro-bolometers, sensors and antennas. It works as a converter of optical signal to electrical signal, which is usually current. It is worth to emphasize that many designs work as a converter for preceding purpose, but not as efficient as perfect absorbers perform. Due to this reason, design of perfect absorbers is important either in research or industry.

Perfect absorber designs have significantly improved over time. Miscellaneous designs are demonstrated using metals and various nanofabrication technologies were used to manufacture more complex and demanding designs [32]. Although the number of designs and types of devices generalized, the need for more efficient perfect absorbers has not been reduced [33, 34, 35]. The main issue is high fabrication cost and the difficult and efficiency-vanishing elaboration of the expensive fabrication methods that have been used.

1.5 Experiments

After theoretical design procedure and simulation of the the desired devices, proof of concept of the optical response of the design are required. In this way, theoretical modeling and simulation is validated by experimental results. In this thesis, designed perfect absorbers were fabricated using Inductively Coupled Plasma (ICP) to etch the surface of the devices to achieve desired surface structures. For

the designs that require patterning, optical lithography is utilized after desired patterns are drawn on a mask by using Mask Writer.

Environmental Scanning Electron Microscopy (ESEM), Optical Microscopes and Atomic Force Microscopy (AFM) were used to image the fabricated devices. These devices allowed us to inspect the thickness variation, surface roughness and surface topography of the fabricated devices after experimental processes. In few cases, Focused Ion Beam (FIB) was used to verify layer thickness if the thickness is on the order of few micro meters.

Fourier Transform Infrared Spectroscopy (FTIR) and Infrared Ellipsometry were mainly used to measure the optical response of fabricated devices. For angular light incidence and gathering the reflected light Ellipsometry was utilized. For transmission and reflection under perpendicular light incidence, FTIR was the main measurement utility.

1.6 Thesis Overview

In this work, we theoretically modeled Si and using our models we achieved to tune optical parameters of Si. The modeling process includes three main steps: (1) electrical modeling that includes modeling of parameters related to mobility, carrier concentration and temperature; (2) Optical modeling that consists of dielectric constant, refractive index and extinction coefficient. Then we designed all-Si perfect absorbers using Si and simulate our design candidates to achieve desired device performance which actually indicates the required device parameters. After these steps, we demonstrated our designs and showed that theoretical performance and experimental performance of our designed devices are consistent [36].

In Chapter 2, the theory behind perfect absorb design methodology is introduced. Key theoretical concepts for this thesis are summarized. In Chapter 3, photonic perfect absorbers are introduced. The process of theoretical design,

simulation and experimental steps are investigated. In Chapter 4, plasmonic polarization independent perfect absorbers are investigated. Theoretical modeling is followed by a careful proof of concept of the designs. In Chapter 5, thermal response of Si is modeled and simulated. In this way, we showed that the optical response of the perfect absorbers can be tailored in infrared regime. In Chapter 6, the thesis is restated via discussing the support of the work in the field of perfect absorbers. Future directions are emphasized.



Chapter 2

Background and Theory

2.1 Drude Model

Drude model sets a frequency-dependent conductivity. Conduction electrons are regarded as independent particles in an ideal gas environment that moves freely [36]. The formula is stated as follows:

$$\sigma = \frac{\sigma_0}{1 + j\omega r} \quad (2.1)$$

where σ is conductivity, ω is frequency, σ_0 is low-frequency conductivity and r is relaxation time. Effective permittivity can be written as in Equation (2.2):

$$\epsilon_e = \epsilon + \frac{\sigma}{j\omega} \quad (2.2)$$

In the Equation (2.2), ϵ_e is effective permittivity. When the effective permittivity is restated using Equation (2.1) and Equation (2.2), as seen in Equation (2.3), frequency-dependent effective permittivity is induced as follows:

$$\epsilon_e = \epsilon + \frac{\sigma_0}{j\omega(1 + j\omega r)} \quad (2.3)$$

For $\omega \gg 1/r$, Equation (2.3) turns into $\epsilon_e \approx \epsilon - \sigma_0/\omega^2 r$ which shows that the conductivity actually reduces the real part of the dielectric permittivity. If the medium has a dielectric which has free space type properties ($\epsilon = \epsilon_0$), effective permittivity can be written as follows:

$$\epsilon_e = \epsilon_0 \left(1 - \frac{\omega_p^2}{\omega^2} \right) \quad (2.4)$$

where $\omega_p = \sqrt{\sigma_0/\epsilon_0 r}$ is named plasma frequency.

2.2 Induction of Optical Constants

The perfect absorber that we examine is a cavity layer of SiO_2 that is sandwiched between two layers (i.e. device layer Si, and handle layer Si of SOI wafers) of n-type Si. As can be seen in Figure 2.1, the top Si film layer has thickness of d_1 , and index of refraction of n_1 . The cavity layer has a thickness of d_2 , and index of refraction of n_2 . t_2 and r_1 should be noted as transmission and reflection coefficients at the air-Si device layer interface, respectively. t_1 and r_2 are transmission and reflection coefficients at the SiO_2 and Si device layer interface, respectively. t_3 and r_3 are transmission and reflection coefficients at SiO_2 and Si handle layer interface, respectively. With a thickness of d_3 and an index of refraction of n_4 , the Si handle layer is thick enough that we can assume that it is semi-infinite. Analytical models for optical response of structures are derived in terms of thicknesses of layers, and complex refractive indices. The permittivity of Si is calculated according to the Drude model [37]. Furthermore, the transmission and reflection coefficients of the absorber can be stated as follows:

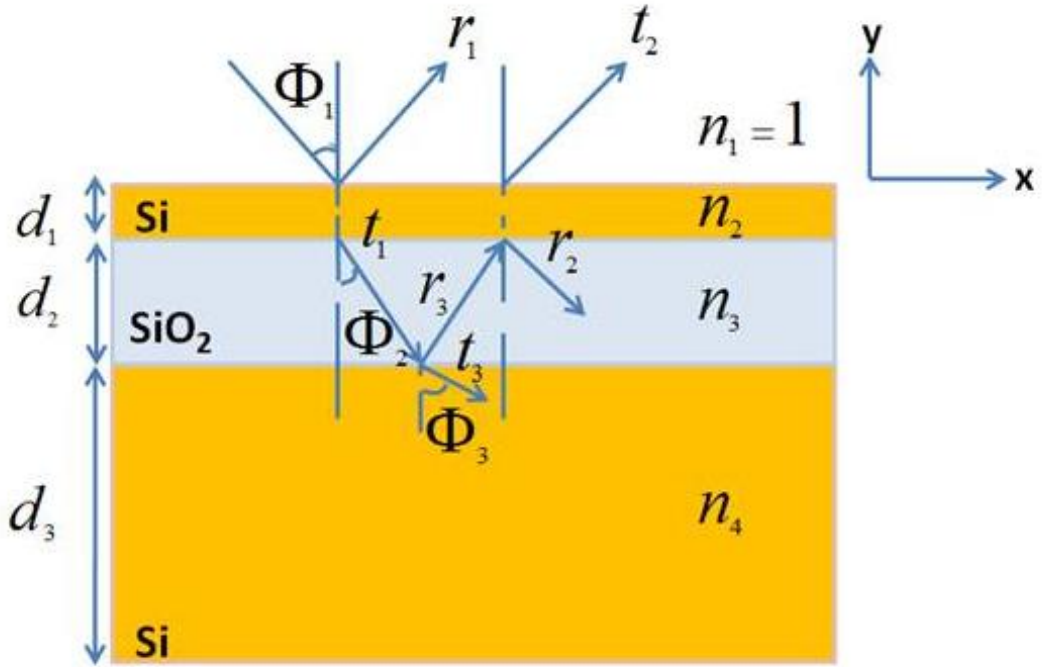


Figure 2.1: The schematic view of the absorber which is formed using a cavity layer of thickness d_2 sandwiched between a film of thickness d_1 and a semi-infinite opaque layer of thickness d_3 . t_1 , t_2 and t_3 are transmission coefficients, r_1 , r_2 and r_3 are reflection coefficients at the corresponding film boundaries, respectively. In addition, these boundaries have corresponding angles of reflection and transmission, Φ_1 , Φ_2 and Φ_3 , used to calculate transmittance and reflectance. In our case, $\Phi_1 = \Phi_2 = \Phi_3 = 0$.

