DIRECT ELECTRON-BEAM PATTERNING OF TEFLON-AF AND ITS APPLICATION TO OPTICAL WAVEGUIDING

Vijayasree Karre

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Thin films of Teflon AF have been directly patterned by electron-beam lithography without the need for post exposure chemical development. The relationship between pattern depth and exposure dose was found to be linear over a wide range of doses. Pattern depth was also observed to be dependent on initial film thickness. Teflon AF can be directly patterned at doses similar to typical e-beam resists. High resolution features as small as ~200 nm have been resolved. FTIR measurements revealed that CF$_3$ and fluorinated dioxole groups play a significant role in the patterning mechanism. Teflon AF films also exhibited an increase in refractive index upon exposure to the electron-beam. This property has been exploited in waveguiding applications. Waveguides in Teflon AF were patterned using direct electron beam lithography technique. Waveguides were clearly visible to the naked eye. Characterization in the visible region showed evidences of light guiding through the waveguides. However light could not cross the entire chip. Characterization in the infrared region revealed the slab mode even though individual waveguides were not detected.

Key Words: Direct Patterning, Electron Beam Lithography, Fluoropolymers, Teflon- AF, Optical Waveguides.

Vijayasree Karre
Author’s Signature

December 16, 2009
Date
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DIRECT ELECTRON-BEAM PATTERNING OF TEFLON-AF AND ITS APPLICATION TO OPTICAL WAVEGUIDING

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering in the College of Engineering at the University of Kentucky

By

Vijayasree Karre

Lexington, Kentucky
Director: Dr. J. Todd Hastings, Associate Professor of College of Engineering, Electrical and Computer Engineering
Lexington, Kentucky
2009

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DEDICATION

Dedicated to my loving parents Kumar and Bharathi Karre, my brothers Prasanjit Santosh Karre and Anand Karre and my dearest sister-in-law Archana Karre.
ACKNOWLEDGEMENTS

This work would not have been possible without the constant support and guidance of my advisor Dr. J. Todd Hastings. His approach towards research, positive attitude in handling technical difficulties, enthusiastic guidance in every situation have set an example, which I hope to reach some day.

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1 INTRODUCTION

Teflon AF is a member of a new family of amorphous fluoropolymers which is of interest to the micro-electronic fabrication and optics industry because of its promising properties. It has very low surface energy as well as high optical transmission and high thermal resistance. It has been used as release layer for both contact and imprint lithography. A method to directly pattern Teflon AF would be useful for the formation of hydrophobic fluidic devices, master molds for soft lithographic stamps and templates for imprint lithography. Teflon AF is also the dielectric with lowest known refractive index because of which it is used in patterning of low refractive index thin-film optical elements. This project discusses in detail the direct patterning of Teflon AF using electron beam lithography and its application to optical waveguiding.

1.1 Fluoropolymers

Fluoropolymers have shown great potential for a variety of applications from household appliances to electronics industry. This potential is attributed to the properties of these compounds. Fluoropolymers are the polymers consisting of carbon (C) and fluorine (F). The atomic structure of fluorine and carbon and the covalent bonding between them in specific chemical structures is responsible for the promising properties. Polytetrafluoroethylene (PTFE) was the first fluoropolymer discovered in 1938 by Dr. Roy Plunkett when he was working at DuPont. It is highly heat resistant, chemically inert, has low coefficient of friction and useful mechanical properties but was non-melt processible. The search for melt processible materials lead to the discovery of Fluorinated Ethylene Propylene (FEP), but it had reduced thermal stability and lower maximum use
temperature compared to PTFE [1]. In 1989 a new family of fluoropolymers called Teflon AF was introduced. Teflon AF is an amorphous fluoropolymer which is soluble in selected halogenated solvents. Teflon AF is the result of copolymerization of tetrafluoroethylene (TFE) and a new molecule called dioxole monomer. Figure 1.1 shows the molecular structure of Teflon AF. Dioxole monomer consists of a five-member ring structure of oxygen, carbon and fluorine. The family of Teflon AF constitutes Teflon AF 1600 and Teflon AF 2400. These polymers differ in the amount of dioxole monomer. As the amount of the dioxole monomer increases the glass transition temperature increases. Glass transition temperature of Teflon AF 1600 is 160°C and that of Teflon AF 2400 is 240°C.

![Molecular structure of Teflon AF](image)

**Figure 1.1 Molecular structure of Teflon AF.**

Teflon AF is of great interest in micro-electronic fabrication and optics industry because of its low surface energy, high chemical resistance, high optical transmission and low dielectric constant. It can be solution processed using fluorocarbon solvents and thin films can be formed by spin or dip coating. It is a perfect match for the release layers in the fabrication of multilayered polymeric microstructures and for mask release layers used in contact [2] and imprint lithography [3] owing to its low surface energy [4]. It is
the dielectric with the lowest known refractive index. It has also been used in optical sensors as a material with a refractive index close to that of water [5,6] and as a cladding layer for liquid core waveguides [7,8].

1.2 Direct Patterning

Direct-write techniques are a result of the quest for improvements in the existing fabrication methods. This single-step fabrication procedure offers the advantage of maskless pattern transfer. Features are defined directly on the substrate eliminating the intermediate resist patterning and post exposure chemical development steps. Direct patterning of fluoropolymers would enable rapid prototyping of hydrophobic fluidic devices, the direct formation of master molds for hydrophobic fluidic devices, the direct formation of master molds for soft lithographic stamps, and patterning of low refractive index thin-film optical elements.

Particle beams such as focused ion beams and electron beams are often used for direct patterning. Focused ion beam techniques often cause problems because of the high energy ion bombardment in spite of the high resolution they offer. S.J. Randolph et al reported focused electron beam induced deposition and etching techniques. EBIE (electron beam induced etching) and EBID (electron beam induced deposition) are typically vapor induced processes in which energetic electrons initiate chemical reaction of a precursor (typically a vapor) species in or near the substrate surface. In EBIE the products of the chemical reaction are volatile species which involve substrate material thus etching a part of the substrate. In EBID however the products of chemical reaction
result in volatile species and at the same time leaving behind the material to be deposited [9].

Nitrocellulose resists also exhibit self developing properties when irradiated with electron beam, heat and He$^+$ ions. According to Uchida et al. the self development properties of nitrocellulose material is due to chemical decomposition due to electron collisions and by physical sputtering due to nuclear collisions of incident ions. They also showed that the peaks in the infrared transmission spectrum decrease with increasing doses of irradiation [10]. Upon irradiation with heat the decomposition of the resist is also accompanied by the formation of a nonvolatile residue [11]. When exposed to heavy ions such as Ar$^+$ or Xe$^+$ or to laser radiation of sufficient energy flux, surface ablation is caused by microcombustion. On the other hand, it decomposes into volatile and non-volatile products when exposed to light ions, electrons, or low energy flux UV radiation. The non-volatile products are reported to be responsible for its processing stability [12].

Thin films of metal fluorides like AlF$_3$ and CrF$_2$ are also sensitive to electron beams showing higher resolution than standard electron-beam resists such as PMMA. When exposed at doses below a threshold value the substrate acts like a positive resist and above the threshold it acts like a negative resist requiring the use of a developer [13]. Direct photoetching of different polymeric materials by 157 nm laser radiation was studied by A. Costela et al. They presented the etch rate vs. incident fluence relationships for various polymers including poly-tetrafluoroethylene and concluded that the ablation mechanism of the materials was predominantly photochemical decomposition [14].
Several other groups have studied the effect of Teflon-AF itself to different radiations and observed more complicated mechanisms. Forsythe et al. investigated the radiation chemistry of Teflon AF to $\gamma$-irradiation under vacuum and suggested that the material predominantly undergoes main chain scission upon radiolysis [15]. Leitz et al. found that He$^+$ ion irradiation of Teflon AF reduced the film thickness and increased ultraviolet absorption [16]. M. S. Jahan et al. studied the effect of x-rays on the optical properties of Teflon-AF and observed that UV absorption increases as a function of X-ray dose and that it is caused by the X-ray induced peroxy radical [17]. Blakey et al. examined the properties of Teflon-AF copolymers under 157 nm illumination and concluded that the mechanism of degradation involves reaction at the dioxole unit [18]. This project deals with direct electron beam patterning of Teflon AF 1600 without chemical development.

1.3 Fluoropolymer Waveguides

Fluoropolymers could play an important role in expanding existing optical communication networks and in other optical systems. They are an interesting material choice for optical waveguides owing to low optical losses in the visible and near infrared spectral regions, including the telecommunication window (1300-1500 nm). Most importantly, fluoropolymers can have extremely low refractive indicies which makes them ideal for waveguide cladding layers. In addition, low refractive indices are essential when materials must be matched to the optical properties of liquids. Finally, polymer waveguides can be easily fabricated using Si and GaAs fabrication technology. High volume production ensures low fabrication cost.
N. Kehagias et al. fabricated two embedded polymer single-mode waveguides. Polystyrene/Teflon AF waveguides were fabricated by nano-imprint lithography of Teflon AF and spin coating Polystyrene to fill the grooves and spinning a second layer of Teflon AF. mr-L 6000/Teflon AF waveguides were fabricated by electron beam lithography of mr-L 6000 spin coated over a layer of Teflon AF. They reported waveguiding in the polymer mr-L 6000 for the first time. They also concluded that waveguiding in PS/Teflon AF needs further improvements particularly cutting and polishing the waveguides[19].

