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I, Amilcar Santamaria Hernandez, hereby submit this original work as part of the requirements for the degree of Doctor of Philosophy in Electrical Engineering.

It is entitled:
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Aluminum Nitride (AlN) Waveguides
for Potential Soliton Propagation.

by
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Abstract

The primary objective of this work was to build optical waveguide structures based on amorphous Aluminum Nitride (AlN) to study the coupling of short optical pulses into optical waveguides and their subsequent propagation through the waveguides and interfaces.

A thin film of amorphous Aluminum Nitride, (AlN), was used as waveguide core, which was deposited by reactive plasma sputtering on various substrates, such as silicon and soda-lime glass to characterize their performance. Structures on AlN deposited thin film were built, by photolithography with negative photoresist and chemical etching with Sodium Hydroxide, (NaOH).

Material characterization of deposited AlN, was performed. Electrical and optical properties were established. An attenuation rate of 0.09 dB/cm was determined at a wavelength of 1550 nm, and 0.22 dB/cm at a wavelength of 650 nm.

The soliton is a very short light pulse that can be generated in optical fiber. It was proposed to launch solitons in AlN. Analysis proved that its dispersion has a crossover point at around 1550 nm, which would allow bright solitons to exist.
... dedicated to the most wonderful, generous and loving person, my wife Raquel, whose love, patience and sacrifice knows no limit. To my adorable twin boys Alejandro and Sebastian, for their unconditional love and sacrifice, who have walked with me in this journey. To the loving memory of my beloved parents in law Doña Maria de los Angeles Mendoza, Don Roberto Flores Machado and my dear grandmother Victorina Escobar Matute.
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Amilcar Santamaría Hernández
Chapter 1

Introduction

1.1 Prelude

Optical solitons are short light pulses, that display very unique properties when they propagate in silica fibers due to the special properties of SiO$_2$, [1]. The coupling of solitons into Aluminum Nitride optical waveguides, on rigid substrates such as silicon and glass, presents the possibility for new photonic devices utilizing solitons.

Novel devices in current and future electronics and photonics require new dielectrics with special optical, thermal and electrical properties, [2], [3]. Aluminum Nitride, AlN, which is fundamentally a wide bandgap semiconductor, [4] that presents superior properties in all of the above mentioned categories. Some of its unique higher refractive index than SiO$_2$, broad spectral transmission range properties are very high breakdown field and exceptionally low leakage current even at high temperatures exceeding 300 °C, as reported by Werner [5], and Neudeck [6].

1.2 Optical Solitons

The soliton is the shortest light pulse that preserves its shape inside silica fiber, over large distances, [7], [8]. Solitons display particle like properties which suggest its use
Research on Optical Solitons and their use in optical communications was initially motivated by the work of Hasegawa and Tappert in which they proposed a novel method of ultra short electromagnetic pulse propagation in optical fiber; [11], [12]. The soliton pulse envelope has the property of maintaining its shape during propagation in a nonlinear dispersive environment [13]. Experimental proof of the existence of solitons came about in 1980 when Mollenauer et. al. [14], successfully launched solitons in a single mode optical fiber.

A nonlinear term of the refractive index, known as the Kerr effect, is proportional to the second order of the propagating electric field, [15], [16]; it will modify the refractive index of media [11], due to the high intensity of the optical field [17]. Namely, optical fiber presents this nonlinear behavior when subject to a high power optical field, especially when confined in a very small region, such as a single mode optical fiber or thin film optical waveguide. The Nonlinear Schrödinger Equation (NSE) which describes the way nonlinear optics and dispersion affect electromagnetic wave propagation in optical fiber, with either Normal or Anomalous dispersion, was first derived by Hasegawa and Tappert [11], [12]. It represents the propagation of light pulses in a waveguide.

The Korteweg de Vries (KdV) equation was initially proposed by Diederik Korteweg and Gustav de Vries in 1895 to describe solitons in shallow water [18]; it can also model solitons in acoustic waves [19], and cold plasma [20]. Solitons are essential to describe various nonlinear phenomena such as: localized waves in Bose–Einstein condensate [21], plasma physics, hydrodynamic waves [22], ultra short pulses propagation in optical fibers [23], and charge transport in conducting polymers among others.
Research on plasma physics lead Gardner et. al. in 1967 [25] to develop the Inverse Scattering Transform (IST) to solve the KdV equation [26].

![Figure 1.1: Kerr Effect and Group Velocity Dispersion (GVD)]

The Nonlinear Schrödinger Equation is derived from a Taylor’s expansion of the dispersive term around a central frequency [27], [28]. Figure 1.1 shows a traveling optical pulse where the dispersion gets canceled by the nonlinear Kerr effect. The Nonlinear Schrödinger Equation is completely integrable and has a unique solution by using the Inverse Scattering Transform, as shown by Zakharov and Shabat [29] and the Split-step algorithm [30]. A thorough description and extensive work on the Inverse Scattering Transform (IST) to solve the Nonlinear Schrödinger Equation (NSE) was done by various investigators [31], [32], [33], [25], [34].

Interest to study optical solitons, in our group, was initially triggered by an advanced course in Nonlinear Optics taught by Dr. Peter Kosel, called “Photonic Devices”. It was in this course that nonlinear properties of optical devices were addressed.
and studied in detail.

1.3 Soliton Logic

Optical computing has been the interest of few researchers since the early days of the existence of lasers [35], [36]. Solitons are self focused and propagate without change their shape, they may be best candidates for information carriers, they simultaneously exhibit wave and quasi particle properties [37]. Sawchuk proposed a non Von Neumann machine where photons are entirely the primary carrier of information [38]. Guided wave electro-optic devices were proposed to be implemented logic gates by Taylor [39] and Liquid crystal valves were proposed to operate as optical logic gates [40] before the optical soliton was demonstrated by Mollenauer in 1980, [14].

Due to their nonlinear properties of solitons and their particle like behavior a boolean logic based on optical solitons was developed by Islam in 1992 [10] in contrast with the existing physical gates i.e. Mach-Zehnder interferometers of Lithium Niobate devices. The logic proposed must be Boolean complete, that is it includes NOR, NAND gates and it must be cascadable, so one gate output is another gate input. A soliton trapping AND gate was demonstrated, consisted of a birefringent fiber and a frequency filter [41].

Another approach was followed by Serak et. al, where spatial solitons immersed in Azobenzene liquid crystalline cells were successfully used to build all-optical logic gates (AND, NOR, XNOR), who anticipated the demonstration of complex operations for all-optical computing [42].

Although Islam proposal is successful it requires, equipment of a rather large size,
which renders the optical logic implementation unpractical to replace the well developed digital electronic based computer as we know it.

1.4 Aluminum Nitride

Research results reported in this doctoral dissertation have arisen from the interests of our group in the investigation of novel applications of Aluminum Nitride ($AlN$), for photonic device applications. Due to its remarkable combination of electrical, thermal and optical properties; it was suggested for investigation as a core waveguide material in photonic devices on glass and semiconductor materials.

Aluminum Nitride $AlN$ was discovered in 1862 by F. Briegler and A. Geuther and synthesized for the first time in 1877 by J. W. Mallets [43], but it remained mostly, an academic curiosity. It was only around 1980’s that researchers showed serious interest in Aluminum Nitride $AlN$, as a prospective semiconductor material of the III-V group [44].

Within the past decade, thin films of amorphous Aluminum Nitride $AlN$, have been successfully deposited on various substrates by means of RF plasma enhanced sputtering at near room temperature conditions by various investigators [45]. Sugiyama et. al. reported in 1990 a preparation method using Reactive Sputtering to easily deposit amorphous films of Aluminum Nitride [46].

Aluminum Nitride due to its large and direct bandgap is a good candidate material to build LEDs and lasers that emit in the ultraviolet regime, namely 210 nanometers [47]. A high vacuum system with magnetron sputtering head was meticulously cleaned and fine tuned to produce the highest quality possible and reproducible $AlN$ films.
used in this research.

1.5 Optical & Electronic Properties of AlN

According to the results reported by *Aluminum Nitride*, by Jergel et. al., [48] the refractive index of amorphous is moderately larger at $\lambda = 632.8$ nm. They report slight variation, of their values in the range: $[1.861 \leq n \leq 1.993]$.

![Figure 1.2: Aluminum Nitride Refractive Index](image)

The refractive index of single crystal Aluminum Nitride published by Adachi [49] is shown in figure 1.2, for 300 K for the electrical field vector $\vec{E}$, perpendicular to the $c$-axis of the crystal.

These high index values suggest potential use of Aluminum Nitride in photonic waveguides for that would confine light pulses to smaller dimensions that in free
space or silica waveguides because of the wavelength relationship:

\[
\lambda_{\text{AlN}} = \frac{\lambda_{\text{freespace}}}{n_{\text{AlN}}}
\]  

(1.5.1)

![Figure 1.3: Aluminum Nitride Extinction Coefficient](image)

The imaginary part of the refractive index, called the extinction coefficient \( k \), of \( \text{AlN} \) is nearly zero from 0.3 to 2.5 \( \mu m \), as reported in figure 1.3. For \( \lambda \leq 0.3 \mu m \) the extinction coefficient is larger but still, rather small, being \( k = 0.006 \) at its largest value [49].

Aluminum Nitride (AlN), belongs to the \( \text{III-V} \) semiconductor class together with Gallium Nitride (GaN), Gallium Arsenide (GaAs), and Indium Phosphide (InP) which have well established roles in photonics, due to their direct energy band gaps; Aluminum Nitride (AlN) has high thermal conductivity (\( \sim 3.2 \text{ W cm}^{-1} \text{K}^{-1} \) at 300 K) a
feature that warrants its use in high power electronic applications as a heat spreader or substrate where heat dissipation is an issue. AlN was successfully used in combination with polymer composites to dissipate heat in 1990 [50]. It appears AlN has better thermal properties than Boron Nitride and Beryllium Oxide as reported by Miyashiro et. al. [51], this was confirmed in 2006 by Lee et. al. who found AlN thermal conductivity superior to Silicon Carbide (SiC) and Boron Nitride (BN) [52].

Aluminum Nitride has found applications in different applications such as:

- Opto-electronics
- Optical storage media as dielectric layers
- Crucible to grow GaAs crystals in semiconductor industry
- Surface acoustic wave sensors on silicon wafers, due to piezoelectric properties.
- Thin film acoustic resonator, RF filters in mobile phones.
Aluminum Nitride (AlN), has a direct energy band-gap of 6.2 eV, see Figure 1.4, which is the highest among available semiconductors. It crystallizes in a hexagonal wurtzite structure, as shown in Figure 1.4, that has a large piezoelectric constant (≈ |2 − 5|×10^{-10} \text{ cm/v at 300 K}) [53]. Its lattice constants are a = 3.11 and c = 4.98 ångstrom respectively.

The emission wavelength for direct electron - hole recombination in AlN is 210 nm, the shortest value among the known semiconductors, therefore it is a potential candidate for deep-UV detector applications [47]. A major use of AlN exist in ternary alloys with Gallium Nitride (GaN), as Aluminum Gallium Nitride (AlGaN) for the generation of light in the ranges from 210 to 365 nm which covers the deep-UV to near-UV regions.
Our current research is focused on studies of optical and electrical properties of Amorphous Aluminum Nitride thin films which are deposited by Reactive Sputtering from an RF excited plasma at a frequency of 13.8 Mega Hertz, and output power levels from 300 to 500 W.

Previous research at U.C. by M. Samiee had produced Aluminum Nitride thin films with properties in agreement with published documentation, [54]. The table 1 below, lists various physical properties as reported by Ceram Research Ltd. [55]. The table 2 below, lists an updated version of various physical properties as reported by Ceram Research Ltd. [56]
<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Energy Bandgap</td>
<td>6.2</td>
<td>eV</td>
</tr>
<tr>
<td>Density</td>
<td>3.32</td>
<td>g cm(^{-3})</td>
</tr>
<tr>
<td>Modulus of rupture</td>
<td>300-350</td>
<td>MPa</td>
</tr>
<tr>
<td>Elasticity Modulus</td>
<td>310</td>
<td>GPa</td>
</tr>
<tr>
<td>Fracture toughness</td>
<td>3.35</td>
<td>MP(^{-1/2})</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion RT-1000</td>
<td>5.6</td>
<td>x10(^{-6}) K(^{-1})</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>140-177</td>
<td>W/m K</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>780</td>
<td>J kg K(^{-1})</td>
</tr>
<tr>
<td>Volume Resistivity</td>
<td>10(^{10})</td>
<td>ohm cm</td>
</tr>
<tr>
<td>Dielectric Strength</td>
<td>&gt; 20</td>
<td>kV/mm</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>8.6</td>
<td></td>
</tr>
<tr>
<td>Loss Tangent</td>
<td>5x10(^{-4})</td>
<td>@ 1 MHz</td>
</tr>
</tbody>
</table>

Table 1.1: Physical Properties of Aluminum Nitride, 2001

1.6 Optical Waveguide with a Core of AlN

A hollow dielectric waveguide using Aluminum Nitride as material of choice was tested by Matsushima et. al. [57] to operate at a wavelength of \(\lambda = 10.6 \, \mu m\) to build a CO\(_2\) sensor and replace a Beryllia based hollow waveguide due to its toxicity. Attenuation was found 0.017 dB/m at a wavelength of \(\lambda = 10.6 \, \mu m\). The complex refractive index was \(n=0.81 + i0.035\) measured by ellipsometry at \(\lambda = 10 \, \mu m\). Although these results are promising they are far from the optical communications transmission wavelength, \(\lambda = 1.55 \, \mu m\), which corresponds to the minimum attenuation for optical fiber light transmission.