$$r = r_1 + \frac{t_1 t_2 r_3 e^{-i2\beta}}{1 - r_2 r_3 e^{i2\beta}} \quad (2.5)$$

$$t = \frac{t_1 t_3 e^{i2\beta}}{1 - r_2 r_3 e^{i2\beta}} \quad (2.6)$$

Where $\beta = \frac{2\pi n_3 d_3 \cos \Phi_2}{\lambda}$ is the phase shift, n_3 is the refractive index of SiO_2 , d_2 is the thickness of SiO_2 and Φ_2 is the angle of refraction at the interface of Si device layer, and SiO_2 . Reflectance and transmittance of the absorber can be calculated as follows:

$$R = rr^* \quad (2.7)$$

$$T = \frac{Re(\cos \Phi_3 / n_3)}{Re(\cos \Phi_1 / n_1)} tt^* \text{ for } TM \text{ waves} \quad (2.8)$$

$$T = \frac{Re(\cos \Phi_3 n_3)}{Re(\cos \Phi_1 n_1)} tt^* \text{ for } TE \text{ waves} \quad (2.9)$$

$Re()$ indicates the real part of a complex quantity, the asterisk stands for the complex conjugate, and n_1 and n_2 indicate the complex refractive indices of air and Si device layer, respectively.

$$rr^* = \frac{(p_1 + p_3 \delta)^2 4p_1 p_3 \sin^2 \gamma_1}{(1 - p_2 p_3)^2 4p_2 p_3 \sin^2 \gamma_2} \quad (2.10)$$

and

$$tt^* = \frac{\alpha_1 \alpha_3}{(1 - p_2 p_3)^2 + 4p_2 p_3 \sin^2 \gamma_2} \quad (2.11)$$

where $p = |r_j|$ and $\alpha = t_j t_j^*$, j indicates 1, 2 or 3 for the corresponding subscript, $\delta = |t_1 t_2 - r_1 r_2|$, $\gamma_1 = (2\beta - \Phi_1 + \Phi_3 + \Phi_2)/2$, $\gamma_2 = (2\beta + \Phi_2 + \Phi_3)/2$, where $\Phi_j = \arg(r_j)$ and $\Phi_2 = \arg(t_1 t_2 - r_1 r_2)$.

Absorption, transmission and reflection are calculated utilizing Fresnel equations for conventional thin-film wave propagation in absorbing media [38]. In our case, light is incident normal to the surface of the absorber. For the case of multiple interfaces, reflection and transmission coefficients can be obtained using Airys formulae [39]. The reflectance and transmittance of the perfect absorber can be calculated by using Eqns. (2.7), (2.8) and (2.9). Since the Si handle layer is considered as semi-infinite, the absorptivity of the perfect absorber can be written as by Kirchhoffs law [40], where R is reflectivity.

2.3 Modeling of Mobility

In order to model the dielectric constant of Si that is expressed as a function of carrier mobility [37], the carrier mobility of n-type Si is calculated as

$$\mu = 88T_n^{-0.57} + \frac{7.4 \times 10^8 T^{-2.33}}{1 + \left[\frac{N}{1.26 \times 10^{17} T^{2.4}} \right] 0.88 T_n^{-0.146}} \quad (2.12)$$

where $T_n = T/300$, T is the temperature value in Kelvin, and N is the carrier concentration in cm^{-3} [41]. In this study, T is taken as 300 Kelvin. When Drude Model and Equation (2.12) are used, optical parameters of Si for various carrier concentrations can be computed.

2.4 Plasmonic Parameters

Coupling condition and analytical solution of plasmon dispersion is useful for plasmon generation. For a square array arrangement the momentum mismatch

between SPP modes and free space light can be satisfied by Braggs coupling equation [42]:

$$k_{mode} = k_0 \sin \theta \pm iG_x \pm jG_y \quad (2.13)$$

where, k_0 is the wavevector of the incident light, θ is the angle of incidence, G_x and G_y $G_y(|G_x| = |G_y|) = 2\pi/P$ are the reciprocal vectors of the structure, i and j are grating orders, k_{mode} is the wavevector of the structure with a specific mode. Surface plasmon polariton dispersion relation is given by [43]:

$$k_{spp} = k_0 \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}} \quad (2.14)$$

where k_{spp} is the wavevector of the surface plasmon polaritons and k_0 is the wavevector of the incident light, ϵ_m and ϵ_d are dielectric constants of the metal and surrounding medium, respectively.

Chapter 3

Practical Photonic Perfect Absorbers: Theoretical Modeling and Experimental Demonstration

3.1 Introduction

After their introduction, perfect absorbers consisting of metallic split ring resonators saw followed by many modifications to improve the band property [44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54]. However, most of the absorbers work at a single band frequency in limited wavelength spectrum. This restricted wavelength spectrum limits many practical applications such as multi-frequency spectroscopy and detection [55]. Moreover, the improvements in the performance of perfect absorbers usually require complex and expensive fabrication methods which present significant bottleneck for scalable implementation of perfect absorber technologies [56, 57, 58]. Thus, simple and high-performance absorbers that can operate in a wide spectral band without requiring extra metallic patterns are desirable. Based on theoretical models, we propose, and experimentally demonstrate perfect absorber surfaces based on silicon-on-insulator (SOI) wafers whose Si device layer and Si handle layer have appropriate carrier concentrations. Center wavelength

of absorption of such absorber surfaces can be varied in infrared (IR) spectrum, and bandwidth of such absorber surfaces can be designed to be as large as 2.5 μm .

3.2 Simulation

In simulations, a plane wave light spectrum of 2 μm to 25 μm is normally incident to the absorber surface. The minimum mesh size is set to 1 nm. The reflected light power from the absorber is calculated by the field/power monitor above the structure. Power absorption is calculated using electric field intensity and the imaginary part of permittivity.

Thicknesses of the n-Si device and cavity layers were varied from 20 nm to 5000 nm for each layer, keeping the distance between the light source and top surface of the absorber constant. The carrier concentration of n-Si handle layer was chosen at 10^{20} cm^{-3} . However, carrier concentration of the Si device layer was varied between 10^{17} cm^{-3} and 10^{20} cm^{-3} . We used n-Si for both layers instead of intrinsic Si to shift the plasma wavelength into the IR range.

3.3 Results

We classify our results as simulation results and experimental results that confirm our model.

3.3.1 Simulation Results

Appropriate carrier concentrations were chosen to find proper sets of refractive indices that will yield perfect or near perfect absorption by modifying the thicknesses of the layers [40, 59]. The carrier concentrations of Si device layers were

chosen on the order of 10^{18} cm^{-3} to provide refractive index contrasts with respect to the Si handle layer in the IR spectrum. Absorption mechanism of our designs is based on destructive interference of the reflected waves. If the waves destructively interfere at a specific wavelength value, we observe single-band absorption. However, when the waves destructively interfere at multiple wavelength values, we are able to observe wide-band or multiple band absorption depending on how close the wavelength values are. Since refractive index of highly doped Si is strongly dependent on wavelength, it is possible to bring two or more values of resonance wavelength of perfect or near perfect absorption closer to each other. If many of resonance wavelength values are very close to each other, wideband absorption is observed, otherwise multiple band absorption is achieved. As demonstrated in Figure. 3.1, perfect absorption is achieved in the wavelength range of $10 \text{ }\mu\text{m}$ to $22 \text{ }\mu\text{m}$ with proper perfect absorber design. We have also observed multiple bands of perfect absorption in the IR range as can be seen in Figure 3.2.