Others studied single-mode benzocyclobutene (BCB) optical waveguides fabricated by electron-beam lithography and observed refractive index increase in the irradiated region for TE and TM polarizations for an e-beam dose of 800 $\mu$C/cm$^2$ [20]. Maruo et al. studied the effects of synchrotron radiation on fluorinated polyimide films. Increase in index and decrease in the film thickness in the irradiated films were observed. X-ray photoelectron spectroscopy of the irradiated surface revealed that synchrotron radiation would result in a fluorine-poor surface [21].

Kobayashi et al. fabricated a grating structure in an embedded waveguide through an x-ray mask with a grating pattern and concluded that refractive index of fluorinated polyimide can be controlled by varying the dose of synchrotron radiation [22]. Fabrication of a waveguiding layer in Teflon AF by He$^+$ ion irradiation was reported by Leitz et al. An increase in refractive index of the irradiated Teflon AF film as obtained
from the leaky-mode spectroscopy has been recorded. It was proposed that the irradiated film is considered as a bilayered system with the unexposed area having low refractive index and the exposed area having high refractive index thus forming an optical waveguide. Increase in UV absorption and decrease in initial film thickness also have been reported [16].
2. DIRECT PATTERNING OF TEFOLON AF

The objective of this project is direct- electron beam patterning of Teflon AF 1600 without post exposure chemical development. We demonstrate that the residual thickness of Teflon AF and the electron dose are linearly related. As a result, electron-beam exposure of Teflon AF could provide a straightforward means for creating 3-D structures. Patterning was accomplished at doses similar to that of commonly used electron-beam lithography resists which is unusual for direct patterning processes. High-resolution patterning experiments show that surface relief structures with resolution of at least 200 nm can be formed. Fourier transform infrared (FTIR) measurements reveal that the mechanisms for electron-beam patterning of Teflon AF are likely similar to those identified for deep-UV photodegradation [23].

2.1 Casino Modeling of electron penetration through Teflon AF

Monte Carlo simulations were done prior to electron beam exposure to obtain the optimum beam energy. CASINO (Monte CARlo SImulation of electroN trajectory in sOlids) is a program designed to perform Monte Carlo simulations of electron trajectories in solids which is specifically designed for low beam interactions in bulk and thin foils and can be used to generate signals like backscattered electrons and X-rays as in a scanning electron microscope.

At first, the beam energy was chosen to ensure complete penetration of electrons through the Teflon AF layer to the substrate. Simulations were carried out for a 4000 nm thick
Teflon AF layer over silicon. First step was to create a layered model of Teflon AF over the silicon substrate. This was followed by specifying the thickness of Teflon AF and silicon layers and then the chemical composition of Teflon AF. The density of the material is automatically calculated. The next step was to select a physics model and setup the simulation parameters. We chose beam energy of 20KeV, beam radius of 10nm, and 10,000 electrons per simulation. The simulation results for 200 displayed trajectories are shown in Figures 2.1 and 2.2. Figure 2.1 shows the secondary electron and backscattered electron trajectories. It is seen that at an acceleration voltage of 20 KeV, the electrons penetrate completely through the Teflon layer. Figure 2.2 shows the energy distribution by position. It is observed from the energy distribution that ~90% of the energy is concentrated in the top 1µm. Hence a Teflon AF thickness of 1µm at 20 KeV would ensure complete penetration of electrons through it.
Figure 2.1 Casino modeling of electron penetration through Teflon AF at 20 KeV.
2.2 Experimental Methods

2.2.1 Overview

Device fabrication is the next step after modeling. Figure 2.3 shows a schematic of the fabrication process. A silicon wafer was used as a substrate. Teflon AF 1600 solution (5% by weight solution in FC-40 solvent) was prepared for spin coating. The first step was to clean the silicon wafer. Since Teflon AF poorly adheres to silicon, adhesion promoter was first spin coated on the cleaned silicon wafer. This was followed by the soft bake of adhesion promoter layer. Teflon AF 1600 was then spin coated over it
followed by soft baking to evaporate the solvent. We observed that it is easy to spin coat Teflon thicknesses less than a micron compared to the thicknesses more than a micron. A two-layer process was used to coat thicker Teflon AF films. Ellipsometer measurements were made to verify the thickness and refractive index of the coated thin film, prior to sample exposure.

The next step was electron beam lithography (EBL). Patterns to be written were first designed in the design editor of the electron beam lithography tool. Spin coated Teflon AF film was then exposed in the EBL system according to the desired exposure parameters. After the exposure, parameters of the sample were measured again. Post-exposure FTIR measurements for one of the samples were obtained in order to observe the mechanism of direct patterning of Teflon AF to e-beam irradiation. Following sections cover each of the process steps in detail.
2.2.2 Coating and Curing Teflon AF 1600

The first step is to clean the wafer. RCA1 and RCA2 are not required in this case because the silicon wafer only acts as flat substrate with negligible effect on the patterning mechanism. Hence a preliminary wafer clean with acetone and IPA would suffice. The wafer was first cleaned in acetone to remove any organic contamination. Then it was
rinsed in isopropyl alcohol (IPA) for 2 mins to remove acetone residue and it acts as a further cleaning process. It was then rinsed under running deionized water (DI) thoroughly to remove any IPA residue and blown dry with a nitrogen gun. The next step is spin coating.

Prior to spin coating, Teflon AF 1600 (DuPont, Inc.) solution was prepared by diluting Teflon AF (5% by weight solution in FC-40 (Acros Organics, Inc)) solvent with FC-40. Concentration of the material in the solvent plays a prominent role in spin coating because viscosity of the solution determines the thickness of the spin coated film. In this case uniform coatings were obtained when Teflon AF (5% by weight solution in FC-40) and FC-40 were mixed in the ratio 1: 2.6.

Adhesion promoter was used to improve the adhesion of Teflon AF to silicon substrate. 1H, 1H, 2H, 2H perfluoro-decyltriethoxy silane (Alfa-Aesar, Inc.) was the adhesion promoter used. It consisted of 2% fluorosilane, 93% ethanol, and 5% water by weight.

For spin coating, the wafer is first placed on the spin chuck and is held in place by vacuum. The substance to be coated is then dispensed on to the wafer and is spun at the desired speed for the required amount of time. Low spin speeds yield thicker coatings and vice-versa. In addition to the default speed settings there is an option to set the desired speed. Similarly the ramp up speeds can also be controlled. There are two separate speed controls and timers to achieve this.

Three different thicknesses of Teflon AF were used for electron beam patterning. For all the three samples, adhesion promoter was first spun at 3000 RPM and was baked at 110°C for 12 min on a hotplate. Because the adhesion promoter is only one molecule
thick it does not affect the device performance. Hence the speed settings are not crucial in this case. Next step is to spin-coat Teflon AF. Teflon was spin coated at a speed of 400 RPM to form a thicker film and at 5000 RPM to form a thinner film. Both samples were subsequently baked at 165°C for 20 min on a hotplate to ensure all the solvent evaporates and leaves the top surface dry. Usually a material is baked at temperatures above the glass transition temperature. Glass transition temperature for Teflon AF is 160°C so baking is done slightly above that temperature.

A third sample of Teflon AF with comparatively larger working area and thickness was required for FTIR analysis. It was difficult to spin uniform thicker films of Teflon AF with the conventional slow speed settings. This method posed a problem if large uniform working areas of thick Teflon AF films were desired. To solve this problem a two layer spin procedure was used. Instead of spinning a single thick Teflon layer at slow spin speed, two subsequent layers were spun at a higher speed following the spin-bake-spin-bake process. When compared to the slow spin speed coating, the two layer procedure produced a film with greater uniformity (rms roughness of about 3nm) over the relatively large area required for FTIR measurements. Teflon was spin coated twice at 4000 RPM and was baked at 165°C for 15 min after each coating.

2.2.3 Pre Exposure Measurement of Properties

Properties of the spin coated Teflon AF films were noted prior to the electron beam exposure. Thickness of the film was measured using an M-2000 spectroscopic ellipsometer (J.A. Woollam Co., Inc.). The thicker sample measured 1.2 µm and the thinner sample measured 280 nm. The sample prepared for FTIR analysis measured 850
nm. FTIR spectrum of the unexposed 850 nm sample was measured using a Varian 7000e FT-IR spectrometer. An attenuated total internal reflection (ATR) configuration was been used.