A slab waveguide was built by Gräupner et. al. by a very similar method used in this research, namely reactive sputtering with a Aluminum target in a Nitrogen environment. [58]
<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Energy Bandgap</td>
<td>6.2</td>
<td>eV</td>
</tr>
<tr>
<td>Electron Mobility</td>
<td>≤ 300</td>
<td>cm² V⁻¹ s⁻¹</td>
</tr>
<tr>
<td>Hole Mobility</td>
<td>≤ 14</td>
<td>cm² V⁻¹ s⁻¹</td>
</tr>
<tr>
<td>Electron Diffusion Coefficient</td>
<td>≤ 7</td>
<td>cm² s⁻¹</td>
</tr>
<tr>
<td>Hole Diffusion Coefficient</td>
<td>≤ 0.3</td>
<td>cm² s⁻¹</td>
</tr>
<tr>
<td>Melting Point</td>
<td>2200</td>
<td>°C</td>
</tr>
<tr>
<td>Density</td>
<td>3.260</td>
<td>g cm⁻³</td>
</tr>
<tr>
<td>Young's Modulus</td>
<td>308</td>
<td>GPa</td>
</tr>
<tr>
<td>Bulk Modulus</td>
<td>21 x 10¹¹</td>
<td>dyn cm⁻²</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>2.85</td>
<td>W cm⁻¹ °C⁻¹</td>
</tr>
<tr>
<td>Thermal Diffusivity</td>
<td>1.47</td>
<td>cm² s⁻¹</td>
</tr>
<tr>
<td>Thermal Expansion Coefficient</td>
<td>5.27 x 10⁻⁶</td>
<td>°C⁻¹</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>0.6</td>
<td>J g⁻¹ °C⁻¹</td>
</tr>
<tr>
<td>Refractive Index @ infrared</td>
<td>2.1 - 2.2</td>
<td></td>
</tr>
<tr>
<td>Radiative Recombination Coefficient</td>
<td>0.4 x 10⁻¹⁰</td>
<td>cm³ s⁻¹</td>
</tr>
</tbody>
</table>

Table 1.2: Physical Properties of Aluminum Nitride, 2013
Chapter 2

Theory of Soliton formation and Propagation

2.1 Introduction

Due to interaction with intense light, certain material properties change or special optical properties arise [59]. This is due to the onset of a nonlinear response [16]. Nonlinear optics is a very broad field which deals with many different aspects, [60] that will not be discussed in this chapter. Laser light might be, arguably, the only light source able to trigger nonlinear optical response due to its well known high coherence and optical power density.

Most relevant theoretical considerations of Nonlinear Optics pertaining to Soliton work are discussed here. First a quantitative description of the electromagnetic field then the nonlinear dependance of the refractive index is presented. More detailed derivation can be found in [28], [15], [61], [59] among others.
2.2 Nonlinear Optics

2.2.1 Kerr Effect

The refractive index has essentially two elements, one is the linear term which describes the speed of light in the media, the second one is the nonlinear term which is only triggered when the propagating field is sufficiently high as evidence shows by research [62], [63], [64], [65]. Nonlinear optics predicts that the refractive index is modified due to the high intensity of the applied optical field perturbing the atoms of the material which induce various scattering processes [66], [67], [68], [11]. This leads to a nonlinear phenomenon called the Kerr effect. The following equation represents the two essential elements.

\[ n(\omega) = n_0(\omega) + n_2E^2 \]

(2.2.1)

where \( n_0 = 1.4570 \) is the linear refractive index for silica at \( \lambda = 633 \) nm, and \( n_2 = 3 \times 10^{-22} \text{ (v/m)}^{-2} \) is known as the Kerr coefficient, as reported by Hasegawa & Tappert [11]. Researchers seem to agree on Kerr coefficient values that range from \( n_2 = 1 - 3 \times 10^{-22} \text{ (m/\nu)}^2 \) [69], [70] and [71].

The Kerr effect refers to phenomena than can be simply described by an intensity-dependent refractive index, which yields to a intensity dependent phase shift, in a fiber. Kerr nonlinearities can affect the frequency spectrum of a pulse traveling through a fiber, [72]. At higher intensities the perturbations are no longer linear functions of the applied field, so that inelastic scattering results, [73], [74]. The Kerr effect is assumed to be a consequence of photoexcitation [75].
Optical power launched into an optical fiber at a given wavelength is transferred to a set of longer wavelengths [76], [77]. The exact nature of the shift is determined by certain characteristic vibrations of the fiber materials which induce changes in the refractive index [8]. Applications of these nonlinear effects includes Raman amplifiers, Brillouin amplifiers, soliton propagation, pulse compression, and all-optical switching [78], [79].

### 2.3 Nonlinear Schrödinger Equation

Hasegawa and Tappert [11], [12] proposed for the first time the nonlinear Schrödinger equation as a way to describe the evolution of $\vec{E}$ along optical fiber waveguide. Information carried by soliton pulses in optical fibers is achieved by modulating the electric field of CW lasers [80], [81], [82], [14].

The evolution of $\vec{E}$ at the group velocity $\tau = t - k'z$ is:

$$
\begin{align*}
\frac{i}{\partial z} \frac{\partial \vec{E}}{\partial z} - \frac{1}{2} \frac{\partial k}{\partial \tau} \frac{\partial^2 \vec{E}}{\partial \tau^2} + \frac{\omega_0 n_2}{2c} |\vec{E}|^2 \vec{E} = 0 
\end{align*}
$$

(2.3.1)

Derivation details of equation 2.3.1, can be found in the work of various researchers, namely: A. Hasegawa and M. Matsumoto [28], P. Kosel [83], and L. F. Mollenauer, [84].

whose envelope after a few changes of variable, to normalize distance $Z$ and time $T$, turns into an evolution equation of the Nonlinear Schrödinger Equation.

$$
\begin{align*}
\frac{\partial q}{\partial Z} = i \frac{\partial^2 q}{2 \partial T^2} + i |q|^2 q 
\end{align*}
$$

(2.3.2)
\[
\frac{A}{i \partial z} + \frac{\beta_0}{2} \partial^2 A - \frac{3 \mu_0 \epsilon_0 \omega_0^2}{2 \beta_0} |A|^2 A = 0
\] (2.3.3)

an equation which is similar to the well known schrödinger equation e.g.

\[
i\hbar \frac{\partial \psi}{\partial t} + \frac{\hbar^2}{2m} \nabla^2 \psi - V \psi = 0
\] (2.3.4)

### 2.3.1 Nonlinear Schrödinger Equation solution

An exact solution of Nonlinear Schrödinger Equation was proposed by Kaup [31]. As discussed before, various methods to solve the Korteweg Devries, were used to solve the Nonlinear Schrödinger equation numerically [85], in a generalized form, [86] and analytically with an exact solution by Serkin [87].

\[
\vec{E}(\vec{r}, t) = \vec{F}(r, \phi) A(z, t) e^{i(\omega_0 t - \beta_0 z)}
\] (2.3.5)

this expression describes the \( \vec{E} \) field, that satisfies the NSE, where

\[
A(z, t) = \int_{-\infty}^{\infty} \psi(\omega) e^{i(\omega_0 - \omega) t} e^{-i(\beta_0 - \beta) z} d\omega
\] (2.3.6)

solving the Fourier transform of (2.3.5) and rearranging all variable substitutions, the following equation is obtained, that represents the envelope of a soliton:

\[
A(z, t) = A_0 e^{-iz\omega_0^2/2} \text{sech} \left[ \frac{A_0}{\lambda} \sqrt{\frac{2\pi c y}{D_{\text{mat}}} \left( t - \frac{z}{v_g} \right)} \right]
\] (2.3.7)
where

\[ D_{\text{mat}} = -\frac{\lambda d^2 n}{c d\lambda^2} \]  \hspace{1cm} (2.3.8)

represents the waveguide material dispersion.

\[ D_{\text{mat}} \] must be positive for bright solitons to exist, otherwise the argument of the \( \text{sech} \) function becomes imaginary.

## 2.4 Dispersion Analysis

### 2.4.1 Material Dispersion

Material dispersion is a fundamental property of the specific material used at the core of a waveguide. It is a consequence of the wavelength dependence of the refractive index. The following analysis intends to set a ground level upon which optical effects will be constructed.

The group velocity is defined as

\[ v_g = \frac{d\omega}{d\beta} \]  \hspace{1cm} (2.4.1)

where \( \omega \) is the angular frequency and \( \beta \) is the propagation constant

\[ \beta = nk = \frac{2\pi n}{\lambda} \]  \hspace{1cm} (2.4.2)

and

\[ \lambda = \frac{2\pi c}{\omega} \]  \hspace{1cm} (2.4.3)
\( \tau \) is the transit time for the pulse to travel a distance \( L \)

\[
\tau = \frac{L}{\nu_g} = \frac{L}{v} \frac{d\beta}{d\omega} = \frac{L d\beta}{d\lambda} \frac{d\lambda}{d\omega}
\]  

(2.4.4)

the transit time can be expressed as

\[
\tau = \frac{L}{c} (n - \frac{dn}{d\lambda})
\]  

(2.4.5)

the dispersion term is the change in time with respect to the wavelength as:

\[
D_{\text{mat}} = \frac{1}{L} \frac{d\tau}{d\lambda} = -\frac{\lambda}{c} \frac{d^2 n}{d\lambda^2}
\]  

(2.4.6)

the meaning of (2.4.6) is that different wavelengths arrive at different times, causing the pulse envelope to "spread" after propagation. Bit rate in transmission systems is limited by the dispersion factor [60], which effect in an optical fiber waveguide is to overlap bit pulses. Dispersion management of transmission systems has been heavily used to compensate such effects and increase transmission capacities, that operate at a rate of 40 Gbit/s per channel, [88], [89], [90].

### 2.4.2 Sellmeier Equation

A quantitative representation of the refractive index as a function of the wavelength is achieved by the Sellmeier equation, which will be used here. Its derivation is based on the well known Lorenz Oscillatory Model. A very thorough derivation of the Cauchy and the Sellmeier equations can be found in Born and Wolf [15].

\[
n^2(\lambda) = a_0 + \frac{a\lambda^2}{\lambda^2 - A} + \frac{b\lambda^2}{\lambda^2 - B} + \frac{c\lambda^2}{\lambda^2 - C}
\]  

(2.4.7)
Sellmeier equation parameters for fused silica, as reported by Malitson [91]:

\[ n^2(\lambda) = 1 + \frac{0.6961663\lambda^2}{\lambda^2 - 0.0684043^2} + \frac{0.4079426\lambda^2}{\lambda^2 - 0.1162414^2} + \frac{0.8974794\lambda^2}{\lambda^2 - 9.896161^2} \]  

(2.4.8)

Ghosh et. al. reported a temperature dependant Sellmeier model for optical fiber glasses [92]. Dispersion of GeO$_2$-SiO$_2$ fiber was investigated by Fleming [93], in accordance with advanced doping in fabrication techniques of modern optical fiber core/cladding refractive index profiles.

Figure 2.1 shows the material dispersion of fused silica, from 0.9 $\mu$m to 2.0 $\mu$m. Zero dispersion happens at a wavelength around 1300 nanometers. Which means that solitons, in order to exist in silica, they require dispersion to occur at wavelengths longer than 1300 nm, hence it is natural to exploit the 1550 nm regime, where minimum attenuation happens in fused silica fiber, i.e. 0.154 dB/km at 1.55 – 1.56 $\mu$m [94].
Figure 2.1: Optical Fiber Material Dispersion

SiO$_2$ Dispersion

Dispersion (ps/km/nm)

Wavelength (meter)

$2 \times 10^{-6}$
2.4.3 Simulation

Soliton simulation has been performed to obtain the predicted electric field and envelope of the soliton pulse to propagate on silica fiber and in amorphous aluminum nitride. Assuming optical powers of $P_0 = 100$ mW, and $P_0 = 1$ W.