Comparing this work to that of Dayal et al. [60], it is clear that our structure is significantly simpler. Moreover, in Figure 3.3 we observe wide-band perfect absorption bands in the IR region. For design 11, there is a reflection dip (with average reflection below 6 %) with a bandwidth of almost $2.5 \text{ }\mu\text{m}$. For design 10, around wavelength of $14 \text{ }\mu\text{m}$, there is a dip of less than 6 % with a spectrum range of almost $2 \text{ }\mu\text{m}$. And for design 12, there is a reflection dip less than 2 percent whose wavelength range is almost $1.5 \text{ }\mu\text{m}$ in the wavelength range of $4\text{-}6 \text{ }\mu\text{m}$.

3.3.2 Experimental Results

To experimentally confirm our models and simulations we followed the microfabrication approach below: The starting wafer is an SOI wafer with device layer resistivity in the range of $31.5\text{-}38.5 \text{ }\Omega\text{cm}$ and Si handle layer resistivity in the range of $3\text{-}5 \text{ }\Omega\text{cm}$. The thickness of Si handle layer is $575 \text{ }\mu\text{m}$. Orientation of the both Si layers is (100). Initially, device layer thickness of SOI is $54.5 \text{ }\mu\text{m}$ with $\pm 1.5 \text{ }\mu\text{m}$ variation as reported by the vendor. SOI wafer is cleaned with

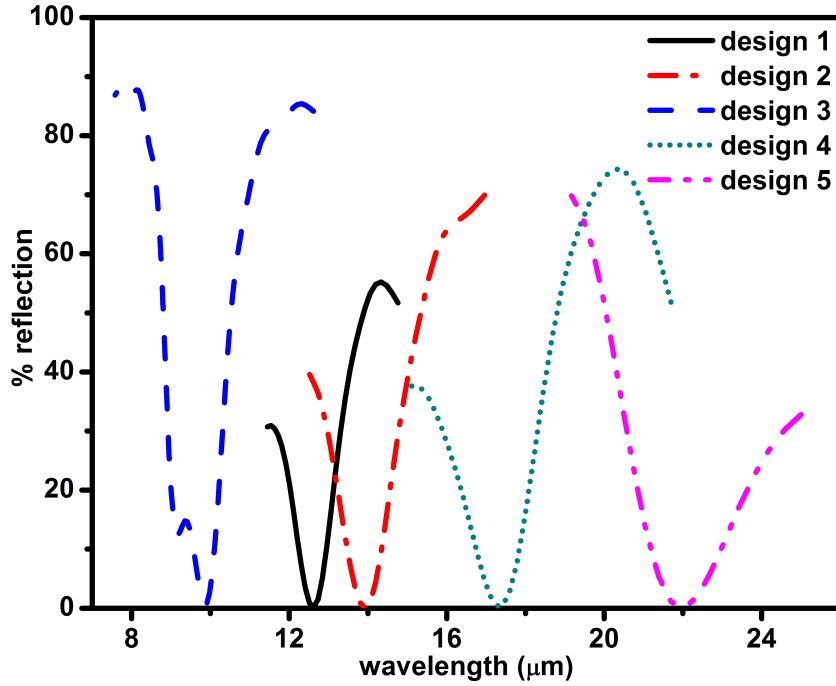


Figure 3.1: Zero-reflection-dips for 5 different designs. With altered perfect absorber designs we observe zero/near-zero reflection which is actually perfect absorption since transmission is zero. Perfect absorption is achieved in the IR region. For designs 1-5, center wavelengths of absorption are $12.6 \mu\text{m}$, $13.9 \mu\text{m}$, $9.8 \mu\text{m}$, $17.3 \mu\text{m}$, $22 \mu\text{m}$, respectively. For designs 1-5, the parameters (d_1 , d_2 , carrier concentration of Si device layer) are $(5000 \text{ nm}, 5000 \text{ nm}, 10^{17} \text{ cm}^{-3})$, $(5000 \text{ nm}, 3000 \text{ nm}, 10^{18} \text{ cm}^{-3})$, $(4000 \text{ nm}, 600 \text{ nm}, 10^{17} \text{ cm}^{-3})$, $(3000 \text{ nm}, 4500 \text{ nm}, 10^{17} \text{ cm}^{-3})$, $(1500 \text{ nm}, 3500 \text{ nm}, 10^{18} \text{ cm}^{-3})$, respectively.

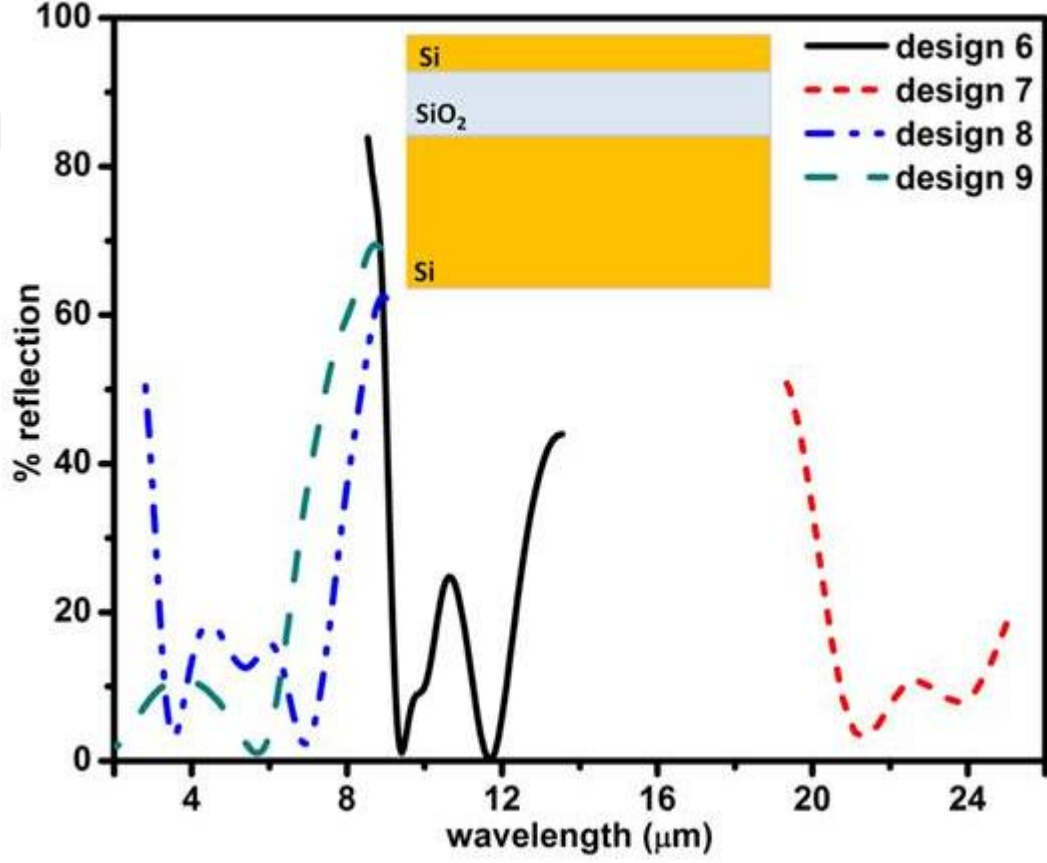


Figure 3.2: Multiple-band reflection dips for 4 different designs. We achieved multiple-band near-perfect absorbers in the IR region. For designs 6-9, center wavelengths of absorption are $10.7 \mu\text{m}$, $22.4 \mu\text{m}$, $6.2 \mu\text{m}$, $4.1 \mu\text{m}$, respectively. We achieved absorption bandwidths greater than $2 \mu\text{m}$ where reflection is below 10 %. For designs 6-9, design parameters (d_1 , d_2 , carrier concentration of Si device layer) are (2500 nm, 4000 nm, 10^{17} cm^{-3}), (1000 nm, 5000 nm, 10^{17} cm^{-3}), (100 nm, 1500 nm, 10^{20} cm^{-3}), (100 nm, 100 nm, 10^{17} cm^{-3}), respectively.