### 2.2.4 Electron Beam Lithography

As discussed earlier, patterns were written using a Raith e-LiNE electron beam lithography tool. Patterns to be written are first designed in the GDSII design editor. 200 µm × 200 µm squares spaced by 200 µm on the 1.2 µm thick Teflon AF sample were written using a beam energy of 20 KeV and a beam current of 300 pA. Doses ranged from 100-1000 µC/cm². As observed from the CASINO simulations the beam energy was chosen to ensure penetration of electrons through the entire Teflon layer. 100 µm × 100 µm squares spaced by 100 µm on the 280 nm sample were written using beam energy of 10keV and a beam current of 216 pA with dose ranging from 100-1000 µC/cm². On the same sample, sets of single pixel lines with 0.5 µm spacing with dose ranging from 300-3000 pC/cm were written at 10 keV and 204 pA. For the thinner film the lower beam energy still allows full penetration of the electrons to the substrate. The exposure parameters for the three exposures are as tabulated in Table 1.1. An area of 25 mm² on the 850nm sample was exposed at 20 keV and 5.08 nA at a dose of 1000 µC/cm² for FTIR measurements. Four large squares of 3 mm spaced by 1 mm were also exposed on the 280 nm sample at a beam energy of 20 KeV and a beam current of 1.7 nA. The doses for the four squares were 10, 40, 70 and 100 µC/cm².
Table 2.1: Electron-beam exposure parameters

<table>
<thead>
<tr>
<th>EHT</th>
<th>Working Distance</th>
<th>Dose Factor</th>
<th>Area Step Size</th>
<th>Area Dose</th>
<th>Area Dwell Time</th>
<th>Beam Current</th>
<th>Line Step Size</th>
<th>Line Dose</th>
<th>Line Dwell Time</th>
</tr>
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<tr>
<td>20KeV</td>
<td>10 mm</td>
<td>1-10</td>
<td>0.0032 µm</td>
<td>100 µC/cm²</td>
<td>0.0082 ms</td>
<td>300pA</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>10KeV</td>
<td>10 mm</td>
<td>1-10</td>
<td>0.0192 µm</td>
<td>100 µC/cm²</td>
<td>0.0017 ms</td>
<td>216pA</td>
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<tr>
<td>10KeV</td>
<td>10 mm</td>
<td>1-10</td>
<td>0.0192 µm</td>
<td>100 µC/cm²</td>
<td>0.0018 ms</td>
<td>204pA</td>
<td>0.0096 µm</td>
<td>0.0014 ms</td>
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</tbody>
</table>

2.3 Results and discussion

Properties of Teflon AF films were analyzed after the electron-beam exposure. Pattern depth vs. dose was measured using a Dektak 6M surface profilometer (Veeco Inc.). The changes in thickness and refractive index of the large exposed areas were also measured using an M-2000 spectroscopic ellipsometer (J.A. Woollam Co., Inc.). SEM micrographs of the high resolution features were obtained on the Raith e-LiNE tool. FTIR characterization of the exposed area was also performed on the Varian 7000e FT-IR spectrometer.
2.3.1 Depth versus Dose Measurements

Topography of the irradiated Teflon AF thin films was analyzed on the Dektak 6 M surface profilometer (Veeco, Inc.) after the electron beam exposure. Variation of pattern depth with dose (position) for the uniformly spaced 200 μm squares on the 1.2-μm-thick Teflon AF film are as shown in Fig 2.4. It is observed that the pattern depth decreases with decreasing dose from left to right. Depth versus dose plots for the uniformly spaced 200 μm squares on the 1.2-μm-thick Teflon AF film and the 100 μm squares on the 280-nm-thick Teflon AF are shown in Fig 2.5 and Fig 2.4 respectively. Pattern depth for the thick sample exposed at 20 keV was given by $d = [0.49 (\text{nm} \cdot \text{cm}^2)/\mu\text{C}]D + 93 \text{ nm}$ and that for the thinner sample exposed at 10 keV was given by $d = [0.12 (\text{nm} \cdot \text{cm}^2)/\mu\text{C}]D + 42 \text{ nm}$, where $d$ denotes depth of the pattern and $D$ denoted dose. It is clear that the pattern depth and dose are linearly related for both thin and thick samples in a range from approximately 100 to 1000 μC/cm² as shown in the figures 2.5 and 2.6.
Figure 2.4: Variation of pattern depth with dose (position) for the uniformly spaced 200 μm squares on the 1.2-μm-thick Teflon AF film.
As opposed to the conventional resists used for lithography, the depth vs dose relationship for Teflon AF is linear. Owing to this, Teflon AF is a suitable material for grayscale lithography and formation of 3D topography. However from figures 2.5 and 2.6 it is noted that depth vs dose relation is non-linear for doses less than a 100 $\mu$C/cm$^2$. The non-linear intercepts may be because of the spin coating skin effect. The solvent content on the top surface of the spin coated film may be lower compared to the body of the film. The doses used in these direct patterning experiments are comparable to the commonly used low-speed, high resolution electron-beam resists such as hydrogen silsequioxane (HSQ) and polymethyl metacrylate (PMMA). The doses are orders of magnitude lower.
than those required to directly pattern metal chlorides and fluorides; however, the ultrahigh resolution (<10 nm) obtainable with these inorganic materials makes them suitable for different applications [19].

\[ d = 0.12 \text{ nm} \cdot \text{cm}^2/\mu \text{C} D + 42 \text{nm} \]

Figure 2.6: Depth versus dose plots for the uniformly spaced 100 μm squares on the 280-nm-thick Teflon AF.

One other interesting observation from the above plots is that the sample with a greater initial film thickness also exhibits a greater pattern depth for a given exposure dose. Even though a higher energy beam was used for the exposure, film with greater initial thickness showed a greater pattern depth for a given exposure dose. Typically, higher primary beam energies require higher doses to achieve the same effect compared to the
low beam energies because higher energy primary electrons interact more weakly with polymer films. However in this case, despite the high beam energy, the thicker film yielded a larger change in thickness. This implies that patterning involves a mechanism that depends on initial film thickness. In addition to ablation, mechanisms like densification may also be occurring.

2.3.2 Ellipsometer Measurements

To confirm the depth vs. dose relationship using ellipsometry, four larger 3 mm squares on the 280 nm sample were scanned using the ellipsometer (J.A. Woollam Co., Inc.). The doses of the four squares are 10, 40, 70, 100 $\mu$C/cm$^2$. A new scan recipe was set up in the VASE manager, to scan an area of 1 cm x 1 cm using a grid fill of 2600 points. 1 cm x 1cm was chosen to ensure all the four 3 mm squares were scanned. A model fit to the experimental results was created and the results were graphed. 3D surface plots of the fit parameters, thickness and index are as shown in fig 2.7 and 2.8.

Figure 2.7 shows thickness changes for the four squares. Top view of the 3D plot shows the thickness changes for the four squares. Doses for the top left and bottom left squares 10 $\mu$C/cm$^2$ and 40 $\mu$C/cm$^2$ respectively. Top right and the bottom right squares have doses 70 $\mu$C/cm$^2$ and 100 $\mu$C/cm$^2$ respectively. It is observed that there is a decrease in thickness in each of the exposed regions and the thickness change (pattern depth) is more for higher doses. The pattern depth for the four exposed squares were also measured using Dektak 6 M surface profilometer (Veeco, Inc). The largest difference between the ellipsometric and the profiler measurements was 10.5%. Table 1.2 shows the comparison of results.
Figure 2.7: 3D surface plot showing the thickness changes for the four larger 3mm squares on the 280nm sample. Thicknesses given on the scale bar are in angstroms.
Table 2.2: Comparison of profilometer and ellipsometer results for the pattern depth of four large 3 mm squares on the 280 nm sample.

<table>
<thead>
<tr>
<th>Dose ((\mu)C/cm(^2))</th>
<th>Profilometer results</th>
<th>Ellipsometer results</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>24</td>
<td>21</td>
</tr>
<tr>
<td>70</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td>40</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>10</td>
<td>Region not visible</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 2.8 shows the changes in refractive index in the four exposed regions. Considering the top view of the 3D surface plot in the x direction, the doses for the top left, bottom left, top right and the bottom right squares are 10 \(\mu\)C/cm\(^2\), 40 \(\mu\)C/cm\(^2\), 70 \(\mu\)C/cm\(^2\) and 100 \(\mu\)C/cm\(^2\) respectively. In all the four exposed regions an increase in the refractive index was observed and the increase is proportional to the exposure dose. Maximum increase in the refractive index obtained was 1.23 % for a dose of 100 \(\mu\)C/cm\(^2\).

Hence we propose that Teflon AF films irradiated with electron beam show a reduction in the thickness and an increase in refractive index. The section on FTIR results explains the degradation mechanism in detail.
Figure 2.8: 3D surface plot showing the refractive index changes for the four larger 3mm squares on the 280nm sample.

2.3.3 SEM micrographs

As discussed in the experimental methods, sets of single pixel lines with 0.5 µm spacing and dose ranging from 300-3000 pC/cm were written at 10 keV and 204 pA on the 280 nm Teflon AF sample. Figure 2.9 shows the SEM micrograph of the exposed high resolution lines. It shows the crossectional view of the patterned Teflon on the silicon substrate. For single pixel lines at doses greater than 1500 pC/cm, 200nm wide lines were resolved. It is observed that the exposed regions cleave cleanly compared to the unexposed regions which deforms. Figure 2.10 shows a low resolution pattern which also
shows the cleanly cleaved exposed area and the deformed unexposed area. This suggests that polymer chain scission reactions are occurring.

Figure 2.9: SEM micrograph showing the cross-sectional view of high resolution lines in Teflon AF over silicon.
2.3.4 Fourier Transform Infrared Spectroscopy

An 850 nm Teflon AF film was spin coated on silicon for FTIR analysis. Varian 7000e FT-IR spectrometer was used. FTIR spectrum of the unexposed Teflon AF was first measured following which an area of 25 mm$^2$ was exposed at 20 KeV at the dose of 1000 $\mu$C/cm$^2$. To investigate the mechanism of degradation the FTIR characterization of the exposed area was carried out. FTIR spectrum of both the exposed and the unexposed samples are as shown in figure 2.11. Referring to the spectrum of the unexposed sample, the peak at 983 cm$^{-1}$ was ascribed to the CF$_3$ group and those at 1098, 1136, 1202, and
1236 cm$^{-1}$ were attributed to the fluorinated dioxole component [24]. Comparing the spectrum of the exposed and the unexposed samples, it is observed that the peaks at 1098 and 1136 cm$^{-1}$ are no longer identifiable and the peaks between 1225 and 969 cm$^{-1}$ are clearly reduced. The reduction in the peak at 969 cm$^{-1}$ is likely due to the reduction in CF$_3$ groups and the reduction in the peaks at 1225, 1098 and 1136 cm$^{-1}$ is hypothesized to result from degradation at the dioxole unit [18] [24].