The traveling electric field pulse is:

\[ E_z = \vec{F}(r, \phi)A(z, t)e^{i(\omega_0 t - \beta_0 z)} \]  

(2.4.9)

where

\[ A(z, t) = A_0 e^{-izA_0^2/2} \text{sech} \left[ \frac{A_0}{\lambda} \sqrt{\frac{2\pi c y}{D_{\text{mat}}}} \left( t - \frac{z}{v_g} \right) \right] \]  

(2.4.10)

\[ E_z = \text{Re}[A(z, t)e^{i(\omega_0 t - \beta_0 z)}e^{i(\omega A_0^2 t/2)}]. \]  

(2.4.11)

Re stands for the real part of the expression between brackets, which leads to the following expression:

\[ E_z = A_0 \text{sech} \left[ \frac{A_0}{\lambda} \sqrt{\frac{2\pi c y}{D_{\text{mat}}}} \left( t - \frac{z}{v_g} \right) \right] \cos \left[ \omega_0 t - (\beta_0 + \frac{y A_0^2}{2})z \right]. \]  

(2.4.12)

The Poynting vector leads to

\[ < \vec{S} > = \frac{1}{2} \text{Re}[\vec{E} \times \vec{H}] = \frac{E_m^2}{2\eta} = \frac{A_0^2}{2\eta}. \]  

(2.4.13)
Power and irradiance are related by the area $\pi a^2$

$$P = \pi a^2 S = \frac{\pi a^2 A_0^2}{2\eta}. \tag{2.4.14}$$

The pulse amplitude is then

$$A_0 = \frac{1}{a} \sqrt{\frac{2\eta P}{\pi}} (v/m). \tag{2.4.15}$$

Soliton simulations shown from Figures 2.2 through 2.5 were performed on silica fiber, the traditional media candidate for soliton propagation, as originally proposed by Hasegawa [11], [12]. Simulation results to explore soliton propagation on amorphous aluminum nitride are shown from Figures 2.6 through 2.9. Dispersion analysis of aluminum nitride, described in Chapter 3, predicted solitons to exist in this material.

It is evident from the soliton simulations on both silica fiber and amorphous aluminum nitride, shown in Figures 2.2 through Figure 2.9, that the soliton pulse length shortens as optical power is increased and the soliton amplitude increased when optical power is higher.

Optical powers of $P = 100$ mw and $P = 1$ Watt, generate solitons with dimensions are a fraction of a centimeter. Approximately 2-4 millimeter in length, which suggest the possibility to study their propagation in optical waveguides whose dimensions must be within such order of magnitude. Kerr coefficient of AlN is assumed to be the same as that of silica.
Figure 2.2: Silica Fiber Soliton, Electric Field, $P = 100 \text{ mW}$

Figure 2.3: Silica Fiber Soliton, Envelope, $P = 100 \text{ mW}$
Figure 2.4: Silica Fiber Soliton, Electric Field, $P = 1 \text{ W}$

Figure 2.5: Silica Fiber Soliton, Envelope, $P = 1 \text{ W}$
Figure 2.6: Amorphous AlN Soliton, Electric Field, $P = 100 \text{ mW}$

Figure 2.7: Amorphous AlN Soliton, Envelope, $P = 100 \text{ mW}$
Figure 2.8: Amorphous AlN Soliton, Electric Field, $P = 1 \text{ W}$

Figure 2.9: Amorphous AlN Soliton, Envelope, $P = 1 \text{ W}$
Chapter 3

Design and Modeling of AlN Optical Waveguides

3.1 Method of Normal Modes

The wave equation is a solution of the Maxwell’s equation as long as both \( \varepsilon \) and \( \mu \) are considered constant; i.e. \( \nabla \varepsilon = 0 \). Modes can be defined as the Eigen-solutions of Maxwell’s equation belonging to a particular eigenvalue and satisfying all the boundary conditions of the problem. They can be expressed with the following definition of plane waves:

\[
\vec{E} = \hat{r} A \exp[i(\omega t - \vec{k} \cdot \vec{r})] \quad (3.1.1)
\]

\[
\vec{H} = \hat{s} B \exp[i(\omega t - \vec{k} \cdot \vec{r})] \quad (3.1.2)
\]

where \( A \) and \( B \) are scalar amplitudes and \( \hat{r} \) and \( \hat{s} \) are unit vectors that represent any vector along \( \hat{x}, \hat{y}, \hat{z} \) direction. Substituting equations 3.1.1 and 3.1.2 into wave equations for \( \vec{E} \) and \( \vec{H} \) respectively we arrive to the following equation system:

\[
-i(\vec{k} \times \hat{s})B = i\omega \varepsilon A \hat{r} \quad (3.1.3)
\]

\[
-i(\vec{k} \times \hat{r})A = -i\omega \mu B \hat{s}. \quad (3.1.4)
\]
These last two equations are satisfied if and only if these relations exist:

\[ \hat{n} \cdot \hat{r} = 0 \quad (3.1.5) \]

\[ \hat{n} \times \hat{r} = \hat{s} \quad (3.1.6) \]

\[ B = \sqrt{\frac{\varepsilon}{\mu}} A. \quad (3.1.7) \]

Equation 3.1.5 indicates that these are transverse plane waves. The proposed wave equations e.g. 3.1.1 and 3.1.2 are solutions of the Maxwell’s equation; only if \( \varepsilon \) has no spatial dependance along \( z \).

For certain specific applications, such as optical waveguides, device symmetry can be conveniently exploited; a coordinate origin can be chosen in such a way that the \( \varepsilon \) has no dependance on \( z \) variation. It is not uncommon to find that to be true. Equations 3.1.1 and 3.1.2 can be written as follows,

\[ \vec{E} = \vec{E}_0(x, y) \exp[i(\omega t - \beta z)] \quad (3.1.8) \]

\[ \vec{H} = \vec{H}_0(x, y) \exp[i(\omega t - \beta z)] \quad (3.1.9) \]

The propagation constant \( \beta \) is the eigen-value as discussed above. By substituting these two wave equations into the two rotational Maxwell’s equations, e.g.

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (3.1.10) \]

\[ \nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} \quad (3.1.11) \]

which leads to the following equation system
\[ i \omega \varepsilon E_x = i \beta H_y + \frac{\partial H_z}{\partial y} \quad (3.1.12) \]

\[ i \omega \varepsilon E_y = -i \beta H_x + \frac{\partial H_z}{\partial x} \quad (3.1.13) \]

\[ i \omega \varepsilon E_z = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \quad (3.1.14) \]

\[ -i \omega \mu H_x = i \beta E_y + \frac{\partial E_z}{\partial y} \quad (3.1.15) \]

\[ i \omega \mu H_y = i \beta E_x + \frac{\partial E_z}{\partial x} \quad (3.1.16) \]

\[ -i \omega \mu H_z = \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} \quad (3.1.17) \]

since propagation is along \( z \) axis, we can arrange these equations to express the transverse field components in terms of \( E_z \) and \( H_z \)

\[ E_x = -\frac{i}{\kappa^2} \left( \beta \frac{\partial E_z}{\partial x} + \omega \mu \frac{\partial H_z}{\partial y} \right) \quad (3.1.18) \]

\[ E_y = -\frac{i}{\kappa^2} \left( \beta \frac{\partial E_z}{\partial y} - \omega \mu \frac{\partial H_z}{\partial x} \right) \quad (3.1.19) \]

\[ H_x = -\frac{i}{\kappa^2} \left( \beta \frac{\partial H_z}{\partial y} - \omega \varepsilon \frac{\partial E_z}{\partial x} \right) \quad (3.1.20) \]

\[ H_y = -\frac{i}{\kappa^2} \left( \beta \frac{\partial H_z}{\partial x} + \omega \varepsilon \frac{\partial E_z}{\partial y} \right) \quad (3.1.21) \]

\[ k = \omega^2 \mu \varepsilon \quad (3.1.22) \]

\[ \kappa^2 = k^2 - \beta^2 \quad (3.1.23) \]

Notice the difference between \( k \) and \( \kappa \) (kappa) now defined in equation 3.1.23
A wave equation in terms of $z$ component for $E$ or $H$ field can be found by substituting equations, which leads to the following result:

$$\frac{\partial^2 E_z}{\partial x^2} + \frac{\partial^2 E_z}{\partial y^2} + (k^2 - \beta^2)E_z = 0 \quad (3.1.24)$$

$$\frac{\partial^2 H_z}{\partial x^2} + \frac{\partial^2 H_z}{\partial y^2} + (k^2 - \beta^2)H_z = 0 \quad (3.1.25)$$

Equations 3.1.24 and 3.1.25 are exact solutions of the Maxwell’s equations only if $\varepsilon$ is constant. They are, however, good approximations, if the relative variation of $\varepsilon$ is much less than unity over the region of one wavelength. It is only safe to assume that these approximations are very good for optical electromagnetic fields with their extreme short wavelengths; this simplify the calculations considerably.

It is evident now that the longitudinal components of $\vec{E}$ and $\vec{H}$ are uncoupled. There is no restriction in choosing the the coordinates as long as they satisfy equations 3.1.24 and 3.1.25. Mode solutions can be obtained with either $E_z = 0$ or $H_z = 0$, they are called transverse electric (TE modes) and transverse magnetic (TM modes) respectively.

### 3.2 Slab Waveguides

Complex mathematical analysis of guided modes in cylindrical optical fiber, has been extensively discussed in the existing literature [95], [96]; efforts in discussing such analysis will not be endeavored here, reader can refer to [97], [98].

Light transmission in an optical structure such as a slab waveguide is a relatively simple optical structure to analyze, its radiation and mode conversion properties will
be discussed.

The slab waveguide structure as it can be seen in figure 3.1, consists of 3 layers:

1. Substrate: SiO$_2$ or glass $n_s = 1.45$

2. Film: Aluminum nitride $n_f = 2.1$

3. Upper layer (air) $n_c = 1.0$

Figure 3.1: Slab Waveguide; refractive index $n_f > n_s > n_c$

Analysis can be simplified by assuming there is no variation of the field distribution
in \( y \) direction.

\[
\frac{\partial}{\partial y} = 0 \quad (3.2.1)
\]

This restriction allows us to decompose the field of the slab waveguide into TE and TM modes. Using equation 3.2.1 and by defining \( E_z = 0 \) on the following equations:

\[
E_x = -\frac{i}{\kappa^2} \left( \beta \frac{\partial E_z}{\partial x} + \omega \mu \frac{\partial H_z}{\partial y} \right) \quad (3.2.2)
\]

\[
E_y = -\frac{i}{\kappa^2} \left( \beta \frac{\partial E_z}{\partial y} - \omega \mu \frac{\partial H_z}{\partial x} \right) \quad (3.2.3)
\]

\[
H_x = -\frac{i}{\kappa^2} \left( \beta \frac{\partial H_z}{\partial x} - \omega \varepsilon \frac{\partial E_z}{\partial y} \right) \quad (3.2.4)
\]

\[
H_y = -\frac{i}{\kappa^2} \left( \beta \frac{\partial H_z}{\partial y} + \omega \varepsilon \frac{\partial E_z}{\partial x} \right) \quad (3.2.5)
\]

the following components of the field are nonzero: \( H_z, H_x \) and \( E_y \) they become

\[
E_x = 0 \quad (3.2.6)
\]

\[
E_y = \frac{i}{\kappa^2} \left( \omega \mu \frac{\partial H_z}{\partial x} \right) \quad (3.2.7)
\]

\[
H_x = -\frac{i}{\kappa^2} \left( \beta \frac{\partial H_z}{\partial x} \right) \quad (3.2.8)
\]

\[
H_y = 0 \quad (3.2.9)
\]

now, using these equations and applying the above conditions i.e. \( E_z = 0 \) and equation 3.2.1.
\[-i\omega\mu H_x = i\beta E_y + \frac{\partial E_z}{\partial y}\]  \hspace{1cm} (3.2.10)

\[i\omega\mu H_y = i\beta E_x + \frac{\partial E_z}{\partial x}\]  \hspace{1cm} (3.2.11)

\[-i\omega\mu H_z = \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y}\]  \hspace{1cm} (3.2.12)

It renders the following results

\[-i\omega\mu H_x = i\beta E_y\]  \hspace{1cm} (3.2.13)

\[i\omega\mu H_y = i\beta E_x\]  \hspace{1cm} (3.2.14)

\[-i\omega\mu H_z = \frac{\partial E_y}{\partial x}\]  \hspace{1cm} (3.2.15)

and

\[H_x = -\frac{i}{\omega \mu} \frac{\partial E_y}{\partial y}\]  \hspace{1cm} (3.2.16)

\[H_z = -\frac{i}{\omega \mu} \frac{\partial E_y}{\partial x}\]  \hspace{1cm} (3.2.17)

The component \(E_y\) as a solution of the reduced wave equation, is similar to the equation obtained before, as follows:

\[\frac{\partial^2 E_y}{\partial x^2} + (k^2 - \beta^2) E_y = 0\]  \hspace{1cm} (3.2.18)

\[\frac{\partial^2 E_y}{\partial x^2} + (n^2 k_0^2 - \beta^2) E_y = 0.\]  \hspace{1cm} (3.2.19)
3.2.1 Even TE Modes

Solutions of equations 3.2.18 or 3.2.19 are modes that exist in the core of the symmetrical slab waveguide, for $|x| < d$, there is an equation where the subindex $e$ stands for even modes:

$$E_y = A_e \cos \kappa x$$  \hspace{1cm} (3.2.20)

and
\[ H_z = -\frac{i\kappa}{\omega \mu} A_e \sin \kappa x. \] (3.2.21)

As defined previously

\[ \kappa^2 = n_1^2 k_0^2 - \beta^2. \] (3.2.22)