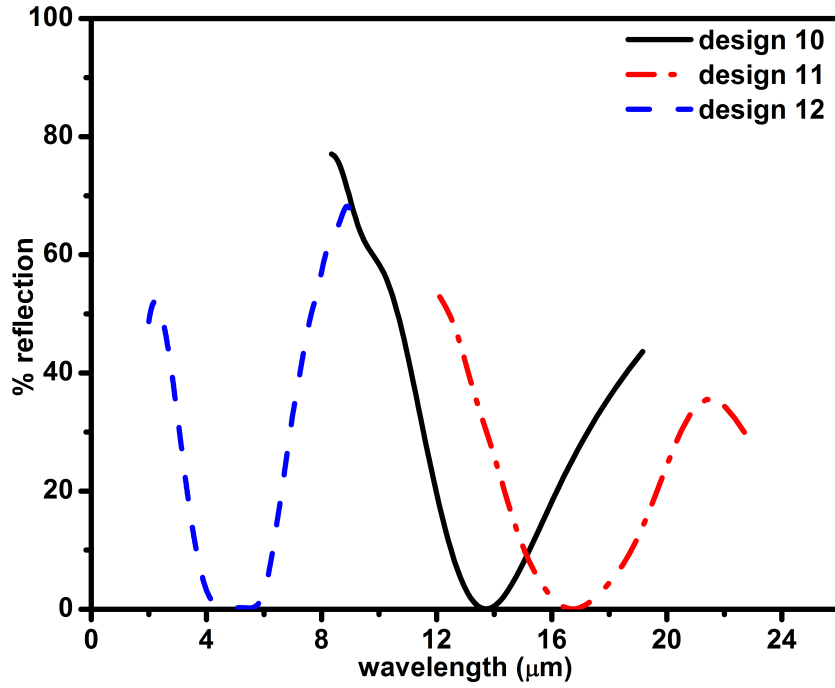


Figure 3.3: Wide-band reflection dips for 3 different designs. We obtain wideband zero-reflection, which is essentially wideband perfect absorption since transmission is zero. Wideband dips can be seen for various ranges of infrared spectrum. For design 10-12, d_1 , d_2 and carrier concentration of n-Si at the top are 1000 nm, 100 nm, 10^{19} cm^{-3} ; 600 nm, 1500 nm, 10^{19} cm^{-3} and 60 nm, 600 nm, 10^{20} cm^{-3} , respectively. The carrier concentration of Si at the bottom is 10^{20} cm^{-3} . Center wavelengths of design 10-12 are $13.6 \mu\text{m}$, $16.7 \mu\text{m}$ and $5.4 \mu\text{m}$, respectively. Bandwidths of absorption less than 10 % of design 10-12 are $2.6 \mu\text{m}$, $3.5 \mu\text{m}$ and $2.7 \mu\text{m}$, respectively.

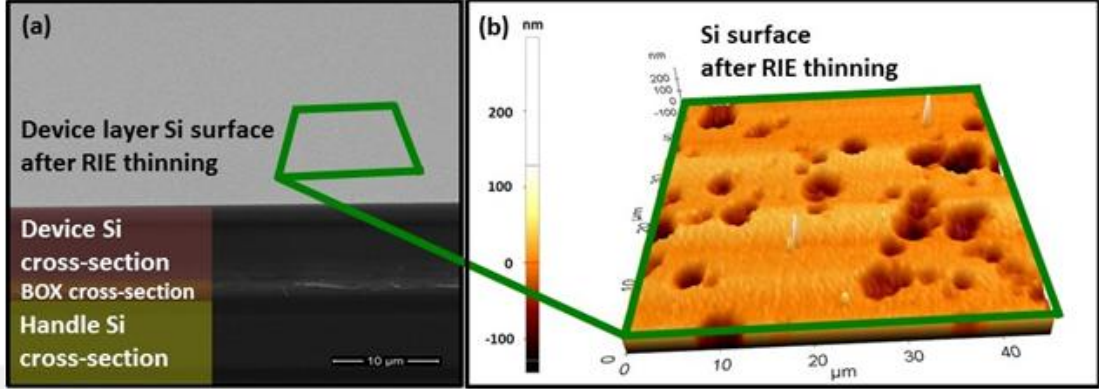


Figure 3.4: Cross-sectional SEM image and AFM scanned surface of thinned SOI wafer, respectively. In (a), from one of the RIE etched chips, we show that the final thickness of the device layer Si can be reduced to desired thickness values for each chip. In (b), the AFM image of the surface of the thinned SOI wafer is shown. Also, in (b) the image shows that surface roughness of the final Si surface is kept as smooth as possible using the SF_6 based RIE recipe.

acetone, isopropyl alcohol, DI water, Piranha ($H_2SO_4:H_2O_2$ 4:1), and HF dip to remove any residues that may be present on the device layer surface of the SOI wafer. Then, using an SF_6 based reactive ion etching (RIE) plasma recipe, we isotropically thin the device layer Si of each sample to the desired Si thicknesses as shown in Fig. 5(a) for one of the experimentally tested devices. To measure the surface roughness of the Si device layer after RIE processing, Atomic Force Microscopy (AFM) is used to scan a $45\ \mu\text{m} \times 45\ \mu\text{m}$ area with a rate of 0.25 Hz using a cantilever whose spring constant is 0.2 N/m. As shown in Fig. 5(b), an average of 36 nm surface roughness is achieved on the Si surface using an optimized RIE recipe. This surface roughness value is much smaller than our wavelength of interest, and satisfies the optical requirements for our experiments.

The thickness of the device layer Si is reduced to an effective thickness of $6.8\ \mu\text{m}$ with an average etch rate of $3\ \mu\text{m}/\text{min}$. Then, we measure the reflection of an SOI sample between the 2-20 μm wavelength ranges using Fourier Transform Infrared Spectroscopy (FTIR). The simulation data and corresponding experimental data are shown in Fig. 6 indicating a good agreement between the simulation and experimental results. The experimental measurements are valid for light beams that are within 5° uncertainty with respect to the surface normal. For higher

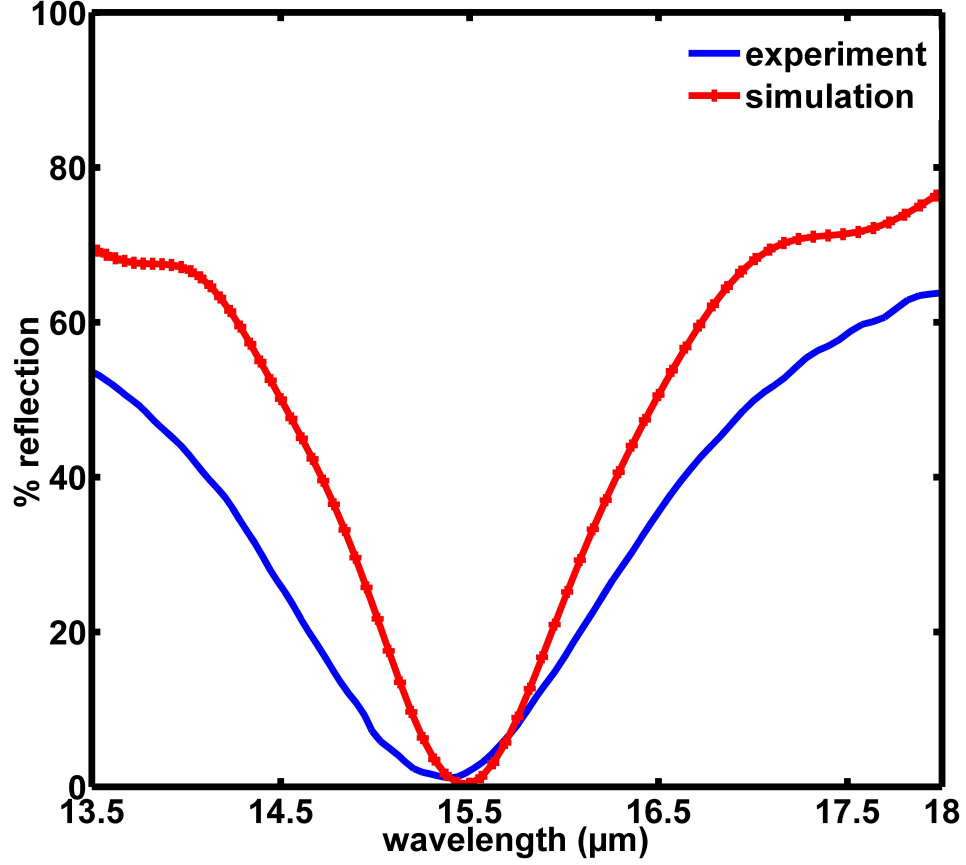


Figure 3.5: The theoretical and experimental reflection dips for a design whose effective device layer thickness is $6.8 \mu\text{m}$. We observed an evident consistency between the theoretical and experimental optical responses of the design in IR wavelength spectrum, which is measured using FTIR.

deflection angles, the external reflection considerably reduces the optical power which penetrates into the absorber.