Several groups have addressed the degradation mechanism of Teflon AF exposed to different radiations. Ding et al reported the effect of thermal treatment on the spin coated Teflon AF 1600 films. They hypothesized that Teflon AF undergoes thermal decomposition and the products of the reaction may be hexafluoroacetone (HFA) and acid fluoride radical. Further the acid fluoride radical may form new CF$_2$ groups recombining with the fluorine-free radicals resulting from the CF$_3$ groups (Bond energy of C-F in CF$_3$ is lower than that in CF$_2$) [24]. This suggests reduction in CF$_3$ groups which is in agreement with the FTIR results. Forsythe et al proposed that CF$_2$ radical is a result of loss of fluorine radical from CF$_3$ which would lead to the decrease in CF$_3$ groups [15]. Blakey et al studied the effect of 157 nm radiation on Teflon AF and concluded that photo-chemical degradation involves reaction at the dioxole unit. Even though the FTIR measurements indicate that the electron-beam-induced patterning is related to degradation of the fluorinated dioxole group present in amorphous Teflon and reduction in the CF$_3$ groups, the degradation mechanism is a complex phenomenon. SEM images reveal that the exposed areas cleave cleanly compared to the unexposed areas. This suggests that chain scission is also occurring.
Figure 2.11: FTIR spectra of unexposed and exposed Teflon AF with a beam energy of 20 KeV at a dose of 1000 $\mu$C/cm$^2$. 
3. **TEFLON AF WAVEGUIDES**

This project deals with waveguiding in Teflon AF. Waveguides have been fabricated in Teflon AF using the direct electron beam patterning technique. Modeling and fabrication of direct electron-beam patterned Teflon AF waveguides, Teflon AF- FEP waveguides and Teflon AF-PMMA waveguides is discussed in detail in this chapter. All the waveguides have been fabricated using fixed beam moving stage mode (FBMS) of the electron beam lithography tool. The results of characterization of the waveguides in visible and infrared spectral regions have been presented. A procedure for polishing the chip (waveguide) edges in an effort to identify the waveguides has also been discussed.

![Figure 3.1: Schematic of a rectangular channel waveguide.](image-url)
Figure 3.1 shows a rectangular channel waveguide. A waveguide constitutes of a high refractive index core and a low refractive index cladding and light can be confined in the core through total internal reflection. As discussed in the direct patterning section of the previous chapter, electron beam irradiation of Teflon AF results in an increase in refractive index and a decrease in the initial thickness of the irradiated Teflon AF film. The increase in refractive index was the motivation to fabricate optical waveguides in Teflon AF. From the direct patterning experiments, it was observed that a dose of 100 μC/cm² caused a 1.23% increase in the refractive index in the irradiated thin film of Teflon AF. The irradiated film would act like a two layered structure with the irradiated layer (with high refractive index) forming the core and the un-irradiated layer underneath forming the cladding for the surface plasmon waveguide.

3.1 Overview
The single step process of fabricating the waveguides was first implemented by directly patterning straight waveguides with Bragg gratings in Teflon AF through electron beam lithography. Characterization of these waveguides exhibited a dip in the transmission spectrum at 1550 nm even though the characteristic distinct bright spots associated with a waveguide were absent on the output IR camera. Unfortunately this spectrum could not be recorded but it gave the impetus to improve the test setup and reduce the chip-edge deformities.

A new chip with straight Teflon AF waveguides was once again fabricated. This time waveguides without gratings were written end to end on the chip without the need for
manually cleaving the edges of the chip. The edge quality of the chip was better than the previous one, however characterization of the new set of waveguides did not yield expected results. Now that the edge quality was improved, it was assumed that an increase in index as achieved by e-beam irradiation was not sufficient to support waveguiding. Hence an effort was made to increase the refractive index contrast between the core and cladding layers by sputtering FEP on the directly written Teflon AF waveguides. There was no success even with the high index contrast of Teflon and FEP. Waveguides were observed edge on and the SEM images confirmed that they were clearly patterned edge to edge on the chip. At this stage the only factor which could prevent the characteristic bright spot on the IR camera image typically associated with a waveguide was thought to be the excessive stray light.

Hence the next trial was to fabricate curved waveguides. Curved waveguides with constant length and bend radii but varying thickness and dose were fabricated in Teflon AF. Precautions were taken to keep the edge quality clean and not to touch the waveguides once they were fabricated. Characterization of the curved waveguides did not yield clearly guided light. A great deal of stray light was still observed in the slab region which might be preventing the visibility of a typical waveguide. However, the waveguides were clearly visible to the naked eye and encouraged us to move to the next step.

This time the chip with the curved Teflon AF waveguides was coated with PMMA to achieve maximum index contrast and the characterization was repeated. Such high index
contrast also could not achieve optical waveguiding through Teflon AF. As reported by several other groups who have fabricated waveguides using Teflon AF and other polymers, poor quality of the chip edges could prevent coupling of light from the optical fiber to the waveguide. So polishing was the next step. The chip with straight waveguides with gratings in Teflon AF was coated with another layer of Teflon AF to protect the waveguides in the polishing process. Both the edges of the chip were polished and the characterization was repeated. Even at this stage, no guided modes were observed.

3.2 Modeling
Before proceeding to fabrication of waveguides one must have an initial approximation of optimum dimensions of the devices. This section deals with theoretical modeling of waveguides to find the optimum electron-beam energy, thickness and width of core and thickness of the cladding. COMSOL simulations for direct patterned Teflon AF waveguides have been discussed. This design could not be fabricated practically owing to the spin-coating problems of Teflon AF. Hence an alternative design was proposed and Casino simulations were carried out to find the optimum electron beam energy. COMSOL simulations for two other alternative designs were performed to find the thickness and width of core such that there is a single guided mode.
3.2.1 COMSOL Modeling for a Direct E-beam patterned Teflon AF waveguide

COMSOL is a multiphysics modeling tool used for various physics and engineering applications. It was formerly FEMLAB. It is based on the use of partial differential equations (PDE’s) which are solved using finite element method. For all the three types of surface plasmon waveguides discussed in this chapter the same modeling procedure is followed. Waveguides are modeled in 2D in the electromagnetics module of COMSOL using the perpendicular hybrid mode. The process starts with drawing a waveguide model followed by specifying the parameters for the domains and the boundaries. Next a finite element mesh is generated and the solver is invoked to solve the partial differential equations. All the waveguides discussed in this chapter are straight waveguides.

This section explains the modeling of a direct e-beam patterned Teflon AF waveguide. A waveguide model with Teflon AF as cladding and high index Teflon AF as core, as shown in figure 3.2 was drawn using COMSOL. In all the COMSOL simulations discussed in this chapter, there is symmetry about x and y axis of the waveguides. The x-axis represents width and y-axis represents thickness of the waveguide in meters respectively. After defining the geometry, the next task is to set up the domain and the boundary parameters. Teflon AF, high index Teflon AF and air are the domains here. The thickness and refractive indices of the three domains are as follows:

Core (High Index Teflon AF) : 4 µm wide and 2 µm thick.

Cladding (Teflon AF) : 10µm wide and 7 µm thick.
Air: 10µm wide and 3 µm thick.

Figure 3.2: COMSOL drawing of a direct e-beam patterned Teflon AF waveguide.

Waveguides were modeled for optical communication purposes so all the simulations were carried out at 1550 nm. The refractive indices for all the three domains are as follows:

Refractive Index of Teflon AF at 1550 nm: 1.33.

Refractive Index of high index Teflon AF at 1550 nm was approximated as 1.34.

RI of Air: 1.

At this stage the boundary conditions for the waveguide structure had to be specified. All the boundary conditions were set to perfect electric conductors. The goal of COMSOL simulation is to solve for the modes of the 2D waveguide. There are several methods to
solve for the modes of a waveguide. COMSOL makes use of the finite element method. A requirement for the finite element method is to impose a grid of points on the waveguide and calculate the fields at each grid point. COMSOL provides the facility to automatically generate this finite element mesh. The mesh generated is as shown in figure 3.3. It can be refined by the user. Processing time and memory are the two main constraints which affect the number of elements in the mesh.

![Mesh generated as part of finite element method.](image)

Once the mesh is created, the solver solves for electric field. In all the simulations discussed in this chapter Eigen value type of solver was used. Figure 3.4 shows the field profile for the 2D direct patterned Teflon AF waveguide. The solver also returns the effective index of the waveguide mode which is shown at the top of the field profile. For the above mentioned dimensions of the waveguide, a single guided mode was obtained and the field penetrated well into the cladding. But the thickness of Teflon AF obtained
from these simulations was practically difficult to achieve. Hence an alternative Teflon AF waveguide design was proposed. This alternative design is discussed in the next section.

Figure 3.4: Mode profile of a direct e-beam patterned Teflon AF waveguide.

3.2.2 CASINO Modeling

Figure 3.5: Model of a direct patterned Teflon AF waveguide on silicon.
A waveguide design with Teflon AF cladding and high index Teflon AF core as shown in figure 3.5 was modeled using Casino. Given the maximum thickness of uniform Teflon AF films that could be spin coated (it was difficult to obtain uniform Teflon AF films with thickness greater than 1 µm) the core and the cladding were modeled to be 500 nm and 700 nm thick.