For \(|x| > d\) i.e. the field outside the core slab:

\[ E_y = A_e \cos \kappa d e^{-\gamma(|x|-d)} \] (3.2.23)

and

\[ H_z = -\frac{i \kappa y}{|x| \omega \mu} A_e \cos \kappa d e^{-\gamma(|x|-d)} \] (3.2.24)

where

\[ \gamma^2 = \beta^2 - n_2^2 k_0^2 \] (3.2.25)

for positive values of \(\gamma^2\), the field on the outside of the slab is decaying with increasing values of \(|x|\). The condition for a guided mode is thus

\[ \gamma^2 > 0. \] (3.2.26)

From the boundary condition at the interface \(x = \pm d\) of the slab waveguide with the field component \(H_z\)
\[ H_z = -\frac{i\kappa}{\omega\mu} A_e \sin \kappa x = -\frac{ixy}{|x|\omega\mu} A_e \cos \kappa d e^{-\gamma(|x|-d)} \quad (3.2.27) \]

\[ H_z = -\frac{i\kappa}{\omega\mu} A_e \sin \kappa d = -\frac{id\gamma}{|d|\omega\mu} A_e \cos \kappa d e^{-\gamma(|d|-d)} \quad (3.2.28) \]

\[ H_z = -\frac{i\kappa}{\omega\mu} A_e \sin \kappa x = -\frac{ixy}{|x|\omega\mu} A_e \cos \kappa d \quad (3.2.29) \]

\[ H_z = \kappa A_e \sin \kappa x = \gamma A_e \cos \kappa d. \quad (3.2.30) \]

Thus the eigenvalue equation is obtained

\[ \tan \kappa d = \frac{\gamma}{\kappa}. \quad (3.2.31) \]

The power carried by the mode can be expressed as follows:

\[ P = -\frac{1}{2} \int_{-\infty}^{\infty} (\vec{E} \times \vec{H}^*)_x dx = -\frac{1}{2} \int_{-\infty}^{\infty} E_y \times H^*_x dx \]

\[ = -\frac{\beta}{\omega\mu} \int_{0}^{\infty} |E_y|^2 dx \quad (3.2.32) \]

\[ A_e = \left( \frac{2\omega\mu}{\beta d + \frac{\beta}{\gamma} P} \right)^{1/2} \quad (3.2.33) \]

3.2.2 Odd TE Modes

The field inside the slab for \(|x| < d\) can be expressed with a subindex \(o\) to denote odd modes, as such:

\[ E_y = A_o \sin \kappa x \quad (3.2.35) \]
and

\[ H_z = \frac{i\kappa}{\omega \mu} A_o \cos \kappa x. \]  

The field outside the slab at \( |x| > d \) is given by

\[ E_y = \frac{x}{|x|} A_o \sin \kappa d e^{-\gamma(|x| - d)} \]  

and

\[ H_z = -\frac{i\gamma}{\omega \mu} A_o \sin \kappa d e^{-\gamma(|x| - d)} \]  

the boundary conditions for the field \( H_z \) must be continuous at the dielectric interface, which leads to the eigenvalue equation

\[ \tan \kappa d = -\frac{\kappa}{\gamma} \]  

in an analogous fashion as proceeded before, the amplitude coefficient is expressed in terms of the power flow as done in equations 3.2.32 and 3.2.33 and that leads to this result:

\[ A_o = \left( \frac{2\omega \mu}{\frac{\beta}{\gamma} + \beta d P} \right)^{1/2} \]  

this equation is a solution of the eigenvalue equation \( \tan(\kappa d) \)

### 3.2.3 Eigenvalues of TE Modes

The eigenvalue equations for the even and odd TE modes of the slab waveguide can be plotted by using
\[ \tan \kappa d = \frac{-\kappa}{\gamma} = \frac{\gamma}{\kappa} \]  
(3.2.41)

Solutions are obtained at the intersections between the curves. It is immediately apparent that, for a given frequency or film thickness there is a number of finite number of guided mode solutions. The following equation is found

\[ \frac{\gamma}{\kappa} = \sqrt{\left(\frac{n_1^2 - n_2^2}{n_1^2 - n_2^2}\right)k_0^2 - \kappa^2} \]  
(3.2.42)

The lowest order of even TE modes can propagate at arbitrarily small frequencies. It is the only mode that is never cut off as \( \kappa d \) is tends to zero. The cutoff condition for the even TE modes is obtained when \( \frac{\gamma}{\kappa} \) intersects the axis \( \kappa d \) i.e. The zero crossing of \( \tan \kappa d \).

\[ \kappa_c d = \nu \pi = k_0 d \sqrt{(n_1^2 - n_2^2)} \]  
(3.2.43)

At cutoff \( \beta = n_2k_0 \) and \( \gamma = 0 \)

\[ \frac{\beta_c}{\kappa_c} = \frac{n_2}{\sqrt{n_1^2 - n_2^2}} \]  
(3.2.44)

### 3.3 Asymmetrical Slab Waveguide

The mathematical derivation pertinent to the symmetrical waveguide renders equations and results also applicable to the asymmetrical waveguide case.

#### 3.3.1 TE Modes

The discussion above covered material that led to the equations 3.2.18 and 3.2.19 as follows:
Thin film thickness is $d$

Figure 3.3: Slab Waveguide; refractive index $n_l > n_s > n_c$

$$\frac{\partial^2 E_y}{\partial x^2} + (k^2 - \beta^2) E_y = 0 \quad (3.2.18)$$

$$\frac{\partial^2 E_y}{\partial x^2} + (n^2 k_0^2 - \beta^2) E_y = 0 \quad (3.2.19)$$
where

\[ k^2 = \omega^2 \mu \varepsilon_0 \varepsilon_r = k_0^2 \varepsilon_r \]  \hspace{1cm} (3.3.1)

\[ k = \omega \sqrt{\mu \varepsilon_0 \varepsilon_r} = k_0 \sqrt{\varepsilon_r} = k_0 n \]  \hspace{1cm} (3.3.2)

\[ k_0 = \omega \sqrt{\mu \varepsilon_0} = \frac{\omega}{c} = \frac{2\pi}{\lambda_0}. \]  \hspace{1cm} (3.3.3)

The TE modes of the asymmetrical waveguide as shown in Figure 3.3 are found by solving equations 3.2.19, 3.3.4, and 3.3.5.

\[ H_x = -i \frac{\omega \mu}{\omega} \frac{\partial E_y}{\partial y} \]  \hspace{1cm} (3.3.4)

\[ H_z = -i \frac{\omega \mu}{\omega} \frac{\partial E_y}{\partial x} \]  \hspace{1cm} (3.3.5)

solutions must satisfy the boundary conditions at the dielectric interfaces where the tangential components of the fields \( E \) and \( H \) must be continuous precisely, as shown in Figure 3.3, where the refractive indexes change from the thin film to the substrate at \( x = 0 \) and from the thin film to the layer on top at \( x = d \).

\[ E_y = (A \cos \kappa x + B \sin \kappa x)e^{\gamma(d-x)} \quad x \geq d \]  \hspace{1cm} (3.3.6)

\[ = A \cos \kappa x + B \sin \kappa x, \quad 0 \leq x \leq d \]  \hspace{1cm} (3.3.7)

\[ = Ae^{\delta x} \quad x \leq 0 \]  \hspace{1cm} (3.3.8)

It can be readily seen that the solutions vanish at \( x = \pm \infty \). and,
\[\kappa = (n_1^2 k^2 - \beta^2)^{1/2} = n_1 k \sin \theta_1 \]  
(3.3.9)

\[\gamma = (\beta^2 - n_2^2 k^2)^{1/2} = [(n_1^2 - n_2^2)k^2 - \kappa^2]^{1/2} \]  
(3.3.10)

\[\delta = (\beta^2 - n_3^2 k^2)^{1/2} = [(n_1^2 - n_3^2)k^2 - \kappa^2]^{1/2} \]  
(3.3.11)

From equation 2.6.4 the magnetic field can be also be found

\[H_z = \frac{iy}{\omega \mu_0} (A \cos \kappa x + B \sin \kappa x) e^{\gamma(d-x)} \quad x \geq d \]  
(3.3.12)

\[= \frac{i\kappa}{\omega \mu_0} (A \sin \kappa x - B \cos \kappa x), \quad 0 \leq x \leq d \]  
(3.3.13)

\[= \frac{i\delta}{\omega \mu_0} A e^{\delta x} \quad x \leq 0 \]  
(3.3.14)

\(H_z\) must be continuous at \(x = 0\) and \(x = d\), which leads to

\[0 = \delta A + \kappa B \]  
(3.3.15)

\[0 = (\kappa \sin \kappa d - \gamma \cos \kappa d)A + (\kappa \cos \kappa d + \gamma \sin \kappa d) \]  
(3.3.16)

The eigenvalue equation is determined by making the determinant equal to zero.

\[0 = \delta(\kappa \cos \kappa d + \gamma \sin \kappa d) - \kappa(\kappa \sin \kappa d - \gamma \cos \kappa d). \]  
(3.3.17)

Finally the eigenvalue equation is obtained

\[\tan \kappa d = \frac{\kappa(y + \delta)}{\kappa^2 - y\delta} \]  
(3.3.18)
or

\[
\tan \kappa d = \frac{\kappa (\gamma + \delta)}{\kappa^2 - \gamma \delta} = \frac{\kappa \delta (\gamma d + \delta d)}{(\kappa d)^2 - (\gamma d)(\delta d)}
\]

\[
\tan \kappa d = \frac{\kappa d [\sqrt{(n_1^2 - n_2^2)(kd)^2 - (\kappa d)^2} + \sqrt{(n_1^2 - n_2^2)(kd)^2 - (\kappa d)^2}] + \sqrt{(n_1^2 - n_2^2)(kd)^2 - (\kappa d)^2}[\sqrt{(n_1^2 - n_2^2)(kd)^2 - (\kappa d)^2}] (\kappa d)^2 - \sqrt{(n_1^2 - n_2^2)(kd)^2 - (\kappa d)^2} (\kappa d)^2 - (\kappa d)^2}
\]

the function above has a pole at

\[
V = \kappa d = kd \sqrt{n_1^2 - n_2^2} \tag{3.3.19}
\]

the cutoff condition

\[
V_c = \tan^{-1} \left( \frac{\sqrt{n_s^2 - n_r^2}}{\sqrt{n_i^2 - n_s^2}} \right) + l\pi \tag{3.3.20}
\]

\(l\) is an integer number

### 3.4 Effective Index Method

Planar waveguides confine light in one dimension \(x\) of the \(x - y\) plane. Structures that can confine light in two dimensions, such as ridge and strip waveguides do not have an exact mathematical solution to describe them, numerical analysis is the used approach.

The effective index method is a rather simple way to analyze these types of waveguides. It uses the normalized frequency.
Figure 3.4: Aluminum Nitride Effective Index

\[ V_h = k h \sqrt{n_f^2 - n_s^2} \]  \hspace{1cm} (3.4.1)

\[ V_l = k f \sqrt{n_f^2 - n_s^2} \]  \hspace{1cm} (3.4.2)
A ridge waveguide structure, as seen in Figure 3.4 (front view) shows the pertinent variables used in these equations. The uppercase letters represent the effective refractive index associated as displayed on Figure 3.4 (upper view)

\[ N_h^2 = n_s^2 + b_h(n_i^2 - n_s^2) \]  \hspace{1cm} (3.4.3)

\[ N_i^2 = n_s^2 + b_h(n_i^2 - n_s^2) \]  \hspace{1cm} (3.4.4)
A normalized $\omega - \beta$ relation as reported by Kogelnik and Ramaswamy [99] is displayed in Figure 3.5. Normalized frequency for each respective region, is determined by equations 3.4.1 and 3.4.2.

Waveguide asymmetry is defined by this:

$$a = \frac{n_s^2 - n_e^2}{n_f^2 - n_s^2} \quad (3.4.5)$$

Effective index method is applied to a waveguide structure as displayed in Figure 3.4 under conditions specified below; $b_f$ and $b_b$ are normalized guide index $b$, related to the effective index and determined from the eigenvalue equation; results are summarized in the following table.
Table 3.1: Effective Index (N) on ridge waveguide

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<th>$\lambda(\mu m)$</th>
<th>$V_h$</th>
<th>$b_h, b_f$</th>
<th>$N_h$</th>
<th>$N_f$</th>
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</tbody>
</table>

- $n_s = 1.55$
- $n_f = 2.1$
- $n_c = 1.0$
- $f = 50$ nanometer
- $h = 300$ nanometer
- $w = 1$ micrometer

Normalized frequencies for the strip (h) a thin film (f) regions are listed on Table 3.1 as their dependance on wavelength for the asymmetric waveguide. $N_f$ and $N_h$ are
their respective effective indexes.