3.4 Conclusion

In this part, practical multi-featured perfect absorbers are designed and manufactured using SiO_2 as a cavity layer that is sandwiched between an n -type Si device

layer on top and an n -type Si handle layer at the bottom. When the carrier concentrations of the device and handle layers are chosen wisely with correspondingly appropriate thicknesses, we are able to achieve perfect absorbers whose resonance wavelengths vary between 2-25 μm . Moreover, multi-band perfect absorbers are observed for specific thicknesses and carrier concentrations of Si in the IR region.

We would like to emphasize four main achievements of this study that are reached by selecting the carrier concentration wisely, and the proper thicknesses for SOI layers: (i) We are able to obtain perfect absorbers whose resonance wavelengths vary between 2 μm and 25 μm . (ii) Multi-band perfect absorbers are observed in the IR region. (iii) We achieve perfect absorbers with greater than 98% absorption whose bandwidth is more than 1.5 μm . (iv) Starting from analytical formulations, we chose functional models, simulated the models, and eventually experimentally validated our models. In addition to these four main achievements above, it is also important to emphasize that the structural complexity, microfabrication costs, and implementation difficulty of the proposed perfect absorbers are significantly lower compared to the state of the art perfect absorbers. With the contribution of the four achievements above, this design is envisioned to be a crucial part in many future applications of detectors, sensing devices, meta-materials, modulators, micro-bolometers, sensors and antennas.

Chapter 4

Design of All-Silicon Plasmonic Perfect Absorbers

4.1 Introduction

Plasmonic and metamaterial electromagnetic absorbers have induced extensive research not only for their fascinating electromagnetic properties, but also their potential for various applications.

Researchers tried to increase absorption waveband by exploiting multiple resonances together for energy harvesting, and some of the detection and imaging applications where the broadband absorption is desirable [61]. On the other hand, some other applications, such as selective thermal emitters and detectors and biochemical and refractive index sensors, require narrow absorption bands [62, 22]. Due to the fact that resonance wavelength of metamaterial absorbers strongly depends on the size of the device itself, they can be used as spectrally selective detectors such as bolometers [63]. Plasmonic metamaterials, confined to metal dielectric surface, are extremely sensitive to refractive index of the surrounding dielectric medium. Such a strong dependency paves the way for ultra sensitive label-free refractive index sensing applications [64, 65].

In the preceding cases, conventional metallic components are utilized as their material building blocks. Since the magnitude of the real part of the permittivity is very large at mid-infrared wavelengths, plasmonic mode confinement significantly decreases at mid-infrared regime [66]. Conventional metals also pose fabrication challenges and have degradation issue on exposure to air or humidity that limits the process of integration of devices [26]. However, conductivity Si exhibits plasmonic behaviors at a wide range of infrared regime [67, 68], which makes Si a source of alternative to metals in plasmonics depending on the necessity.

In this part, we theoretically and experimentally demonstrated all silicon frequency selective infrared absorbers. Different two-dimensional grating structures with different periodicities implemented and their incidence angle sensitivity is studied. Furthermore we demonstrated that our plasmonic devices can be used sensing or detection mode which measures the spectral shift of the resonance in response to a refractive index change of the medium.

4.2 Results and Discussion

Two dimensional grating structures were patterned on a heavily doped Silicon wafer by using optical lithography and inductively coupled plasma etching technique. Scanning electron microscope image of the 2D Silicon gratings are shown in Figure 4.1 (a). 2D surface pattern provides polarization insensitive optical behaviour for the device. Optical properties of highly-doped semiconductors are dominated by electron plasma of the material, and can be modeled using Drude formalism. We extracted optical properties of the highly doped silicon using Drude formalism [37]. Reflection spectra from the fabricated samples were obtained using a Bruker HYPERION IR microscope and Bruker Vertex 70v Fourier transform infrared (FTIR) spectrometer with a gold mirror as the reference for background measurement.

Structures in FDTD simulations were imported by using digitized SEM images

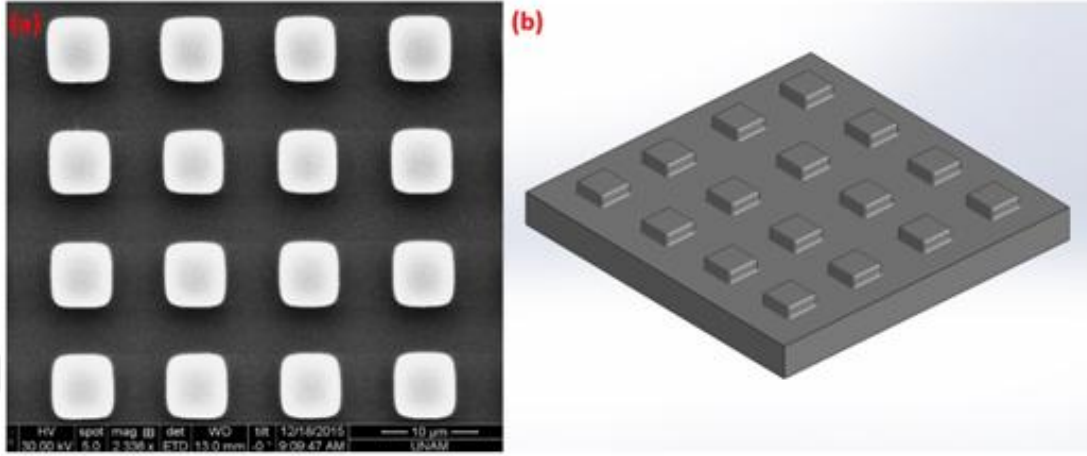


Figure 4.1: (a) Scanning Electron Microscope image of 2D plasmonic absorber structure. (b) Schematic illustration of 2D grating structures.

of experimentally fabricated 2D gratings. Angular reflection measurements were obtained using J. A. Woollam spectroscopic ellipsometer. The optical response of the plasmonic absorbers was also calculated with FDTD technique.

Figure 4.2 shows measured and calculated reflection spectra of the 2D plasmonic absorber structures for arbitrarily polarized light at normal incidence in the wavelength range from $7 \mu\text{m}$ to $20 \mu\text{m}$. Measured reflection spectra for 2D grating with period, $P = 8 \mu\text{m}$, shows 98 % absorption at the resonance wavelength. This near perfect absorption is due to efficient coupling of incident light into SP modes through momentum matching.

In Figure 4.3, the reflection spectra for two different 1D periodic samples in the case of three different angles of incidence were compared. Simulated (dashed lines) reflectance spectra for these different samples are in agreement with experimental results (solid lines). For the simple 1D grating of grooves, phase-matching takes place whenever the following condition holds: $\beta = k \sin \theta \pm \nu k_x$ is fulfilled, where $k_x = 2\pi/P$. Hence, greater incident angle causes redshift of the resonance wavelength. When the period increased, effect of reciprocal vector lowered, hence angular sensitivity increases with increase of the period of the structures. This relationship is shown in Figure 4.3 with demonstration of periodicities $P = 12 \mu\text{m}$ and $P = 9 \mu\text{m}$.