Monte Carlo simulations were performed to determine the optimum electron beam energy which would ensure that the beam penetrates through the 500 nm core. Firstly a three layer model of high indexed Teflon (which would result after the electron-beam exposure) over Teflon AF on a silicon substrate was created. Thickness of high indexed Teflon AF and Teflon AF were modeled as 500 nm and 700 nm respectively. Chemical composition of both the materials was specified and density of the materials was automatically calculated. The next step was to select a physics model for simulation and setup the simulation parameters. Simulation was carried out for multiple beam energies ranging from 1-10 KeV with a step of 1 KeV. Number of electrons for simulation was 10000 and the beam radius was 1 nm.

Simulation results for the beam energies of 6 KeV and 10 KeV for 200 displayed trajectories are shown in figures 3.6-3.9. As shown in figure 3.6 for an e-beam energy of 6 KeV the beam penetrates through the 500 nm Teflon AF core (modeled as Teflon AF1), but does not reach the bottom Teflon AF layer that will form the lower cladding. However, for beam energy of 10 KeV as shown in figure 3.7 the beam does penetrate into the bottom Teflon AF layer also. Since the criteria was to choose the beam energy which
would ensure complete penetration of electrons through the core, energies between 6 KeV and 10 KeV would be good. Hence 7 KeV was choosen for the electron beam exposure. Figure 3.8 and 3.9 show the energy distribution by position for 6 KeV and 10 KeV respectively.

Figure 3.6: Casino modeling of electron trajectory in a direct e-beam patterned waveguide at 6 KeV.
Figure 3.7: Casino modeling of electron trajectory in direct e-beam patterned waveguide at 10 KeV.
Figure 3.8: Casino modeling of energy distribution in a direct e-beam patterned waveguide at 6 KeV.
3.2.3 Modeling of Teflon AF-FEP Waveguide

Modeling of the waveguide with Teflon AF cladding and FEP core is discussed in this section. The simulation procedure is similar to that explained in the previous section. A waveguide model as shown in figure 3.10 was drawn using COMSOL where the x and y axis represent width and thickness of the waveguide in meters respectively. The domain parameters are as follows:

Core (FEP): 3 µm wide and 1.2 µm thick.
Cladding (Teflon AF): 10µm wide and 3.5 µm thick.

Air: 10µm wide and 1.6 µm thick.

![COMSOL drawing of a direct e-beam patterned Teflon-FEP waveguide.](image)

**Figure 3.10:** COMSOL drawing of a direct e-beam patterned Teflon-FEP waveguide.

The waveguide was modeled for communication purposes so all the simulations were carried out at 1550 nm. Refractive indices of the domains are as follows:

Refractive Index of Teflon AF : 1.31.

Refractive Index of FEP: 1.38.

RI of Air: 1.
All the boundary conditions for the waveguide structure were set to perfect electric conductors. The finite element mesh was created and the solver was invoked.

For the above dimensions of the waveguide a single guided mode as shown in figure 3.11 was obtained. Since the mode extends into the cladding, a cladding thickness of 1 µm was chosen for fabrication. Thickness of FEP chosen was 1 µm.

![Figure 3.11: Mode profile of a direct e-beam patterned Teflon AF- FEP waveguide.](image)

### 3.2.4 Teflon AF-PMMA

This section explains the modeling of a direct e-beam patterned Teflon AF- PMMA waveguide. The waveguide model with Teflon AF cladding and PMMA as core is as shown in figure 3.12. The simulation was done for the following specifications:
Core (PMMA): 3 µm wide and 1.4 µm thick, Refractive Index (RI): 1.47.

Cladding (Teflon AF): 10µm wide and 3.5 µm thick, RI: 1.31.

Width of the upper cladding (Teflon AF): 10µm wide and 1.6 µm thick, RI: 1.31.

Figure 3.12: COMSOL drawing of a direct e-beam patterned Teflon AF- PMMA waveguide.

The result of the simulation after the finite element mesh is created and the solver is invoked is as shown in figure 3.13. A single guided mode is obtained for a PMMA thickness of 1.4 µm.
Figure 3.13: Mode profile of a direct e-beam patterned Teflon AF - PMMA waveguide.

Hence a thickness of 1 µm PMMA was chosen for fabrication.

3.3 Waveguide Fabrication

Device fabrication is the next step after modeling the waveguides. This section explains fabrication of directly patterned Teflon AF waveguides, Teflon AF-FEP and Teflon AF-PMMA waveguides in detail.

3.3.1 Overview

Fabrication of all the waveguides described in this chapter begins with spin coating of Teflon AF 1600 (5% by weight solution in FC-40 solvent). Waveguides are then directly patterned on Teflon AF films by electron beam lithography. For Teflon AF-FEP waveguides, FEP was sputtered on top of the patterned Teflon AF. Waveguides with PMMA as core were formed by spin coating PMMA over the patterned Teflon. However
oxygen plasma etching was necessary before spin coating PMMA to improve the adhesion of PMMA to Teflon.

3.3.2 Sample Preparation
Sample preparation starts with cleaning of the silicon wafer. In this case it is not required to perform RCA1 and RCA2 cleaning procedures because silicon wafer only acts as flat substrate with negligible effect on waveguiding. So rinsing the wafer with acetone and IPA would be sufficient. The wafer is first rinsed in acetone for 60 secs to remove the organic contamination. Then it is rinsed in isopropyl alchol (IPA) for another 60 secs to remove the acetone residue and it also acts as a further cleaning process. It is then rinsed under running deionized water (DI) thoroughly to remove any IPA residue and blown dry with a nitrogen gun.

3.3.3 Preperation of Adhesion Promoter
To improve the adhesion of Teflon AF 1600 to silicon an adhesion promoter is used. 1H, 1H, 2H, 2H perfluoro-decyltriethoxy silane (Alfa-Aesar, Inc.) is the adhesion promoter used. It consists of 2% fluorosilane, 93% ethanol, and 5% water by weight.
3.3.4 Preparation of Teflon AF 1600

Teflon AF 1600 (DuPont, Inc.) solution is prepared by diluting Teflon AF solvent with FC-40 (Acros Organics, Inc). Concentration of Teflon AF in the solvent plays a significant role in spin coating. In other words, viscosity of the solution determines the thickness of the spin coated film. We observed that uniform coatings were obtained when Teflon AF and FC-40 were mixed in the ratio 1: 2.6. Hence Teflon AF: FC-40 in the ratio of 1: 2.6 was used for all the devices.

3.3.5 Spin Coating

Wafer is placed on the spin chuck and is held in place by vacuum. Substance to be spin coated is then dispensed on to the wafer and is spun at the desired speed for the required amount of time. Low spin speeds yield thicker films and vice-versa. There are six default speed settings from 1000 RPM to 6000 RPM. Maximum speed one can go up to is 6000 RPM. In addition to the default settings there is an option to set the desired speed. Ramp up speed, actual spin speed and spin time can be programmed according to the user’s specifications. There are two separate speed control channels to achieve this.

3.3.6 FBMS Mode

Raith e-LiNE electron-beam lithography tool has been used for the fabrication of waveguides. This tool offers two stage movement strategies. One is stationary stage mode and the other is the moving stage mode. The mode used most often is the stationary stage mode wherein large patterns are divided into small sections called write fields. Each field is written one after another by scanning the beam over it which are stitched together to form the pattern. For applications where stitching errors play a vital role in device performance, fixed beam moving stage (FBMS) mode is employed to give a stitch free
exposure and also to reduce long exposure times resulting because of large number of stitching borders. This method avoids stitch field boundaries and is effective for extended paths. Since optical waveguides are long features which extend along the length of the chip, FBMS mode is recommended for better performance. In this mode of exposure, the beam is stationary and the stage travels along the paths of any length and shape at constant speed. However stage inaccuracies are compensated by beam deflection using special motor control unit.

Exposure in FBMS mode differs slightly from the standard exposure procedures, first difference being the preparation of design. GDSII editor has an option to create special FBMS elements or one can directly convert the standard GDSII design to FBMS design using the conversion option in the editor. Each FBMS structure (either a line or an area) is defined by a starting and an ending node and their coordinates. Other parameters like the dose factor, width and layers are defined similar to standard GDSII elements. While designing curved elements an additional attribute called curvature has to be specified. Curvature in the Raith editor is defined as the height of the segment of the circle ‘h’ as shown in figure 3.14.
Depending on the coordinates of \((X_1, Y_1)\) \((X_2,Y_2)\) and \((X_m,Y_m)\) as shown in figure 3.14 ‘a’ is calculated. For a required ‘R’, h is calculated using the above formula. The above procedure was followed for calculating the radius of curvature for the curved waveguides. The next difference is with alignment. Whenever there is a stage inaccuracy, beam deflection comes into play. Hence calibration of the deflection signal is necessary. Special alignment procedures are provided by the scan manager for the FBMS exposure. The FBMS alignment is same as standard write field alignment except that the deflection
is addressed by motor control instead of the pattern generator. Finally in the exposure window the FBMS elements should be selected and the corresponding parameters should be fed. Important exposure parameters are the stage speed and calculation width. Stage speed is automatically calculated and the calculation width should be more than the maximum feature size. One other important exposure detail is step size. Values of step size are comparable to the standard step size.

3.3.7 Teflon AF waveguides with Bragg gratings

3.3.7.1 Bragg gratings in waveguides

As explained in the introduction, light can be made to propagate through a material of high refractive index surrounded by a material of low refractive index through total internal reflection. Usually the refractive index of the core is uniform throughout its length. Nevertheless a periodic variation in refractive index or dimensions can be introduced. These variations in the core are termed as gratings. Bragg grating is a type of grating which reflects light over a narrow wavelength range and transmits the other wavelengths. The grating period of variation and the effective index of the waveguide determine the reflected wavelength.

\[ \lambda_0 = 2\Lambda n_{eff} \]

Where \( \lambda_0 \) is the reflected wavelength, \( \Lambda \) is the grating period and \( n_{eff} \) is the effective index of the waveguide.