The bottom of Figure 3.4 shows the artifact of a symmetrical waveguide. A new normalized frequency associated with the ridge width is:

\[ V_y = kw\sqrt{N_{h}^2 - N_{f}^2} \] (3.4.6)

and

\[ N^2 = N_f^2 + b(N_h^2 - N_f^2) \] (3.4.7)

The effective index \( N \) is 1.9286 at \( \lambda = 1.55 \mu m \), for the conditions above stated and a width of \( w = 1 \mu m \)

![Figure 3.6: Aluminum Nitride Effective Index](image-url)
3.5 Sellmeier Equation

Refractive index as a function of wavelength is expressed by the Sellmeier equation, from which material dispersion can be determined.

\[ n^2 = a_0 + \frac{a\lambda^2}{\lambda^2 - A} + \frac{b\lambda^2}{\lambda^2 - B} \]  

(3.5.1)

\[ \frac{d}{d\lambda}[n^2] = 2n\frac{dn}{d\lambda} \]  

(3.5.2)

\[ n\frac{dn}{d\lambda} = -\lambda(\frac{aA}{(\lambda^2 - A)^2} + \frac{bB}{(\lambda^2 - B)^2}). \]  

(3.5.3)

To determine the second derivative of the refractive index of 3.5.1

\[ \frac{d}{d\lambda}[n\frac{dn}{d\lambda}] = \frac{dn}{d\lambda}\frac{dn}{d\lambda} + n\frac{d^2n}{d\lambda^2} = (\frac{dn}{d\lambda})^2 + n\frac{d^2n}{d\lambda}. \]  

(3.5.4)

The first term on the right hand side of 3.5.4 is already known from 3.5.3, the second term has to be determined.

\[ \frac{d}{d\lambda}[n\frac{dn}{d\lambda}] = \frac{d}{d\lambda}[-\lambda(\frac{aA}{(\lambda^2 - A)^2} + \frac{bB}{(\lambda^2 - B)^2})]. \]  

(3.5.5)

The right hand side of 3.5.5 becomes.

\[ = 4\lambda^2 \left[ \frac{aA}{(\lambda^2 - A)^3} + \frac{bB}{(\lambda^2 - B)^3} \right] - \frac{aA}{(\lambda^2 - A)^2} - \frac{bB}{(\lambda^2 - B)^2} \]  

(3.5.6)
or

\[
\frac{d^2 n}{d\lambda^2} = \frac{aA}{(\lambda^2 - A)^2} \left[ \frac{4\lambda^2}{\lambda^2 - A} - 1 \right] + \frac{bB}{(\lambda^2 - B)^2} \left[ \frac{4\lambda^2}{\lambda^2 - B} - 1 \right] - \left( \frac{dn}{d\lambda} \right)^2
\]  

(3.5.8)

equation 2.4.6 will be used in the next section, to determine the material dispersion of the AlN.

### 3.6 Aluminum Nitride Dispersion

The coefficients of the Sellmeier equation specific for crystalline Aluminum Nitride, are available in the *Handbook of Optical Materials*, edited by Marvin Weber, University of California, Berkeley [100]. Single crystal Aluminum Nitride is birefringent, therefore two equations arise:

for the ordinary axis

\[
n_o^2 = 3.1399 + \frac{1.3786\lambda^2}{\lambda^2 - (0.1715)^2} + \frac{3.861\lambda^2}{\lambda^2 - (15.03)^2}
\]  

(3.6.1)

and for the extraordinary axis.

\[
n_e^2 = 3.0729 + \frac{1.6173\lambda^2}{\lambda^2 - (0.1746)^2} + \frac{4.139\lambda^2}{\lambda^2 - (15.03)^2}
\]  

(3.6.2)
The refractive index behaviour as a function of wavelength of *amorphous aluminum nitride*, sputtered deposited by our research group, is described by the Sellmeier equation. The Electrical Engineering Department does not possess the required equipment to generate the Sellmeier coefficients; samples of our research material were submitted for analysis, to the Materials Engineering group at Brown University via the Nano World Laboratories at the Materials Engineering Department, University of Cincinnati. The Sellmeier coefficients courtesy of Brown University, is expressed by the following equation:

\[
\frac{n_{\text{Amorphous}}^2}{\lambda} = 2.834 + \frac{1.1985\lambda^2}{\lambda^2 - (0.169)^2} + \frac{4.2\lambda^2}{\lambda^2 - (15.21)^2}
\]  

(3.6.3)
The dispersion of aluminum nitride (AlN) with that of a well studied material such as fused silica (SiO₂), in order to establish a reference point of comparison, can be determined by equations 2.4.6, 3.5.8, 3.6.3 and 3.6.2. The Sellmeier coefficients of pure and germanium doped SiO₂ are included, they are available from Specialty Optical Fibers Handbook p. 39 [101], and Handbook of Optics vol IV [102], as follows:

\[
    n^2 = 1 + \frac{0.663044\lambda^2}{\lambda^2 - (0.06)^2} + \frac{0.517852\lambda^2}{\lambda^2 - (0.106)^2} + \frac{0.17592\lambda^2}{\lambda^2 - (0.119)^2}
\]  

(3.6.4)

Figure 3.8: SiO₂ & AlN Dispersion
Figure 3.8 shows the well known SiO$_2$ zero dispersion point at 1.3 $\mu$m. Crystalline aluminum nitride has a dispersion crossover point at 1.6 $\mu$m for the ordinary and about 1.65$\mu$m for the extraordinary axis, in the neighborhood of minimum attenuation for optical fiber at 1.55 $\mu$m, 0.18 dB/km attenuation reported for fused silica [103]. Nagayama reported ultra-low-loss of 0.1484 dB/km on pure silica core fiber [104].

![Image of AlN Dispersion](image.png)

Figure 3.9: AlN Dispersion

Amorphous aluminum nitride shows a zero crossover point at $\lambda = 1.52$ $\mu$m, where the dispersion value is $7.9 \times 10^{-26}$ (zero), which allows solitons to exist at the minimum attenuation wavelength, $\lambda = 1.55$ $\mu$m. The units of dispersion are ps nm$^{-1}$ km$^{-1}$ [60].

Soda lime glass is the material used on various substrates, the corresponding Sellmeier equation is the following:
\[ n = 1.513 - 0.003169\lambda^2 + 0.003962\lambda^{-2} \]  

(3.6.5)

3.6.1 Effective Index Dispersion

![Effective Index Dispersion](image)

Figure 3.10: Effective Index AlN Dispersion
Dispersion of AlN taking into account the waveguide Effective Index allows dispersion to be positive hence the existence of solitons is allowed, as describe in previous chapter.

### 3.7 Photodetector Responsivity

Optical radiation can be detected with both external and internal photoemission devices [105]. Photomultipliers and vacuum photodiodes belong to the class of external photoemission devices but they are large in size and require high voltages to operate. High speed devices have long been the subject of interest of many researchers [106]. Semiconductor photodiodes belong to the class of internal photoemission devices and have good performance and operate with or without inherent gain [107], [108].

Responsivity is defined as the output photocurrent in amperes due to the incident optical power in watts [109], and it is equal to:

\[
R(A/W) = \frac{\eta e \lambda}{hc} = \frac{I_{ph}}{P_{in}}
\]

(3.7.1)

where quantum efficiency, \( \eta \) is a ratio of the number of electrons collected be the number of incident photons, namely:

\[
\eta = \frac{r_e}{r_p}
\]

(3.7.2)

Very high values of quantum efficiencies have been reported by [110] on solar cells and by [111]. Stability of quantum efficiency was addressed by Korde [112].
3.8 Photodiodes

Semiconductor photodiodes belong to the class of internal photoemission have a good performance and operate with or without gain. Silicon photodiodes have a responsivity $400 \text{ nm} \leq \lambda \leq 1100 \text{ nm}$ whereas germanium photodiodes that seem to be the technology of choice for detection in the near infrared optical domain have a responsivity $800 \text{ nm} \leq \lambda \leq 1800 \text{ nm}$. [113], [114]. As early as 1975 [115] the range was extended from $600 \text{ nm} \leq \lambda \leq 1850 \text{ nm}$.

![FDS1010 Responsivity*](image)

*Data from 104 sensors

Figure 3.11: Silicon Photo Diode

In the internal photo emission process, incident photons with energies larger than the semiconductor band-gap excite electrons from the valence band to the conduction band, which creates a photo current. Intrinsic presents a more efficient photon
absorption and faster response than extrinsic and it is therefore preferred, [116]. Responsivity is an inherent property to the material the photo diode is built, Figures 5.22 and 5.23 represent very standard function of responsivity vs. wavelength of Silicon and Germanium Photodiodes, built by Thorlabs Inc.


3.9 Attenuation Measurements

Light intensity measurements were taken at multiples points of a planar waveguide, one millimeter apart, which allowed for at least 12 to 15 data points with the same photodiode, so that $R$ can be eliminated.
\[ R = \frac{l_{ph1}}{P_{in1}} = \frac{l_{ph2}}{P_{in2}} \]  
(3.9.1)

\[ P_{in1} = \frac{l_{ph1}}{R}, P_{in2} = \frac{l_{ph2}}{R} \]  
(3.9.2)

\[ \frac{P_{in2}}{P_{in1}} = \frac{l_{ph2}}{l_{ph1}} \]  
(3.9.3)

Applying 10 base logarithm to both sides to the last equation, leads into the well known, definition of decibels:

\[ 10 \log_{10} \left( \frac{P_{in2}}{P_{in1}} \right) = 10 \log_{10} \left( \frac{l_{ph2}}{l_{ph1}} \right) \]  
(3.9.4)

\[ dB = 10 \log_{10} \left( \frac{l_{ph2}}{l_{ph1}} \right) \]  
(3.9.5)

\[ dB = 10 \log_{10} \left( \frac{V_2}{V_1} \right) \]  
(3.9.6)

\[ Loss(dB) = 10 \log_{10} \left( \frac{V_2}{V_1} \right) \]  
(3.9.7)

These results clearly indicate that optical power measurements had to be taken alongside the waveguide to determine the waveguide optical losses. A rutile prism coupled with a photodiode was mounted on the waveguide for such purpose. More details related to these measurements will be discussed on Chapter 5 that deals with characterization methods.
Chapter 4

Fabrication Methods of Novel Optical Waveguides and Material Properties for Optimal Performance

4.1 Introduction

This chapter describes the various methods used in the fabrication of the AlN waveguides, the steps followed in the fabrication processing that eventually lead to the final device. Some processes already existed in the Standard Operating Procedures of the GaAs Devices & ICs laboratory and some had to be developed during the research process. Thin films of Aluminum Nitride were deposited on silicon and glass substrates. Physical properties of Aluminum Nitride had been studied by our research group in the past, S. Mahmood [54], so it became apparent as an interesting material of choice to be used as a core in the waveguide.

4.2 Substrate Cleaning

RCA Washing

Thorough cleaning of a substrate is essential to maximize device quality. The substrates samples were treated in different ways depending on the intended purpose.
The substrates used in this work were silicon wafers and microscope slides, and both were prepared in the following way.

This method removes foreign matter such as organic material, and metal cations before the processes are performed. The steps are given in Appendix/Procedure I.

4.2.1 Silicon Wafers

Aluminum nitride films were deposited on Silicon, in order to test the electrical quality of the deposited material. Silicon is conductive and can be used as a ground plane in capacitance and voltage measurements. Preparation of silicon substrates involved:

- Cleaving round wafers into quadrants using wafers oriented in (100) direction or by cutting into approximately 1 x 1 inch squares
- repeat steps 1 to 9 given in Procedure 1

4.2.2 Glass substrates

Polished beveled microscope slides were chosen as substrates for deposition of Aluminum Nitride films. Their chemical composition is that of soda lime glass as reported in a paper published by North et. al. [117]. A typical composition is presented in the Table 3.1 alongside the data published by Menzel a german manufacturer of microscopes slides. Both data sets are included in table 4.1 to show the types of variants available.

Two diamond saws are available at the GaAs Devices & ICs Laboratory for cutting glass and quartz. In one of the saws the glass sample is held manually against a
rubber surface by the operator. No clamping or bonding is necessary during cutting is in progress. This renders the process contamination free and the material can be immediately RCA cleaned before deposition, which is sufficient to attain a clean substrate.

The other diamond saw has an x-y stage for preparing special substrate shapes. Unfortunately it requires the use of Apiezon wax, to hold the wafer fixed against a holding surface. This contaminates the sample and makes the washing process more involved. A wax removal method based on xylene, methanol and acetone was necessary before the RCA cleaning was used.

### 4.2.3 Cutting of glass substrates

Microscope slides of 1 x 3 inch size were cut into two smaller pieces of 1 inch x 1 inch squares on the diamond saw without using Apiezon wax in order to simplify the washing process. The cutting required extreme care and the speed of cutting was kept low to minimize roughness of the surface edges.
Figure 4.1: Plasma in Sputtering Chamber
Best results were obtained when all this process was done slowly and carefully. Only two rotational speeds were available, so only the low speed was used. At the high speed the cut surface edges were rougher.