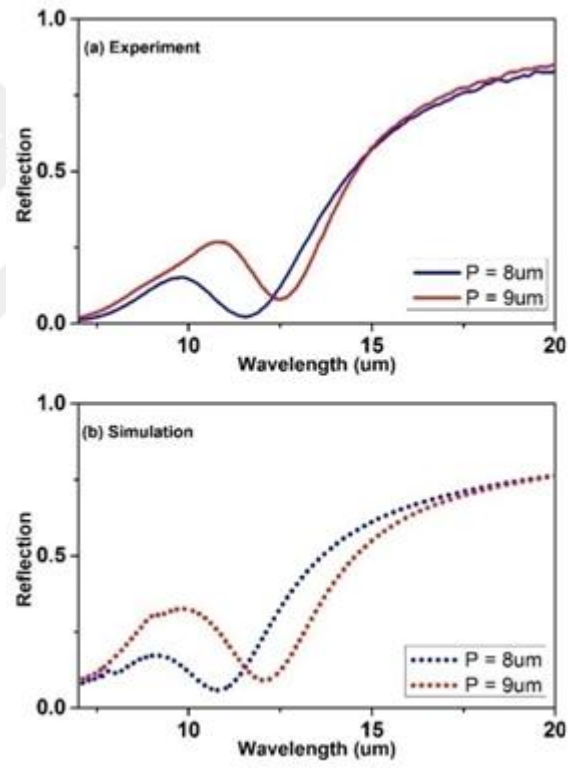


Figure 4.2: (a, b) Measured and calculated reflection spectra, respectively, for samples with periodicity $P = 8 \mu\text{m}$ and $P = 9 \mu\text{m}$.

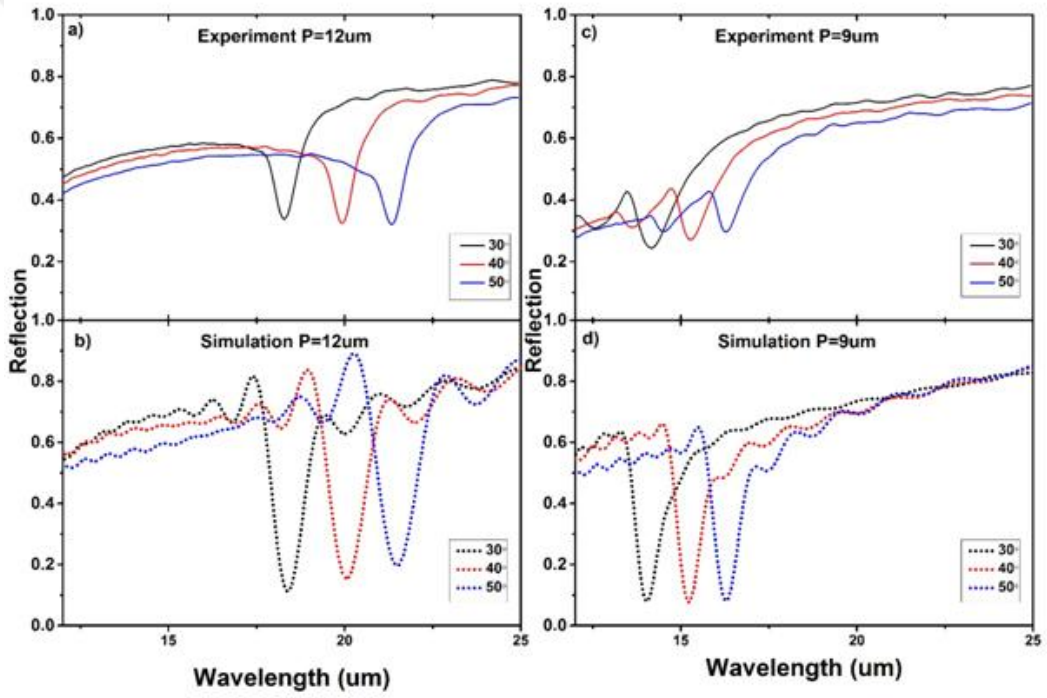


Figure 4.3: Reflection spectrum for three different incidence angles for plasmonic absorber structures with $P = 9 \mu\text{m}$ and $P = 12 \mu\text{m}$. a - b: experimental and calculated reflection spectra for $P = 12 \mu\text{m}$, respectively. c - d :experimental and calculated reflection spectra for $P = 9 \mu\text{m}$, respectively.

We investigated refractive index sensitivity of our plasmonic absorber by immersing the same structure in acetone and measuring the reflection spectrum. The sensitivity of surface plasmon resonance based sensor is defined as the change in resonant wavelength as a function of change in refractive index, $S = \Delta\lambda/\Delta n$ nm/RIU. Since it is easier to detect resonance changes with narrow lines, the sensitivity is divided into full width at half-maximum (FWHM) to determine figure of merit $FOM = S/FWHM$. Figure 4.4 shows the reflection spectra for the same structure in different media, air ($n = 1$) and acetone ($n = 1.36$). In order to eliminate effect of molecular resonances of acetone in mid-infrared regime, reflection measurements of the plasmonic absorber under acetone is normalized to the reflectance spectrum of acetone on the bare silicon surface. Measurements of reflection showed that plasmonic absorber exhibits a sensitivity of 10800 nm/RIU and FOM value of up to 5. It is important to note that similar refractive index sensors works at visible frequencies, and nanofabrication of these sensors are done by using expensive techniques such as e-beam lithography [69]. As a result, it is crystal clear that wafer scale fabrication of plasmonic absorbers yields remarkable fabrication utility for refractive index sensors.

4.3 Conclusion

In conclusion, we have demonstrated all-silicon based plasmonic perfect or near perfect absorbers with excellent absorption performance. Periodic silicon gratings were fabricated by cost effective methods including conventional optical lithography and reactive ion etching technique. We show that the spectral dependence of the resonance wavelength on the period of the structure and we studied the incidence angle sensitivity. We further demonstrate the refractive index capability of silicon absorbers and show a detection limit as low as 10^{-5} RIU which is highly advantageous for label free sensing applications. As the strong selectivity and absorption spectrum and quality is investigated, it is pretty valuable that these designs can be promising for future applications of biological and chemical sensors.

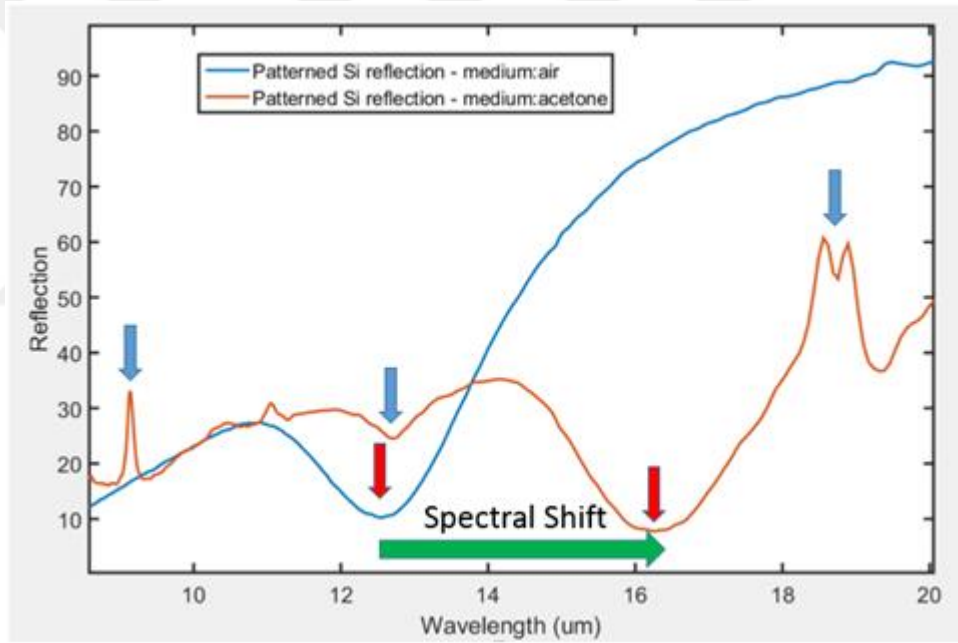


Figure 4.4: Blue arrows show the molecular resonance points of the acetone. Red arrows show the plasmonic resonances of silicon gratings under air and acetone. Spectral shift from air ($n = 1$) to acetone ($n = 1.36$) can be observed clearly.