Light is reflected at each change in refractive index or the dimension of the core. Depending on whether the wavelength satisfies the above equation or not, two cases will arise. If the wavelength of light satisfies the equation, the reflections combine in phase and there is net reflection in the reverse direction. The forward wave decays
exponentially in this case. A significant peak in the reflection spectrum or a dip in the transmission spectrum is observed. If the wavelength of light does not satisfy the above equation the reflections do not combine in phase and most of the light is transmitted.

3.3.7.2 Fabrication of waveguides with Bragg gratings

Teflon AF waveguides with Bragg gratings were directly patterned on spin coated Teflon AF 1600 (DuPont, Inc) film using electron beam lithography. Teflon AF and adhesion promoter solutions were prepared as described in the previous sections. Silicon wafer was used as the substrate. First step was sample preparation (as described in section 3.3.2). Owing to poor adhesion of Teflon AF and silicon, adhesion promoter has to be spin coated prior to coating Teflon AF. Adhesion promoter, 1H, 1H, 2H, 2H perfluorodecyltriethoxy silane (Alfa-Aesar, Inc) was spun at 2000 rpm for 30 sec and baked at 110°C for 15 min on the cleaned sample. Since it is only a molecule thick it does not interfere with the device functionality. Next step was spin coating of Teflon AF.

Thickness of the spin coated film depends on the spin speed. Lower spin speeds result in higher thickness and vice-versa. With Teflon AF however previous experiences revealed that lower spin speeds yield non-uniform coatings. So for films greater than a micron multi-layer coating process was followed. Several thin layers at higher spin speeds were subsequently coated following the spin-bake-spin-bake procedure as opposed to a single thick layer at a lower spin speed. In this experiment three layers of Teflon AF from a 5% by weight solution in FC-40 (Acros Organics) solvent were coated at 4000 RPM and baked at 165°C for 20 min one after another. After spin coating, thickness of the sample was measured using an M-2000 spectroscopic ellipsometer (J. A. Woollam Company, Inc.) which was measured to be 902 nm.
Once we have the spin coated Teflon AF film, the next step is to write the waveguides. Waveguides with gratings were exposed in Teflon AF 1600 film at electron beam energy of 7 KeV and a beam current of 201 pA, using a Raith e-LiNE electron-beam lithography tool in the fixed beam moving stage (FBMS) mode. Ten sets of straight waveguides spaced by 200 µm were written with varying doses from 100-1000 µC/cm². Each set had a single pixel line, 0.5µm, 1µm, 2 µm and 3µm wide waveguides respectively spaced by 100µm. All the waveguides were 1cm long. Each waveguide had a Bragg grating with a grating period of 588 nm and a grating frequency of 1550 nm respectively running for a length of 100 µm across the waveguide. Three sets of straight waveguides with Bragg gratings are as shown in figure 3.15. The electron beam exposure parameter details are as given in the table 3.1.
Table 3.1: Electron-Beam exposure parameters for straight Teflon AF waveguides with Bragg gratings written at beam energy of 7 KeV and beam current of 201 pA on a 902 nm Teflon AF sample.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EHT</td>
<td>7 KeV</td>
</tr>
<tr>
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<td>Beam Current</td>
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<td>Step Size</td>
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</tr>
<tr>
<td>Calculation Width</td>
<td>4 µm</td>
</tr>
<tr>
<td>Deflection cycle Time</td>
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</tr>
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</table>
Figure 3.15: Three sets of directly patterned straight Teflon AF waveguides (vertical bright lines) with Bragg gratings (horizontal dark regions).

3.3.8 Teflon AF –FEP waveguides

Figure 3.16: Schematic of fabrication process for Teflon AF-FEP waveguides.

Waveguides with Teflon AF 1600 (DuPont, Inc) cladding and Fluorinated Ethylene Propylene (FEP, Kurt J. Lesker, Inc) as core were fabricated by sputtering FEP over the patterned Teflon AF. Schematic of the fabrication process is as shown in figure 3.16. Sample cleaning, preparation of Adhesion promoter and Teflon AF as described in the sections 3.3.2, 3.3.3 and 3.3.4 were the preliminary procedures. This was followed by
spin coating adhesion promoter and Teflon AF. Adhesion promoter, 1H, 1H, 2H, 2H perfluoro-decyltriethoxy silane (Alfa-Aesar, Inc) was first spin coated on the cleaned silicon substrate to overcome poor adhesion of Teflon AF and silicon. This solution was spin coated at 2000 RPM for 30 sec and baked at 110°C for 15 min. It does not affect the device functionality since it is only a molecule thick. Subsequently the wafer was coated with Teflon AF from a 5% by weight solution in FC-40 (Acros Organics) solvent. Since we needed a micron thick layer of Teflon AF, multi-layer spin-bake-spin-bake process was followed. Three subsequent layers of Teflon AF 1600 were spun at 4000 RPM for 60 sec and baked at 165°C for 20 min. Uniformity of the of the spin coated Teflon AF film was measured using a Dektak 6 M surface profilometer (Veeco, Inc.). The RMS value of surface roughness of the film was 5.2 nm. Thickness of the film was measured using an M-2000 spectroscopic ellipsometer (J. A. Woollam Company, Inc.). It measured 1.2 µm. The next step was E-beam exposure. Waveguides were written using a Raith e-LiNE electron-beam lithography tool. A design for the straight waveguides was prepared in the GDSII editor.

Straight Waveguides were exposed in Teflon AF at electron beam energy of 20 KeV and a beam current of 487 pA in Fixed Beam Moving Stage (FBMS) mode. Ten sets of straight waveguides spaced by 200 µm were written with varying doses from 100-1000 µC/cm². Each set had four waveguides spaced by 100 µm with widths ranging from 1 µm-4 µm with a step of 1 µm. All the waveguides were 1cm long. The electron beam exposure parameters are as given in table 3.2.
After patterning the waveguides in spin coated Teflon AF 1600 film, FEP was sputter deposited to form the core of the waveguides. FEP (Kurt J. Lesker, Inc) was used as the target. Initially the sample and the target were loaded and deposition parameters were configured. Estimated deposition thickness was 1 µm and material density of FEP was 2.15 units. A constant output power of 30 W was maintained. At a base pressure of 0.2 mTorr, Argon gas was supplied to the chamber at the rate of 15 scc/m. Pre-sputtering was
done for 5 min and the actual sputter deposition on the sample took place at a pressure of 4.25 mTorr. Ellipsometer measurements were carried out after sputtering and the thickness of sputtered FEP was found to be 1.57 µm. Figures 3.17 and 3.18 show the SEM images of the edge view of patterned Teflon AF- FEP waveguides on silicon.

Figure 3.17: Edge view of patterned Teflon AF- FEP waveguides on silicon.

Figure 3.18: Edge view of a set of patterned Teflon AF- FEP waveguides on silicon.
3.3.9 Curved Teflon AF waveguides

Curved waveguides were written in Teflon AF (DuPont, Inc) following the same fabrication process described in the previous sections. Sets of curved waveguides with constant bend radii and constant length were written in spin coated Teflon AF using electron beam lithography. Silicon substrate was cleaned as described in the section 3.3.2. Adhesion promoter and Teflon AF solutions were prepared as described in the previous sections. Adhesion promoter (Alfa-Aesar, Inc) was spin coated prior to Teflon AF. 1H, 1H, 2H, 2H perfluoro-decyltriethoxy silane (Alfa-Aesar, Inc) was spun at 2000 RPM for 30 sec and baked at 110°C for 15 min. The adhesion promoter layer does not interfere with the waveguide functioning as it is only a molecule thick. This was followed by spin coating of Teflon AF. Teflon AF from a 5% by weight solution in FC-40 (Acros Organics) solvent was used. Three subsequent layers of Teflon AF were spun at 4000 RPM for 60 sec and baked at 165°C for 20 min. M-2000 spectroscopic ellipsometer (J. A. Woollam Company, Inc.) measurements indicated that the film thickness was 1.02 µm. Electron beam exposure was the next process step.

Raith e-LiNE electron-beam lithography tool was used for electron beam exposure. Pattern to be exposed was design in the GDSII editor. Curved waveguides with a constant bend radii of 116 µm and a constant length of 1 cm, with input and output offset by 1 mm were written in FBMS mode. Ten sets of curved waveguides spaced by 200 µm were written with varying doses from100-1000 µC/cm². Each set had four waveguides spaced by 100µm with widths ranging from 1µm-4µm with a step of 1 µm. All the waveguides were 1cm long. In addition, three sets of straight waveguides with doses ranging from
800-1000 \( \mu \text{C/cm}^2 \) were also exposed on the same sample. Each set contained four waveguides spaced by 100\( \mu \text{m} \) with widths ranging from 1\( \mu \text{m} \)-4\( \mu \text{m} \) with a step of 1 \( \mu \text{m} \). The electron Beam exposure parameters are as given in table 3.3. The chip with straight and curved waveguides is as shown in figure 3.19.