4.2.4 Polishing of glass substrates

After cutting, the surface edges were improved by polishing in two stages:

- Polishing machine: the first stage consisted of polishing the glass cut edges on a polishing machine equipped with a rotating disk carrying a silicon carbide abrasive paper. The angular speed was adjustable from 0 to 2000 revolutions per minute (RPM). The abrasive paper was cut into circular shapes of 9 inches diameter, then laid on the polishing disk. The polishing was done at about 100 RPM, for best results. Different grit sizes were available for the first stage of the process. The rough edges were polished from coarse to a fine in a sequential order as listed in Table 4.2.

- Aluminum oxide: in the second stage of the process the glass edges were polished, manually with aluminum oxide (Al$_2$O$_3$) powders. The substrate edge was placed up against the flat surface of a glass slab and rubbed with the Al$_2$O$_3$/water abrasive paste. Best results were obtained when the sample was rubbed in a planetary motion.
<table>
<thead>
<tr>
<th>Sandpaper</th>
<th>Standard Grit</th>
<th>size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>step 1</td>
<td>600</td>
<td>18</td>
</tr>
<tr>
<td>step 2</td>
<td>1200</td>
<td>12</td>
</tr>
<tr>
<td>step 3</td>
<td>3000</td>
<td>4</td>
</tr>
<tr>
<td>Aluminum oxide</td>
<td></td>
<td></td>
</tr>
<tr>
<td>step 4</td>
<td>8000</td>
<td>1</td>
</tr>
<tr>
<td>step 5</td>
<td>25000</td>
<td>0.1</td>
</tr>
<tr>
<td>step 7</td>
<td>50000</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 4.2: Abrasives Grit Sizes

4.3 Reactive Magnetron Sputtering Deposition

The Aluminum Nitride films were deposited on substrates of silicon and glass was achieved my means of a Plasma Enhanced Reactive Sputtering System or Magnetron Sputtering System, that required multiple pumps, RF Generator, high purity Nitrogen tank and various meters to keep the system under adequate conditions of operation. This system or piece of equipment is of uttermost importance, for this research work, thus the reason why extensive work was devoted to guarantee that it operates optimally. Details are shown in Figure 4.2

A two-stage pumping system was used: a roughing pump for low vacuum, that can pump down to 1 to 5 mTorr and a diffusion pump for ultra high vacuum that can achieve pressure of $1\times10^{-7}$ Torr, which purpose is achieve the minimum level of contamination inside the chamber. Plasma cannot ignite in very high vacuum, so once the chamber has come down to ultra low pressure; the diffusion pump must be turned off. About 20 minutes pass until chamber pressure has risen to $1\times10^{-4}$ Torr and approximately after 5 more minutes the plasma is turned on as soon the chamber pressure rises to about
1 mT.

A sputtering gun inside the chamber is equipped with a permanent magnet to direct the electromagnetic beam created in the RF Generator (13.8 MHz) that feeds a RF signal to the sputtering gun. A two inch diameter Aluminum target in the sputtering gun, allows for aluminum to be dislodged by the plasma ion current and for a reaction between pure nitrogen that is injected in the chamber to create the reactive plasma gaussian beam that deposits Aluminum Nitride thin film on the substrate.

The Sputtering system is equipped with two cooling sub-systems, one to cool the diffusion pump walls, and another for cooling the magnetron sputtering gun. The water recirculation cooling for the Diffusion Pump, sometimes shut itself off, when the level of De-ionized Water was low. Monitoring and careful attention must be paid and to the
water recirculation cooler to avoid accidents. The sputtering gun cooling sub-system is a small water recirculation system that pumps water through the gun and a small heat radiator, which cools the bottom of the sputtering gun permanent magnet, by exchanging heat with a small forced air loaded radiator. The sputtering gun cooling system clogged and failed once, the S-gun gaskets overheated flooding the plasma chamber. A complete sputtering gun had to be rebuilt completely.

The distance between the substrate and the target is of crucial importance. During the early deposition attempts the distance used between the target and the substrate, was fairly short; which rendered very nice breakdown voltage but unfortunately the
deposited thin film was not homogeneous, which is a serious problem for the core of an optical waveguide. Subsequent depositions have been performed, distance was increased but deposition rate drops as $\frac{1}{r^2}$, this, suggested that RF generator power had to be increased but that rendered overheating in the substrate, peeling off of ground plane aluminum was evident. A middle ground had to be found where a longer distance between target and substrate is available which allows for a more homogeneous thin film to be and a not too excessive RF power which rendered the best deposited films.
A manually operated valve was installed on the roughing line to avoid large changes in pressure during pump down. The standard system operation is given in Appendix/Procedure II:

Sputtering deposition complete process takes a whole day to complete, it is advisable to leave samples in the chamber overnight to continue with the immediate next processing step.
4.4 Aluminum Deposition System

A thermal evaporation system, see Figure 4.5, was used to deposit different metals. Heat radiation by a tungsten filament, under ultra high vacuum conditions, was able to melt small little aluminum hooks mounted on the tungsten filament as its temperature increased by a flowing current that was controlled with a Variac. The system was exclusively used to deposit aluminum as a ground plane, and aluminum dots on top of aluminum nitride to be able to characterize the electrical properties of sputtered-deposited thin films: such as capacitance, leakage current, film thickness and breakdown voltage.

Testing of this deposition procedure and fine tuning was necessary. Two filaments loaded with six aluminum hooks each were able to yield an aluminum deposition thickness of 0.5 micron. Only one loaded filament produce thickness of 250 microns.

The metal deposition system required the use of a roughing pump to reach low vacuum and a diffusion pump for ultra low vacuum. Once the pressure came down to $4 \times 10^{-6}$ Torr, the aluminum was deposited by evaporation for about 20 seconds. Current flowing through the filament is manually controlled to fall between 15 to 20 amperes. The Metal Evaporation System was a workhorse, it operated reliably all the time except for a minor repair was done once on its roughing pump mechanical coupling.

4.4.1 Aluminum Ground Plane Deposition

An aluminum electrode was deposited on a small area of each substrate surface to provide test capacitors for capacitance-voltage evaluation of the deposited AlN films.
Figure 4.6: Upper view of substrate. Top: Aluminum ground plane on silicon/glass substrate. Bottom: Aluminum dots on Aluminum Nitride/substrate.
Substrates were attached to an aluminum plate carrier of 2.5 centimeter thickness, which was then mounted in the thermal evaporator for Al deposition. Besides holding samples in place, the plate acted to dissipate heat during deposition; to avoid overheating. Although the temperature inside the evaporation chamber was not monitored closely with a thermocouple, the tungsten filaments could easily reach temperatures exceeding 1000 °C. The typical deposition times were 15 to 19 seconds to fully evaporate all of the aluminum hooks from a filament.

The sample carrier was mounted on three aluminum posts of 25 centimeters length. This distance was chosen in order to achieve the desired film thickness and uniformity of the deposited aluminum without excessive heating.

The thickness of deposited material follows the inverse square law of the distance \((\text{thickness} \approx \frac{1}{R^2})\). Three tungsten filaments were available in the system; of which only two were needed to obtain a thickness of about 0.5 \(\mu m\) of deposited aluminum. When only one filament was used for deposition, the final thickness was around 0.25 \(\mu m\) which was found to be too thin for the whisker probe of the capacitance-voltage characterization system.

### 4.4.2 Aluminum Dots Deposition

Aluminum nitride sputtered substrates are now ready for the next processing step, which is the deposition of aluminum dots. This process has the following purposes:

- Thickness measurement of aluminum nitride film deposited by sputtering in the previous batch.
- Dielectric properties measurement of the AlN thin film.
Figure 4.7: Front View of Structure Built to Characterize Aluminum Nitride Properties

Figure 4.8: Top: Front view of Aluminum Nitride section where Aluminum dot is placed. Bottom: Upper view of structure built to measure thickness of Aluminum Nitride Deposited on Substrate with Aluminum Dot on Edge
• Leakage current measurement of the AlN thin film.

• Breakdown voltage of the film.

Figure 4.8 shows the way deposition of Aluminum Nitride allowed a small section of bare substrate to be exposed such that an aluminum dot was deposited right on the edge of Aluminum Nitride, in order to measure AlN thickness with the Angstrom-meter, which requires a reflective surface for the Fizeau plate to produce fringes that permit thickness reading.

In the previous section, it was explained with minute detail how the thin film of aluminum nitride was deposited on the substrates. Now efforts are endeavored in describing the processing steps as follows. See details in Appendix/Method III.

4.5 Photolithography

To fabricate an optical waveguide more sophisticated than a slab, such as a ridge type it is necessary to design and build a photo mask in accordance to their intended purpose i.e. due to the small size of the feature dimensions the mask must be photolithographic and cannot be a simple shadow mask.

Pattern generation on red Rubylith were attempted at first. It has been for long, the material of choice to create artwork patterns in photolithography, it had been used in the past in our group, for its well known high contrast between dark and light during exposure. Red thin film of Rubylith must be cut with a plotter first, then carefully peeled off. Use of a magnifier and tweezers is most recommended, to make sure the job is done with a high degree of precision.
An initial pattern was designed by means of an older version of AutoCAD with the intention of using an HP 7470A plotter equipped with a diamond pen. In theory any designed pattern could be printed or "carved" on Rubylith masking paper; only limited by the maximum size the plotter could handle of the Rubylith format e.g. letter size (8½ × 11 square inches).

Unfortunately experimental tests proved this method inadequate; the plotter printing speed was too fast making the diamond pen slip and rendering the cut on thin film red Rubylith inaccurate and discontinuous. AutoCAD version 2000 offered no possible way of controlling the plotter speed. Specially if this involved curvy designs, the plotter could not cut the two dimensional structure neither continuously nor smoothly. Straight lines were not always adequately cut either, rendering the cut design quality inferior and inaccurate. The idea had to be abandoned. Another option must be found in order to build a structure on a slab optical waveguide.

In order to overcome this adversity, alternative ways had to be found since Rubylith was not an option anymore and did not render acceptable results. The next step was to print the AutoCAD generated pattern on a laser overhead transparency, the kind that were used for years to project images and make presentations.

A new complete process had to be developed in order to see if a transparency could be used instead of Rubylith. The artwork printed on the overhead must be reduced and its pattern transferred into a photo-mask, which will be used in the wafer-stepper to imprint the structure. The pre-existing standard operating procedure to develop emulsions from projected rubylith based artwork will necessarily have to be modified and fine tuned for the new conditions. Laser printed overheads will present a different contrast between light and dark.
Initial tests attempted to determine their quality and performance, as photo-mask candidates appeared to be very promising. Laser printers nowadays are very sophisticated and the transparency and high quality of laser overheads the results can be very good. The computer designed, with modern AutoCAD artwork was transferred to an actual slab Aluminum Nitride waveguide in the following way.

- first step is to carefully design the pattern or artwork with AutoCAD to be imprinted on sample.
- second step is to project a 10x reduced pattern onto a light sensitive emulsion film by means of a first stage reduction camera
- third step is to develop the emulsion film.
- fourth step is to transfer the pattern onto slab waveguide with the Mask Aligner.
- fifth step is to etch the Aluminum Nitride, to achieve the 3 dimensional structure.

In the following sections each one of these steps will be described in detail.

4.5.1 Photolithographic Artwork Design

The photolithographic mask design is a very elaborate structure of fine lines. Lines were defined as rectangles filled with a solid black color in the AutoCAD design. The thinnest linewidth is at the center of the mask, right next to the Meander line. Line width dimensions slowly grew wider as moving toward the outer edges of page were they reached their largest value. The overall picture of the pattern concept is shown in Figure 4.9.
In order to control dimensions in the mask quantitatively, the distance between lines is kept at the same value as line width itself, as a geometrical frequency. For instance the first group has a linewidth of 0.2 millimeter and the distance between two adjacent lines is also 0.2 millimeter; the second group has a linewidth of 0.4 millimeter and their distance in between lines is also 0.4 millimeter, and so on. Distance between each group was set at 1 millimeter. Three Meander lines were included for the sake of testing lossy conditions; their linewidth values are also listed in Table 4.3.

4.5.2 Illuminated Screen

An illuminated screen is used to mount the transparency (un-reduced photo-mask) where design artwork has been printed. Light is projected on the objective of a
reduction camera where emulsion film has been previously mounted. The image will be photographed as it will be reduced ten times, as it is imprinted on a photo sensitive emulsion. The performance of the screen must be characterized to establish stability of its light source. Measurements of photocurrent in the center of the screen were taken with respect to time as shown in Figure 4.11.

It is apparent that after 7 minutes the warming process of the lamps have reached a plateau, and the light intensity will show no further change. For processing the photo-mask a warming-up time of 15 minutes was allowed, before exposition took place.
Figure 4.10: Illuminated Screen and Reduction Camera

<table>
<thead>
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<td>34.7</td>
<td>34.5</td>
<td>31.7</td>
<td>19</td>
</tr>
</tbody>
</table>

Table 4.4: Screen Light Distribution

A two dimension mapping of the screen visible area must be established to identify the areas where optimum light conditions are available. A $5 \times 5$ matrix was generated by mapping the photocurrent measured on the screen to identify the area with a more homogeneous light distribution. Both vertical and horizontal axes of the illuminated screen were sectioned in five discrete elements. The results are summarized and
Figure 4.11: Illuminated Screen Warming Up Time

presented in table 4.4. A geometric representation is shown in Figure 4.12 that its distribution in three dimensions. The most homogenous light field is found at $2 \leq x \leq 4$ and $2 \leq y \leq 4$, precisely the area where the transparency is mounted.