Chapter 5

Effect of Temperature on Optical Response of Perfect Absorbers

5.1 Introduction

Current designs of perfect absorbers mostly consist of an elaborate metallic pattern on a thin dielectric film forming a cavity with a thick metal layer. Simpler device architectures based on standard manufacturing techniques and with added functionalities such as frequency tuning have been sought after. Frequency tuning using temperature (heating/cooling) offers dynamic tunability and reconfigurability [70]. In this work, we propose a thin-film Fabry-Perot resonator based on standard VLSI processes and Si substrates whose resonant absorption wavelength can be shifted with temperature. We investigate active tunability of resonance frequency in our design.

5.2 Device Structure

We simulate a Fabry-Perot cavity formed on a standard substrate such as Silicon-on-insulator (SOI) with highly conducting Si layer. The Fabry-Perot resonator formed by SiO_2 layer sandwiched between two Si layers is schematically shown in Figure 2.1. The structure is asymmetric with respect to SiO_2 layer. Reflection and transmission phenomena at the boundaries of Fabry-Perot resonator are illustrated. It should be noted that the Si layer at the bottom is assumed to be semi-infinite, such that any light penetrating to this region is absorbed and is not considered in the calculations of the fields of the resonator. Structure parameters depend on complex refractive index and thickness of Si layer. All coefficients are independent of polarization since the angle of incidence is assumed zero. Hence, all coefficients are valid for both transverse electric (TE) and transverse magnetic (TM) polarizations.

5.3 Simulation

Plane wave of light with a spectral width of 2 to 25 μm is normally incident on the Fabry-Perot resonator. Mesh size was set as 1 nm in the cavity and n-Si region in order to increase the accuracy of the simulations. Plane wave source was placed 30 μm above the resonator. This distance is chosen to be larger than half of the maximum wavelength of interest, which is 25 μm . A frequency domain power monitor was placed 5 μm above the source to capture the reflected light from the resonator.

Thickness of the top silicon layer and SiO_2 layer are varied between 200 to 5000 nm in order to investigate the resonant behavior of the structure. We also varied the temperature from 300 to 500 Kelvin and assumed that there are not thermal gradients in the film stack. The effect of temperature on the optical properties of SiO_2 is neglected since it is known to be very small [71]. From Equation (2.12), it is interpreted that mobility can be changed by varying the

temperature. Then, dielectric constant of Si is expected to change due to mobility change. As the dielectric constant varies, n and k parameters are changed since they are a function of dielectric constant. Therefore, resonance frequency of absorption is expected to shift as temperature changes [72]. In order to have greater shift in the resonance frequency, a larger change in the dielectric constant is desired. In order to achieve considerable spectrum shift due to temperature, appropriate structural parameters are sought after. The cavity and top layer thicknesses were swept between 200 to 5000 nm. Figure 6.1 (a) and (b) show the change of resonance wavelength as the thickness of Si film at the top and thickness of SiO_2 cavity are swept. It is observed that as the thickness of Si film and SiO_2 increase, the resonance frequency shifts to longer wavelengths. This is the expected result considering the spectral range equation in [37].

The carrier concentration of Si layers are deliberately chosen to be high (dopant concentration in silicon film and silicon substrate are assumed 10^{19} cm^{-3} and 10^{20} cm^{-3} respectively) since the refractive index of such highly conductive Silicon films can be changed significantly in the wavelength spectrum of interest which is depicted in Figure 6.2.

5.4 Results and Discussion

As the temperature changed from 300 to 500 K, resonance frequency of absorption shifted as shown in Fig. 17(a), and (b). A spectral shift over $1 \mu\text{m}$ in the wavelength spectrum of 8 to $10 \mu\text{m}$ is estimated.

In Fig. 5(b), nearly 500 nm shift of the resonance wavelength in the wavelength spectrum of 18 to $20 \mu\text{m}$ is shown. There is no significant shift calculated for the wavelength spectrum of 2 to $8 \mu\text{m}$ as we anticipated.

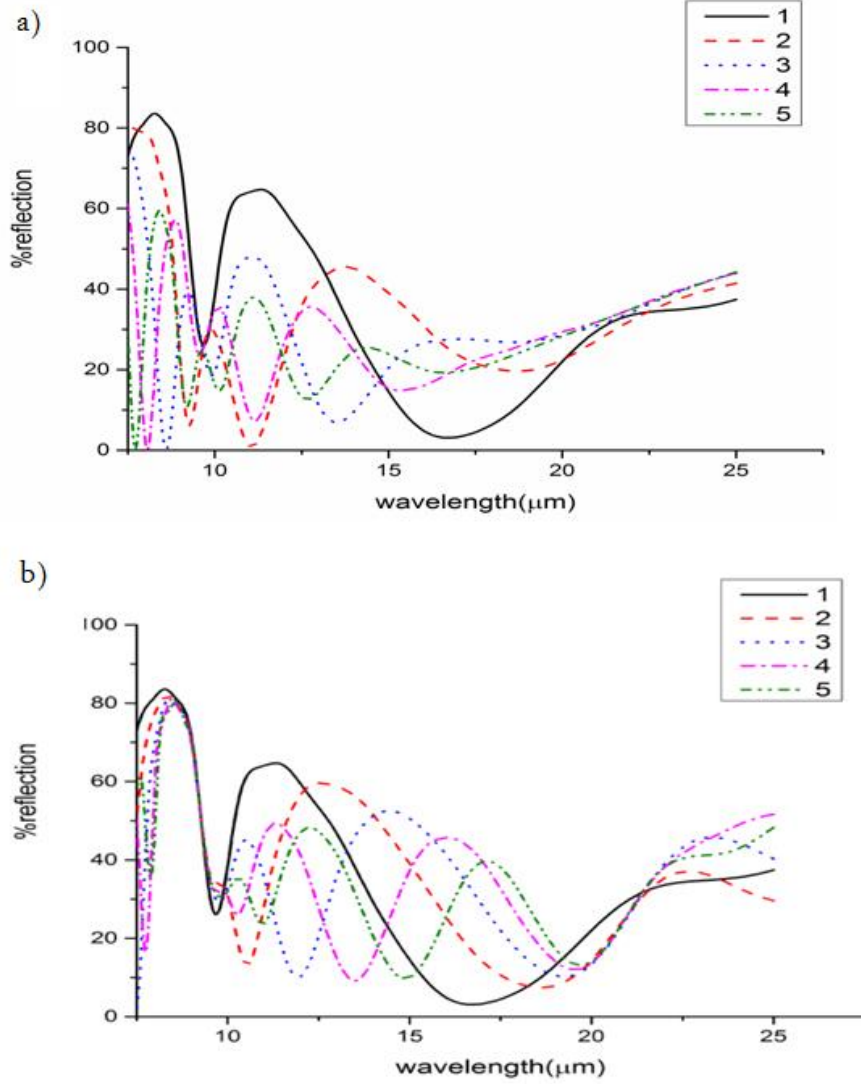


Figure 5.1: Percentage reflection vs. wavelength change (a) as the thickness of Silicon layer at the top changes from 1 to 5 μm when thickness of SiO_2 layer is 1 μm , (b) as the thickness of SiO_2 cavity layer changes from 1 to 5 μm when thickness of Silicon film at the top is 1 μm . Temperature is 300 K, doping concentration of the Silicon film and Silicon substrate are 10^{19} cm^{-3} and 10^{20} cm^{-3} respectively.