Figure 3.19: Chip with sets of straight and curved waveguides with varying dose and thickness on a 1.02 \( \mu \text{m} \) Teflon AF.
Table 3.3: Electron-beam exposure parameters for straight and curved Teflon AF waveguides written at beam energy of 20 KeV and a beam current of 699 pA on a 1.02 µm Teflon AF sample.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<td>EHT</td>
<td>20 KeV</td>
</tr>
<tr>
<td>WD</td>
<td>10 mm</td>
</tr>
<tr>
<td>Aperture Size</td>
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<td>Beam Current</td>
<td>699 pA</td>
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<tr>
<td>WF Size</td>
<td>500 X, 200 µm</td>
</tr>
<tr>
<td>Area Step Size</td>
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</tr>
<tr>
<td>Area Dwell Time</td>
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<tr>
<td>Area Dose</td>
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<td>Beam Speed</td>
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<td>FBMS Area</td>
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<tr>
<td>Stage Speed</td>
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<tr>
<td>Calculation Width</td>
<td>4 µm</td>
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<td>Area Dose</td>
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<td>Dose Factor</td>
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<td></td>
</tr>
<tr>
<td>Step Size</td>
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</tr>
<tr>
<td>Max Structure Width</td>
<td>4.46 µm</td>
</tr>
<tr>
<td>Calculation Width</td>
<td>4 µm</td>
</tr>
<tr>
<td>Deflection cycle Time</td>
<td>5698 µs</td>
</tr>
</tbody>
</table>
Teflon AF - PMMA Waveguides were formed by spin coating PMMA on patterned Teflon AF. PMMA (Micro Chem, Inc) was spin coated on the already existing patterned sample described in section 3.3.9. The schematic of the fabrication process is as shown in figure 3.20. Previous experiments have revealed that PMMA does not adhere well to Teflon AF and thus surface treatment of Teflon AF was necessary. In this experiment the previously patterned Teflon AF sample was oxygen plasma etched at 50 % power for 60 sec in a custom made Plasma-Preen system. In the system, flow of process gas (oxygen) at reduced pressure (2-5 Torr) through the process chamber excites the plasma. Energetic free radicals are produced by plasma which react with the sample surface. The process of plasma etch is believed to oxidize the surface of Teflon AF which enhances its adhesion to PMMA. After the oxygen plasma etch, PMMA was spin coated on Teflon AF. 8% PMMA (Micro Chem, Inc) in Anisol solution was used for spin coating. This solution
was spun at 3000 RPM for 30 sec and baked at 110°C for 5 min to yield a 1.1µm thick layer of PMMA.

3.3.11 Polishing

In order to enhance the edge quality of the chip (waveguides) we resorted to polishing. The sample with straight waveguides and gratings was polished. Before polishing the sample, a 1 µm layer of Teflon AF was spin coated on it to protect the waveguides on the surface against any damage in the process of polishing. Three subsequent layers of Teflon AF were spun at 4000 RPM for 60 sec and baked at 165°C for 20 min following the multiple-layer, spin-bake-spin-bake procedure. Polishing was done using a Model 590 Tripod Polisher (South Bay Technology, Inc) and Buehler ECOMET 3 variable speed grinder-polisher. The sample was mounted on a metal mount using the crystal bond with the side containing waveguides facing upwards. This metal mount fits vertically into a slot in the tripod polisher such that the edge of the chip comes in contact with the surface on which the tripod polisher sits. The height of the chip-edge can be adjusted by adjusting the micrometers on the legs of the tripod. Once the sample is mounted on the polisher it is ready to be used in the spinning system. The tripod was placed on a 1 micron disc, aluminum oxide film (South Bay Technology, Inc) 8” in diameter in the spinning system and slightly held against the rotating surface. Each edge of the sample was polished in this manner at a speed of 200 RPM for a period of 60 min.
3.4 Characterization

This section gives the detail of the experimental setup used for the characterization of waveguides. The objective was to guide laser light through the waveguide and analyze the output. The setup is as shown in figure 3.21.

![Figure 3.21: The Schematic of waveguide characterization set-up.](image)
3.4.1 Experimental Setup

Chip with patterned waveguides was mounted on top of a 2-axis stage. This facilitated the horizontal and vertical movement of the chip (waveguides). Laser light from the optical source was focused onto the waveguide through an optical fiber. Light from the optical fiber can be directly shined at the edge of the chip but in this case an objective has been used to focus the light into the waveguide. The objective was mounted on a 3-axis stage. This gave the flexibility to adjust the input in three directions. However it can be automatically adjusted using a piezo controller. The output from the waveguide was focused onto the detector and cameras using beam splitters through an objective mounted on a lens turret. The idea of using the lens turret was to change the objectives at ease if needed. Figure 3.22 shows the chip mounted on a 2-axis stage, the input objective mounted on a 3-axis stage and the output objective mounted on the lens turret.

Figure 3.22 Chip mounted on a 2-axis stage, the input objective mounted on a 3-axis stage and the output objective mounted on the lens turret.
3.4.1.1 Input sources

Two types of laser sources were used. A visible green light source of 532 nm with a maximum power of 3mW was used to initially align the objectives for maximum power. It was also used in aligning the input of the optical fiber to the waveguide. In addition a tunable laser source, Agilent 8164A lightwave measurement system was also used in identifying the waveguides. The wavelength of the tunable laser ranges from 1480 nm - 1570 nm with a maximum power of approximately 4.2 mW. It has an interface to receive the signal from a detector and a facility to control the laser power and wavelength. It also displays the laser power, wavelength and the detector power.

3.4.1.2 Output Components

To analyze the output from the waveguide the setup consisted of an Agilent 81624A infrared detector, a Hamamatsu IR camera and a visible camera. The output from the waveguide was directed on to a 50:50 beam splitter. This 50:50 beam splitter when placed at an angle of 45° to the incident light reflects visible and transmits IR. A visible camera which is a simple webcam was used to analyze the visible output. Another beam splitter with 90:10 splitting ratio and a 1550 nm filter were placed in line with the IR camera. The 90:10 beam splitter when placed at an angel of 45° to the incident light reflects 90% IR to the IR detector and transmits 10% IR to the IR camera. 1550 nm narrow band filter reduces the background light thus making the signal to the IR camera more visible. The IR signal from the camera can be viewed using WinTV2000 on a computer, using the Hamamatsu camera controller which interfaces with the computer.
Agilent 81624A optical head power sensor makes use of the InGaAs sensor and has an optical range of 800 nm to 1700 nm.

### 3.4.2 Procedure for identifying waveguides

The first step in the procedure for characterization of waveguides is to align the objectives for maximum power. The chip is first removed and the objectives are adjusted such that the distance between them is the sum of their working distances. The output signal in response to the green laser is observed on the visible camera. Focusing is done to obtain a bright green spot at the center of the screen. Same is repeated with the IR laser till a bright spot is obtained. Performing this also ensures that the point of observation is approximately at the same position in the field of view of both visible and the IR cameras. When both the objectives are aligned the IR detector shows maximum power output.

After alignment of both the objectives, chip is mounted back in between them such that the alignment of the output components is intact. Light from a normal visible light source is shined on the edge of the chip at an inclination from the output side and the image is observed on the visible camera. With height adjustment of the 2-axis stage and slight focusing, the edge of the chip can be seen. With the right inclination of light, waveguides can be observed as ‘V’ shaped structures. Once the image on the visible camera is focused, the next step is to align the optical input to the waveguide. This was done using a green laser. The green laser spot is visibly aligned with the desired waveguide using a microscope mounted above the chip. Now that we know we are exactly positioned on the
required waveguide, the optical input is switched to IR. Image on the IR camera will now be out of focus. IR will be in focus when the visible is slightly out of focus. Bring the visible slightly out of focus and adjust the height of the input objective until a pattern of interference fringes is observed. As the height of the input objective is adjusted, the fringes keep moving up and down. Just at the point where the fringes start to disappear, a bright streak of light called the slab can be observed. Slab confines the light vertically in ID. Once the slab is in focus, bright spots of light which are very sensitive to the lateral movement of the input objective can be observed. If a spot is very sensitive to the input and is bright even with attenuation, it should probably be a waveguide. Figure 3.23 and 3.24 shows the set up and the input source respectively.

![Figure 3.23: Waveguide characterization set-up without the sources.](image-url)

Figure 3.23: Waveguide characterization set-up without the sources.
3.5 Results and discussion
This chapter discusses the results of fabrication and characterization of the waveguide devices. A procedure for patterning Teflon AF amorphous fluoropolymer waveguides has been formulated. Direct patterning of Teflon AF using electron beam lithography has been exploited. PMMA has been spin coated over Teflon AF overcoming its adhesion problems. A characterization setup was assembled which facilitated the characterization in both visible and infrared regions. There was no evidence of guided modes in the waveguides but light propagated through the PMMA slab.
3.5.1 Patterning of waveguides

Patterning of waveguides in Teflon AF has been achieved through direct electron beam patterning technique. This single step fabrication technique proved to be very efficient for patterning waveguides. Fixed beam moving stage (FBMS) mode of electron beam exposure was employed in the fabrication of waveguides. This mode of exposure reduced the stitching errors as well as the time of exposure. Fabricated waveguides were clearly visible to the naked eye. Figure 3.25 shows the chip with straight and curved waveguides in Teflon AF mounted on a two axis stage between the objectives.