4.5.3 Reduction Camera

The first stage reduction camera used in this project is shown in Figure 4.13, a shutter release cable that was conveniently mounted to improve accuracy of response time during exposition. Camera is equipped with a 50 mm lens, it can reduce the feature sizes of photolithographic mask, $10\times - 20\times$, by adjusting the distance between illuminated screen and camera objective, which is achieved by simply moving the camera
with a rotating lever.

Feature sizes of the original artwork design was chosen 10× larger than the final intended feature dimension, on the actual photo-mask intended to be used in the Mask Aligner. At 10x reduction rate, the 50 mm lens can see within certain area limits, outside which the artwork is not projected. The size of our original artwork pattern was bound by the overhead paper size the laser printer could handle, namely 11 x 8.5 square inches. Under such conditions the complete mask and some more were visible at a reduction rate of 10 times.

Feature dimensions of printed material were carefully verified before reduction and after reduction. Before reduction with a small monocular lens equipped with a millimetric ruler. After reduction dimension verification was done with a microscope.
Reduced dimensions are listed on the third column of Table 4.3

4.5.4 Camera Depth of Focus

A transparent film, coated with a photo sensitive emulsion was the element chosen to function as photo mask. It was mounted inside the camera between two transparent square pieces of glass to make sure flatness of surface. Illuminated screen has a green coat to limit the wavelength of shining light, \( \lambda = 435 \) nanometers; lens f-number is 2.0; NA is the numerical aperture. The emulsion has a finite thickness that should be no larger than the the depth of focus of the reduction camera, it can vary between 3 and 5 \( \mu \text{m} \).

The depth of focus was determined first by calculating the numerical aperture, then
the angle associated and finally the depth of focus in $\mu m$, as follows:

$$NA = \frac{1}{2f\text{-number}}$$

$$= \frac{1}{2(2)} = 0.25$$

$$NA = n \sin(\alpha) = \sin(\alpha);$$

$$\alpha = \sin^{-1}(NA) = \sin^{-1}(0.25)$$

$$= 14.4775^\circ$$

$$\delta f = \frac{\lambda}{4 \sin^2(\frac{\alpha}{2})} = 6.8495 \mu m$$

Under all these conditions the depth of focus is $\delta f = 6.8495 \mu m$, which appear to be rather on the safe side.

4.5.5 Exposure and Development of Emulsion

Kodak D19 is the developer chosen for this process, such decision was based on the fact that this developer provides higher than normal contrast between dark and light, higher than normal speed, higher than average graininess. Its high performance had previously been observed in our group. The developer contains: Sodium sulphite, Sodium carbonate, monohydrate, Hydroquinone, Potassium bromide, Polyphosphoric acids, sodium salts, and Bis(4-hydroxy-N-methylanilinium) sulphate.

This is a very delicate process; various factors must be taken into account to generate a developed emulsion mask successfully. It has very low tolerance upon light
leaks during processing, absolute darkness conditions is essential inside the dark room. Process also requires absolute control of parameters and such as the exact room temperature, exposition time, and developing time.

As mentioned above the already existing standard operating procedure to expose and develop emulsion films had to be modified. Laser printer overheads had never been used before in the *GaAs Devices & ICs* laboratory, dark areas were black instead of red thin Rubylith film. An optimum exposure time needed to be found. After using different exposition time that rendered inadequate results, a photolithographic mask was successfully built and its final SOP steps are presented in table 4.5

<table>
<thead>
<tr>
<th>Process</th>
<th>time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure</td>
<td>10, 20</td>
</tr>
<tr>
<td>Development</td>
<td>90</td>
</tr>
<tr>
<td>Stop Bath</td>
<td>30</td>
</tr>
<tr>
<td>Fixer</td>
<td>60</td>
</tr>
<tr>
<td>DI H₂O rinse</td>
<td>30</td>
</tr>
<tr>
<td>Hypo</td>
<td>120</td>
</tr>
<tr>
<td>DI H₂O rinse</td>
<td>120</td>
</tr>
</tbody>
</table>

Table 4.5: Emulsion Exposure and Development Procedure

Figures 4.14 to 4.16 show, the emulsion photo mask film that was exposed for 10 seconds once it was developed, ready for processing use in the Mask Aligner. Another mask was exposed for 20 seconds as stated in Table 4.5
Figure 4.14: Emulsion Photo Mask

Figure 4.15: Emulsion Photo Mask
Figure 4.16: Emulsion Photo Mask
4.5.6 Photoresist Spinner

Photoresist thickness is directly related to the spinning time and to the angular speed used during its application. A power supply controls the angular speed of the built-in motor; the rotor current is monitored with an ammeter.

![Graph showing the correlation between angular speed and motor current for silicon and glass substrates.](image)

Figure 4.17: Angular speed - Motor Current Correlation

A very precise correlation between the displayed current and the motor angular speed must be found. A black strip mounted on a white background dummy wafer was mounted on the vacuum chuck. Angular speed was measured with a laser equipped digital tachometer. Correlation between current and angular speed, was established for both types of materials: silicon and glass substrates.

Table 4.6 shows that there is no significant difference between the angular speed
Table 4.6: Angular speed – Motor Current Correlation

<table>
<thead>
<tr>
<th>Si  ( \omega ) (rpm)</th>
<th>2530</th>
<th>2893</th>
<th>3253</th>
<th>3600</th>
<th>4001</th>
<th>4325</th>
<th>4712</th>
<th>5041</th>
</tr>
</thead>
<tbody>
<tr>
<td>i (( \mu )A)</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>45</td>
<td>50</td>
<td>55</td>
<td>60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Glass ( \omega ) (rpm)</th>
<th>2530</th>
<th>2893</th>
<th>3253</th>
<th>3600</th>
<th>4001</th>
<th>4325</th>
<th>4712</th>
<th>5041</th>
</tr>
</thead>
<tbody>
<tr>
<td>i (( \mu )A)</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>45</td>
<td>50</td>
<td>55</td>
<td>60</td>
</tr>
</tbody>
</table>

of the glass substrate and silicon wafer for the same current conditions, despite the fact that glass is heavier than silicon. It also differs from the table already available at the front end of photo resist spinner.

4.5.7 Contact Printing with Wafer Stepper

The generated mask in the photolithographic process was transferred to the slab waveguide. This was done with the use of a Kulicke & Soffa Mask Aligner. The choice between negative or positive photoresist, was not a trivial decision to make. It was based on the photoresist performance during etching at the final stage, as well as the processing conditions that allowed no room for a processing change.

4.5.8 Mercury Discharge Lamp

So far a simple slab waveguide has been successfully built, as described in the previous two chapters. A more ambitious and complex structure will require a more elaborate fabrication process. In order to build a structure on a device, a pattern must be transferred from a photolithographic mask onto the device by contact printing it with
a Mask Aligner system (also called Wafer Stepper) equipped with a high pressure mercury lamp, emitting light in the range of $350 \leq 500$ nm, ideal for most photoresists.

Emphasis is placed on the adjective “photolithographic” to express that such mask will have feature dimensions, much smaller than the wavelength of light used in the contact printing process in contrast with the larger size features of a Shadow Mask.

Spectral irradiance of a typical High Pressure Plasma Arc Discharge Mercury Lamp built by Zeiss, that may be used in the Mask Aligner system, shows its multiple emission lines and their respective wavelength. Ultraviolet emission accounts for one third to one half the total output power. Eyes must be protected when operating this type of powerful source of light.
4.5.9 Positive Photoresist

S1818 a positive photoresist built by Shipley was the photoresist of choice for the photolithographic process. There was ample supply in stock at the GaAs Devices & ICs laboratory of it as well as a Philip A. Hunt the positive photoresist developer used; several jars were available. Unfortunately there was no literature available discussing how to mix deionized water with developer; therefore various combinations had to be tested until the best result was found.

Photoresist and adhesion promoter (HMDS primer) containers, must be placed out of fridge for at least one hour before use. Cold containers must not be open under any circumstance, otherwise ambient humidity that condensates inside of bottle can contaminate solution. As a matter of fact there is no need to keep the adhesion promoter inside the fridge.

The relation here Dev:H₂O denotes, developer versus Deionized Water, in number of volume parts.
• 1:5 solution had, reportedly, been used in the past. Development time is too long and not uniform.

• 1:1 solution had a development time too difficult to control.

• 1:2 solution is the most optimal, development is homogeneous and time is easily controlled accurately.

Positive photoresist processing steps are outlined as follows:

<table>
<thead>
<tr>
<th>Preparation</th>
<th>Temperature/Speed</th>
<th>time (minutes/seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photoresist</td>
<td>room temp.</td>
<td>60+ min</td>
</tr>
<tr>
<td>Adhesion Promoter HMDS</td>
<td>room temp.</td>
<td>60+ min</td>
</tr>
<tr>
<td>Dehydration in oven</td>
<td>120 °C</td>
<td>30 min</td>
</tr>
<tr>
<td>Cooling plate</td>
<td>room temp.</td>
<td>15 sec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Substrate processing steps</th>
<th>Temperature/Speed</th>
<th>time</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMDS primer</td>
<td>2000 RPM</td>
<td>30 sec</td>
</tr>
<tr>
<td>S1818 photoresist</td>
<td>3000 RPM</td>
<td>30 sec</td>
</tr>
<tr>
<td>Soft Bake</td>
<td>90 °C</td>
<td>30 min</td>
</tr>
<tr>
<td>Exposition</td>
<td>-</td>
<td>16 sec</td>
</tr>
<tr>
<td>Development</td>
<td>1:2</td>
<td>90 sec</td>
</tr>
<tr>
<td>Hard Bake</td>
<td>120 °C</td>
<td>30 min</td>
</tr>
</tbody>
</table>

Table 4.7: Positive Photoresist Photolithography

Positive photoresist did not withstand Aluminum Nitride AlN etching with either Potassium Hydroxide KOH, or Sodium Hydroxide NaOH, both etchant wiped it clean. It also showed a melting effect a consequence of hard baking process. Finally another disadvantage of positive photoresist is inherent to its nature. There is no cross linking taking place in the process, which makes the photoresist linewidth dependant on development time, i.e. more prone to dimension errors.
4.5.10 Negative Photoresist

Since the performance of positive photoresist was inadequate, as above described; another alternative had to be found. HNR 100 is a negative photoresist manufactured by Philip A. Hunt Chemicals, that was available at the laboratory, in enough quantities.

Photoresist container must be also placed out of the fridge at ambient temperature for at least one hour before use, otherwise contamination will occur. Negative photoresist own adhesion properties are excellent; it does not require the use of an adhesion promoter as positive photoresist does. It is a very sensitive resist, so the exposure times are much shorter than its counterpart positive PR.

<table>
<thead>
<tr>
<th>Preparation</th>
<th>Temperature/Speed</th>
<th>time (minutes/seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photoresist container</td>
<td>room temp.</td>
<td>60+ min</td>
</tr>
<tr>
<td>Subst Dehydration in oven</td>
<td>120 °C</td>
<td>30 min</td>
</tr>
<tr>
<td>Cooling plate</td>
<td>room temp.</td>
<td>15 sec</td>
</tr>
<tr>
<td>Substrate processing steps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HNR 100 photoresist</td>
<td>3000 RPM</td>
<td>30 sec</td>
</tr>
<tr>
<td>Soft Bake</td>
<td>90 °C</td>
<td>30 min</td>
</tr>
<tr>
<td>Exposition</td>
<td>-</td>
<td>2 sec</td>
</tr>
<tr>
<td>Development</td>
<td>Xylene</td>
<td>60 (3)0 sec</td>
</tr>
<tr>
<td>Rinse</td>
<td>N-Butyl Acetate</td>
<td>30 (15) sec</td>
</tr>
<tr>
<td>Blow Dry</td>
<td>N₂</td>
<td>30 sec</td>
</tr>
<tr>
<td>Hard Bake</td>
<td>140 °C</td>
<td>30 min</td>
</tr>
</tbody>
</table>

Table 4.8: Negative Tone Photoresist Photolithographic SOP

A cross linking process takes place when negative photoresist is exposed to light. The contact printed pattern will not change as a function of the developing time. Exposed areas are cross linked and unexposed are washed away, after about 15 seconds the pattern can be clearly seen with the naked eye.
Developer (Xylene) and rinse (N-Butyl Acetate) can be sprayed on the specimen, while wafer or substrate is being held in place by a chuck operated with a vacuum pump. Unfortunately air pressure in that specific laboratory, where this system is set up, does not go beyond 24 psi; sprayed jet does not hit the sample if mounted on the vacuum chuck. Sample must be held by hand or the whole process can be performed using beakers.

If developing is done in beakers, developing time must be doubled and rinse time is kept the same. If developing is done by spraying the jet impinging the sample actually provides kinetic energy to the sample and this shorten the developing time.