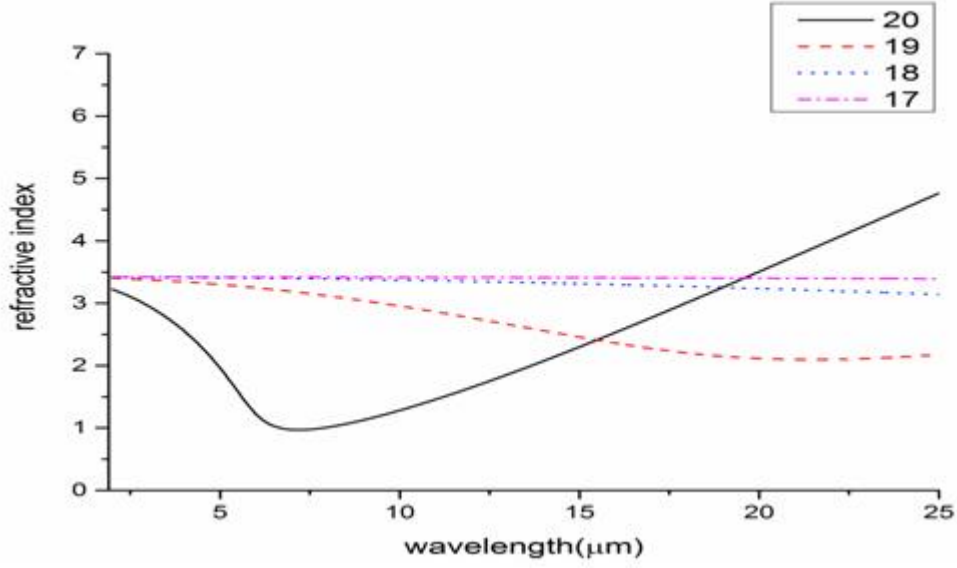


Figure 5.2: Refractive index vs. wavelength change as the doping concentration of Si varies from 10^{20} cm^{-3} to 10^{17} cm^{-3} .

5.5 Conclusion

In this work, we designed a Fabry-Perot resonator utilizing a cavity layer of SiO_2 sandwiched between two highly conducting Si layers whose resonance frequency of absorption can be shifted in the infrared frequency regime by changing temperature. A tunable range of the resonant frequency was modeled by highly doped Si layers and by tuning the dimensions of the nanostructures. Over $1 \mu\text{m}$ shift in resonance wavelength is computationally predicted in the wavelength regime of $8 - 10 \mu\text{m}$ which is in the uncooled microbolometer operation range for thermal imaging. Within the knowledge of being commercially available, easy to fabricate and also with its excellent temperature response, this design can be valuable in many applications such as meta-materials, solar cells, detectors and sensing devices.

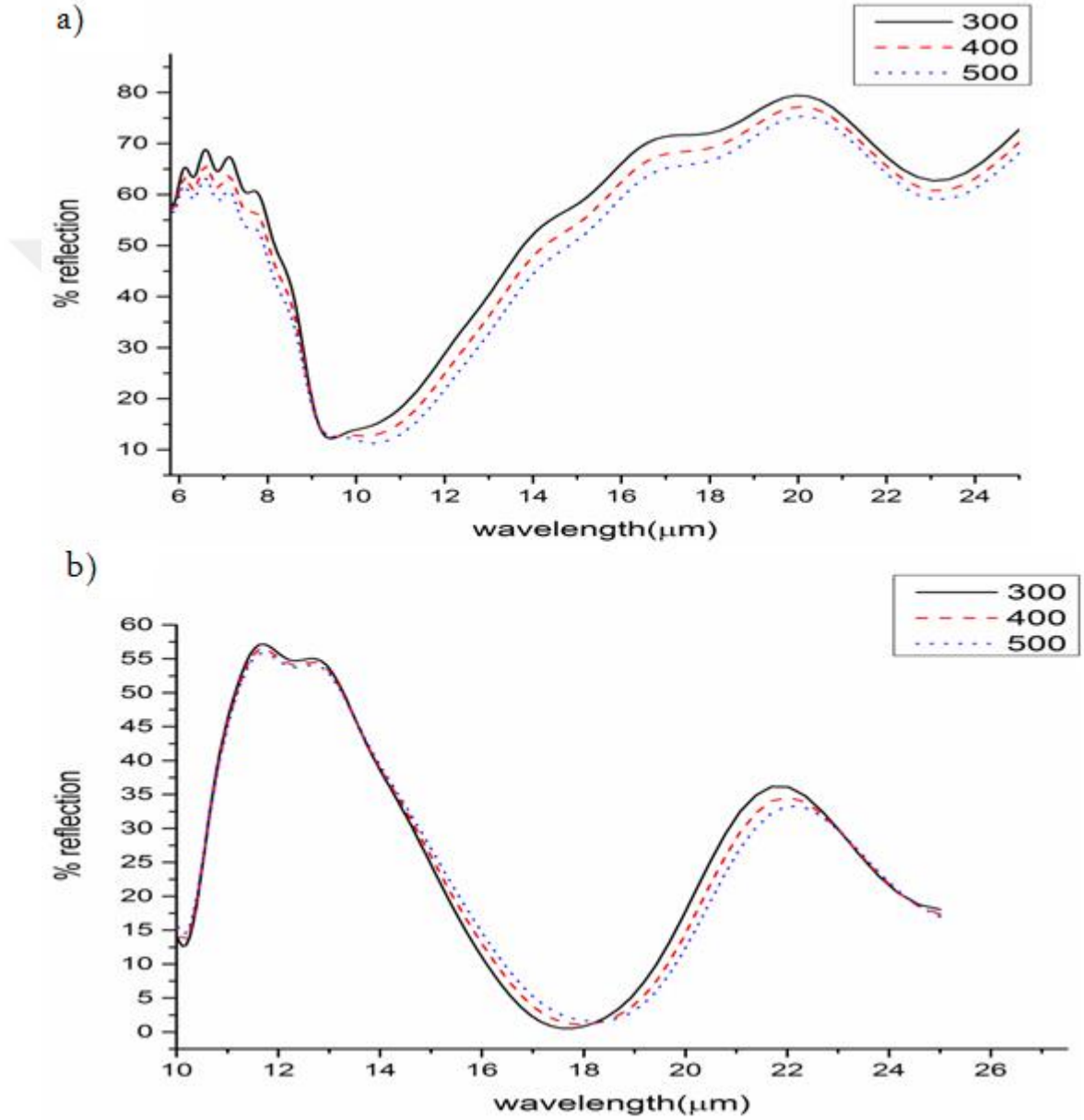


Figure 5.3: Percentage reflection vs. wavelength graphs for temperatures of 300 K, 400 K and 500 K. For (a) $d_1 = 200$ nm, $d_2 = 600$ nm doping concentration of silicon film and substrate 10^{18} cm^{-3} and 10^{20} cm^{-3} respectively (b) $d_1 = 600$ nm, $d_2 = 2000$ nm doping concentration of silicon film and substrate 10^{19} cm^{-3} and 10^{20} cm^{-3} respectively.

Chapter 6

Conclusion and Future Directions

In conclusion, Si based nanophotonic structures are modeled theoretically and are simulated using FDTD method. In order to tune the resonance of reflection properties of Si, relationship between mobility and dielectric values of Si is investigated and is modeled in infrared regime to tune the optical parameters (n , k) of Si. It is realized that plasmonic and photonic properties of Si can be used to design and implement perfect absorbers that work efficiently in infrared wavelength range. Photonic practical multi-featured perfect or near perfect absorbers are modeled, simulated and experimentally demonstrated using very simple structures including only Si. Plasmonic modeling of optical response of Si is also investigated and plasmonic perfect absorbers were designed using grating structures at the surface of the absorber. The experimental demonstration of the plasmonic perfect absorbers is completed with fabrication of plasmonic absorber that consists of two-dimensional grating structures. Then, ultra-wide-band photonic and plasmonic perfect absorbers are designed and are demonstrated experimentally. The structure of the devices includes a Fabry-Pérot structure that consists of two-dimensional gratings at the surface. We also investigated the effect of temperature on photonic perfect absorbers. Temperature is changed under optical exposure and it is observed that resonance frequency of absorption tunes. Computational analysis of such structures show that temperature tuning could be an efficient approach. However, further studies are required to experimentally confirm these

results and support our findings.



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