Figure 3.25: Chip with sets of straight and curved waveguides with varying dose and thickness on a 1.02 μm Teflon AF mounted on the 2-axis stage in between the objectives.
3.5.2 Depositing PMMA on patterned Teflon AF
One of the promising properties of Teflon AF is its low surface energy. But because of this property, adhesion of substances to Teflon AF has been difficult. One of the problems encountered in this regard was spin coating PMMA on patterned Teflon AF. This problem was solved by surface treatment of Teflon AF through oxygen plasma etching. PMMA was successfully spin-coated on patterned Teflon AF after oxygen plasma etching. Surface treatment enabled spin-coating of PMMA without any complications. One of the reasons for improved adhesion may be oxidation. During the plasma etch, fluorine atoms in Teflon AF are knocked out by high energy free radicals and in turn are replaced by oxygen atoms. This allows adhesion of PMMA to its surface. However increase in surface roughness might be another reason for its improved adhesion. Oxygen plasma is assumed to increase the surface roughness of Teflon AF thereby creating grooves on the surface which makes it easy for PMMA to be deposited.

3.5.3 Characterization Set-up
A very flexible set-up was assembled for the characterization of waveguides. It facilitated characterization both in visible and infrared spectral regions. The input sources could be easily switched from visible to IR and vice-versa. Green laser was greatly useful in aligning the optical input to the waveguide without which the characterization would have been tedious. Use of the beam splitters was another important aspect of the assembly. Output signal could be accessed simultaneously on the visible camera, IR detector and the IR camera without major changes to the set-up. A lens turret was used on the output side to change the objectives if required.
3.5.4 Characterization in the visible region

Results of characterization in the visible region have been presented in this section. Figure 3.26 shows the edge view of a direct patterned Teflon AF waveguide in silicon with visible light. The waveguide in Teflon AF is seen as a ‘v’ shaped structure. Figure 3.27 shows the top view of the direct patterned waveguides in Teflon AF with visible light. Visible light was focused at the input of one of the waveguides on the chip directly through an optical fiber and transmission through the waveguide has been examined. As seen in the figure the waveguides were clearly visible in the background. There is evidence of light guiding through the waveguide but it does not cross the entire chip. There was also no evidence of light emission from the output of the waveguide.

Figure 3.26: Side view of a direct patterned waveguide in Teflon AF as observed on the visible camera.
Figure 3.27: Top view of direct patterned Teflon AF waveguides with visible light. Light guiding through one of the waveguides is observed, but light does not cross the entire chip.

3.5.5 Characterization in the infrared region
Characterization of patterned waveguides in the infrared spectral region has been presented in this section. Silicon-on-insulator waveguides were perceptible using the newly developed characterization set-up. Figure 3.28 shows the result of characterization of silicon-on-insulator waveguide in the infrared region. The bright spot at the center is the waveguide and the structure of the waveguide is shown in the insert [25]. Characterization of direct patterned Teflon AF waveguides did not result in perceptible guided modes but the slab mode was visible in all the cases. Figure 3.29 shows the Teflon AF-PMMA slab. Light is guided through the Teflon AF-PMMA slab waveguide at 1550nm. Pattern above the slab are the interference fringes in air.
Figure 3.28: Silicon-on-insulator waveguide at a wavelength of 1550 nm (Modified from: Harish Srinivasan, “Finite element analysis and experimental verification of SOI waveguide losses”, University of Kentucky, Master’s Thesis, October 2007).

Figure 3.29: Teflon AF-PMMA slab waveguide at a wavelength of 1550 nm.
3.5.6  Problems encountered

All possibilities have been explored in the endeavor to guide light through Teflon AF waveguides. Characterization of straight waveguides revealed that excessive stray light might have made the waveguides imperceptible. To avoid excess background light curved waveguide fabrication was proposed. Characterization of curved waveguides was also not successful. Losses at the bends of a curved waveguide might be the reason for the light not getting through the waveguide. Achieving high quality of polished edges was difficult as reported by other groups [19].
4. CONCLUSIONS
Direct patterning experiments revealed that Teflon AF can be patterned directly via electron-beam lithography at doses equivalent to those of typical electron-beam resists. This however is in contrast with the very high does required for direct patterning of inorganic materials. However, Teflon AF is likely to be used for different applications. Direct patterning experiments of Teflon AF concluded that the pattern depth depends on initial film thickness suggesting that densification plays a prominent role. Pattern depth is linearly proportional to dose over a wide range of doses. This suggests that Teflon AF could provide a good material for 3-D lithography. The linear response of the material also suggests that obtaining high-aspect-ratio/high-resolution features will be challenging. In spite of this, features as small as ~200 nm have been resolved as surface relief structures, however, further investigation is required in this regard. SEM micrographs revealed that the exposed film cleaved cleanly compared to the unexposed film. This suggests that chain scission reactions are taking place. Fourier transform infrared spectra suggest that dioxole and CF₃ groups play a prominent role in direct patterning of Teflon AF.

Waveguides in Teflon AF were fabricated using the technique of direct patterning via electron-beam lithography. FBMS mode of exposing long-extended features resulted in stitch-free exposure for waveguides. Patterned waveguides were clearly noticeable end to end on the chip. Adhesion problems of Teflon AF were overcome and PMMA was spin coated on patterned Teflon AF after oxygen plasma etching without any complications. Characterization of silicon-on-insulator waveguides was successful using the newly developed characterization setup. Teflon AF waveguides were visible in both edge and
top views with visible light. There was evidence of light guiding, but light did not cross
the entire chip. Slab mode for the Teflon AF waveguides was visible in the infrared
region however individual waveguides were not detected. It is believed that excessive
stray light around the straight waveguides made them imperceptible. The waveguides are
present but the intensity of stray light in the vicinity was greater than any guided light. In
case of curved waveguides, absence of light guiding across the entire chip is attributed to
the losses in the bends and scattering losses throughout the waveguide.
Appendix

Waveguiding in low refractive index fluoropolymers could be useful for optical sensing applications such as surface plasmon resonance sensing (SPR sensing). Low refractive indices are essential when materials much be matched to the optical properties of liquids. This section gives a brief overview of surface plasmon resonance (SPR) sensing and how low refractive index waveguides can be used for SPR sensing.

Low effective index waveguides for surface plasmon sensing

Surface Plasmon resonance is a technique which has been widely used in bio-chemical sensing over the past few years. Metals like gold, silver and copper exhibit negative real dielectric constants at optical wavelengths. This property of metals is exploited in exciting surface plasmons at the interface of a metal and a dielectric. Surface plasmons are bound electromagnetic waves which propagate along the interface of two materials with real dielectric constants of opposite signs. Surface Plasmon resonance sensors (SPR sensors) make use of these waves to detect refractive index changes in the medium in contact with the metal layer.

Traditionally SPR sensors consisted of a glass substrate deposited with gold or silver on one side and the required bio-sensing layer on top of the metal. A prism was used to couple light to the surface plasmon mode of the structure through the substrate. At angles and wavelengths that strongly couple light to the surface-plasmon wave a minimum in the reflected intensity was observed. Refractive index changes in the bio-sensing layer are measured by detecting the changes in the angles and wavelengths of the reflection minimum. As opposed to free-space optical systems, on-chip SPR sensors are compact,
mechanically robust and allow high channel density for multiple analyte sensing. Several
groups have built integrated waveguide sensors based on planar dielectric waveguides
[26]. A basic SPR sensor based on low-refractive index waveguides is as shown in figure
1. The challenge is to guide light through the low refractive index waveguides and phase-
match the mode of the waveguide with that of the surface-plasmon modes.

![Figure 1: Basic SPR sensor based on low-refractive index waveguides.](image)

**A brief attempt in modeling**

Modeling of a surface plasmon resonance sensor based on dielectric slab waveguide is
discussed in this chapter. Matlab simulations were performed to determine the sensor
parameters. Surface plasmon film dimension, thickness of core and cladding were the
parameters under consideration. An SPR sensor with MgF$_2$ core and Teflon AF cladding
with a gold surface plasmon film was modeled in Matlab. Through trial and error method,
a gold film thickness of 50 nm and a slab thickness of 1500 nm gave a strong coupling between the plasmon modes and the slab-waveguide mode.

Figure 2 shows the dispersion relations for the long range and short range surface plasmon modes of the gold film and the mode of the MgF$_2$ core slab-waveguide. Phase-matching and strong coupling occurs near 600 nm and 840 nm. Another Matlab script was written to define a dielectric slab waveguide and to solve for the propagation constants of all the allowed modes. For the slab waveguide discussed above, all the modes were analyzed and transverse field components for the modes were plotted. Figure 3 plots power as a function of distance for all the modes of the slab waveguide. The distance at which power decays to 0.1% of its maximum is considered to be the optimum cladding thickness.
Figure 2: Dispersion relation for the long range and short range surface plasmon modes of a 50 nm gold film and the fundamental mode of a 1500 nm MgF_{2} core slab-waveguide. Surface plasmon excitation will occur near 600nm for the LRSP and near 850nm for the SRSP where the modes are phase matched.
Figure 3: Power plot for all the modes of the MgF₂ core, Teflon AF clad slab-waveguide.
REFERENCES


VITA

Vijayasree Karre was born in Secunderabad, Andhra Pradesh, India on July 31st, 1984. She received B.Tech degree from the department of Electrical and Electronics Engineering (with distinction) at Jawaharlal Nehru technological university, India in 2005. She joined University of Kentucky in fall 2006 for Master’s in Electrical and Computer Engineering. She worked as a Teaching assistant in the department of Mathematics at University of Kentucky from fall 2006 to fall 2008. Later she worked as a Research Assistant in the department of Electrical and Computer Engineering (Center for Nanoscale Science and Engineering) from fall 2007-spring 2009. She was awarded Kentucky graduate scholarship throughout the Master’s program. Her work on direct electron-beam patterning of Teflon AF was published in IEEE transactions on nanotechnology.