Negative photoresist successfully withstands Aluminum Nitride AlN etchants, e.g. Sodium Hydroxide NaOH, or Potassium Hydroxide KOH, for about twenty four minutes.

Two Different Photo Masks

As explained above, two photolithographic masks were built when emulsion development process took place. The first one was exposed for 10 seconds and it appeared very dark as to provide a good contrast between dark and light. All the lines on the mask were printed continuously so it a seemed it was the best choice. Unexpectedly experimental work did not produce desired results. The printed field on the wafer, was no completely homogeneous, lines were not continuous, the only areas fully printed were the large corner boxes, as shown in Figure 4.14 and 4.15.

Negative photoresist is extremely sensitive, but this problem persisted even with exposures were extended up to 9 seconds. The only possible conclusion that could be
drawn was that such mask was flawed, and another one should be used instead. The second mask appeared to be lighter when inspected, immediate testing followed. In order to determine the level of darkness both mask were mounted on the sensor of the photo current meter as shown in Figure 4.19

Light from a 20 watt lamp is shone directly above each photo mask, the results are very clear. Mask 1 reads 87.7 $\mu$A and Mask 2 reads 133 $\mu$A, the photo current difference is 43.3 $\mu$A. It is evident that Mask 2 is clearer than Mask 1. Further photolithographic with such mask proved to be a success. SOP is summarized in the Table 4.9
4.6 Aluminum Nitride Etching

It is possible to build a structure on an aluminum nitride slab waveguide by contact printing a designed work of art by means of lithography as previously discussed. The sole purpose of this section is to discuss how etching is done.

4.6.1 Potassium Hydroxide

It has been reported by various sources that potassium hydroxide etches Aluminum Nitride [118], [119]. Unfortunately no details are available of the solution concentration or the temperature used when a specific etch rate was reported [120]. It is
Figure 4.22: Mask 2
<table>
<thead>
<tr>
<th>Preparation</th>
<th>Temperature/Speed</th>
<th>time (minutes/seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photoresist container</td>
<td>room temp.</td>
<td>60+ min</td>
</tr>
<tr>
<td>Subst Dehydration in oven</td>
<td>120 °C</td>
<td>30 min</td>
</tr>
<tr>
<td>Cooling plate</td>
<td>room temp.</td>
<td>15 sec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Substrate processing steps</th>
<th>Temperature/Speed</th>
<th>time</th>
</tr>
</thead>
<tbody>
<tr>
<td>HNR 100 photoresist</td>
<td>4000 RPM</td>
<td>30 sec</td>
</tr>
<tr>
<td>Soft Bake</td>
<td>90 °C</td>
<td>30 min</td>
</tr>
<tr>
<td>Exposition</td>
<td>-</td>
<td>2.5 sec</td>
</tr>
<tr>
<td>Development</td>
<td>Xylene</td>
<td>60 (3)0 sec</td>
</tr>
<tr>
<td>Rinse</td>
<td>N-Butyl Acetate</td>
<td>30 (15) sec</td>
</tr>
<tr>
<td>Blow Dry</td>
<td>N₂</td>
<td>30 sec</td>
</tr>
<tr>
<td>Hard Bake</td>
<td>140 °C</td>
<td>30 min</td>
</tr>
</tbody>
</table>

Table 4.9: Negative Tone Photoresist Photolithographic SOP

<table>
<thead>
<tr>
<th>Etch Rate</th>
<th>Temperature</th>
<th>time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2 nm/min</td>
<td>23 °C</td>
<td>57</td>
</tr>
<tr>
<td>10 nm/min</td>
<td>40 °C</td>
<td>30</td>
</tr>
<tr>
<td>17.64 nm/min</td>
<td>50 °C</td>
<td>17</td>
</tr>
<tr>
<td>150 nm/min</td>
<td>70 °C</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 4.10: AlN etching in 10% KOH

currently used to strip positive photoresist after a lithographic process. A solution of 10 % of KOH was used as etchant the results are summarized here.

### 4.6.2 Sodium Hydroxide

Ababneh et. al. reported, chemical etching of aluminum nitride (AlN), using solutions based on potassium hydroxide \( \text{KOH} \) and phosphoric acid \( \text{H₃PO₄} \) [118]. It has been established by our research group that Aluminum Nitride can be etched with, a solution of sodium hydroxide \( \text{NaOH} \).
Table 4.11 summarizes the results of etching a thin film of Aluminum Nitride with a thickness of 250 nanometers, on a solution of 5\% NaOH at different temperatures.
Figure 4.24: Sodium Hydroxide Etch Rates

Table 4.11: AlN etching in 5% NaOH
Figure 4.25: Etching of Aluminum on Glass to test Waveguide Photomask
Figure 4.26: Etching of Aluminum on Glass to test Waveguide Photomask
Chapter 5

Characterization Methods of Waveguide and AlN testing

5.1 Introduction

Measurements of optical waveguide losses is crucial to determining the usefulness of a waveguide. In this chapter the methods used to measure waveguide losses at two wavelengths [650 nm and 1550 nm] are described and the accuracy of the results discussed.

5.2 Aluminum Nitride thickness

The Aluminum Nitride thin films, deposited as described in previous chapter, were characterized thoroughly. AlN thickness was measured by using an ångstrom meter, equipped with a sodium lamp (589 nm), a Fizeau plate, etc. An aluminum patch was deposited over the AlN film edge. The step in the aluminum dot produced a shift in the interference fringes. The shift in the fringes was used to calculate the thickness of the film from:

$$\text{thickness} = \frac{\text{fringe shifting } \lambda}{\text{fringe spacing } 2}$$

(5.2.1)
The top of figure 5.1 displays the side view of the aluminum step used to measure film thickness. Substrate is represented in plaid pattern, over which *Aluminum Nitride* is deposited (wavy pattern) but not entirely leaving part of the substrate exposed. An aluminum dot is deposited over the step between AlN and substrate interfaces. The bottom of figure 5.1 shows a plan view of the circular aluminum dot over the step between substrate and the AlN thin film surfaces.
Figure 5.2: Inhomogeneous Deposition of Aluminum Nitride on Silicon
Figure 5.3: Deposition Aluminum Nitride on Glass with Ground Plane
5.3 Capacitance

Dielectric properties of the Aluminum Nitride AlN, were measured to establish the quality of the material deposited by sputtering deposition. Relative permittivity or dielectric constant of the AlN thin films, was determined from capacitance measurements of simple parallel plate capacitors.

\[ C = \frac{\varepsilon A}{d} = \frac{k \varepsilon_0 A}{d} \quad (5.3.1) \]

Figure 5.4: Aluminum dots to determine AlN permittivity, upper view
Fabrication of capacitor test structure was as follows. First an aluminum stripe was deposited, that was used as ground plane to measure capacitance (see upper picture of figure 5.4). This was followed by deposition of a thin film of aluminum nitride on substrate including the ground plane. A small area of aluminum was left exposed to allow access to the ground electrode. Finally, multiple aluminum dots were deposited as a third layer over the aluminum nitride, as shown in figures 5.4 and 5.5.

![Figure 5.5: Aluminum dots to determine AlN capacitance, cross section](image)

Aluminum dot thickness proved to be a crucial factor, 0.5 µm thick aluminum dots rendered consistent measurements, but 0.25 µm did not allow for stable electrical contact. A cross section of the device structure, which provides a complete picture with the deposited layers sequence, as shown in figure 5.5.

The area of the aluminum dots was measured in square millimeters. From the capacitance measurement, the relative permittivity $k$ was calculated from:

$$k = \frac{Cd}{\varepsilon_0 A}$$  \hspace{1cm} (5.3.2)
where $d =$ film thickness, $A =$ Aluminum dot area, $\varepsilon_0 =$ vacuum permittivity

<table>
<thead>
<tr>
<th>Sample</th>
<th>Thickness nm</th>
<th>Capacitance (pF)</th>
<th>Dielectric Const.</th>
<th>Resistivity $\Omega \cdot \text{cm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>160</td>
<td>1280</td>
<td>4.7</td>
<td>9.2$x10^{12}$</td>
</tr>
<tr>
<td>2.2</td>
<td>180</td>
<td>1090</td>
<td>4.5</td>
<td>8.2$x10^{12}$</td>
</tr>
<tr>
<td>2.3</td>
<td>270</td>
<td>1180</td>
<td>6.5</td>
<td>2.7$x10^{12}$</td>
</tr>
<tr>
<td>2.4</td>
<td>465</td>
<td>1350</td>
<td>7.3</td>
<td>7.8$x10^{12}$</td>
</tr>
<tr>
<td>2.5</td>
<td>488</td>
<td>1120</td>
<td>8.0</td>
<td>4.8$x10^{12}$</td>
</tr>
<tr>
<td>5.1</td>
<td>312</td>
<td>1100</td>
<td>7.9</td>
<td>4.7$x10^{12}$</td>
</tr>
<tr>
<td>5.2</td>
<td>290</td>
<td>930</td>
<td>6.2</td>
<td>5.1$x10^{12}$</td>
</tr>
<tr>
<td>5.3</td>
<td>320</td>
<td>980</td>
<td>7.2</td>
<td>4.6$x10^{12}$</td>
</tr>
<tr>
<td>5.4</td>
<td>350</td>
<td>820</td>
<td>6.6</td>
<td>4.2$x10^{12}$</td>
</tr>
<tr>
<td>5.5</td>
<td>450</td>
<td>790</td>
<td>8.2</td>
<td>3.3$x10^{12}$</td>
</tr>
<tr>
<td>8.1</td>
<td>148</td>
<td>2280</td>
<td>7.8</td>
<td>9.2$x10^{14}$</td>
</tr>
<tr>
<td>8.2</td>
<td>170</td>
<td>1970</td>
<td>7.7</td>
<td>8.7$x10^{13}$</td>
</tr>
<tr>
<td>8.3</td>
<td>165</td>
<td>2000</td>
<td>7.6</td>
<td>8.9$x10^{13}$</td>
</tr>
<tr>
<td>8.4</td>
<td>210</td>
<td>1670</td>
<td>8.1</td>
<td>7.0$x10^{13}$</td>
</tr>
<tr>
<td>8.5</td>
<td>220</td>
<td>1590</td>
<td>8.0</td>
<td>6.7$x10^{13}$</td>
</tr>
<tr>
<td>12.1</td>
<td>218</td>
<td>1715</td>
<td>8.6</td>
<td>6.8$x10^{14}$</td>
</tr>
<tr>
<td>12.2</td>
<td>221</td>
<td>1750</td>
<td>8.9</td>
<td>6.7$x10^{14}$</td>
</tr>
<tr>
<td>12.3</td>
<td>277</td>
<td>1400</td>
<td>8.9</td>
<td>5.3$x10^{14}$</td>
</tr>
<tr>
<td>12.4</td>
<td>300</td>
<td>1270</td>
<td>8.8</td>
<td>4.9$x10^{14}$</td>
</tr>
<tr>
<td>12.5</td>
<td>290</td>
<td>1320</td>
<td>8.8</td>
<td>5.1$x10^{14}$</td>
</tr>
<tr>
<td>17.1</td>
<td>230</td>
<td>1710</td>
<td>9.0</td>
<td>6.4$x10^{14}$</td>
</tr>
<tr>
<td>17.2</td>
<td>240</td>
<td>1620</td>
<td>8.9</td>
<td>6.1$x10^{14}$</td>
</tr>
<tr>
<td>17.3</td>
<td>265</td>
<td>1470</td>
<td>9.0</td>
<td>5.6$x10^{14}$</td>
</tr>
<tr>
<td>17.4</td>
<td>270</td>
<td>1430</td>
<td>8.9</td>
<td>5.5$x10^{14}$</td>
</tr>
<tr>
<td>17.5</td>
<td>280</td>
<td>1390</td>
<td>9.0</td>
<td>5.3$x10^{14}$</td>
</tr>
</tbody>
</table>

Table 5.1: Dielectric Constant and Resistivity Evolution of AlN

Table 5.1 displays the electrical properties of AlN as fabrication technique evolved to ensure the best quality of the deposited film.
5.4 Refractive Index of AlN

The refractive index of transparent and non-transparent media, can be accurately determined, [121]. Measurements of refractive index of aluminum nitride were performed by ellipsometry, which provided high accuracy results. A manually operated Gaertner L117 Null ellipsometer, equipped with a Helium Neon laser, emitting light at 632.8 nanometer, was used to perform refractive index measurements of aluminum nitride thin films deposited on glass substrates.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Thickness nm</th>
<th>Dielectric Const.</th>
<th>Refractive Index</th>
</tr>
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<td>2.045 ± 0.051</td>
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<tr>
<td>n</td>
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<td>2.038 ± 0.049</td>
</tr>
</tbody>
</table>

Table 5.2: Refractive Index of AlN

Refractive index measurements of well known materials like silicon wafers and
glass substrates (microscope slides) by ellipsometry, were determinant to ensure the instrument calibration and accuracy of obtained results. Scattering effects of incident laser beam on the sample under study were minimized by RCA washing each sample before measurements were taken. A thorough description of the measurement procedure is described in the Appendix.

The fabrication process of aluminum nitride was carefully tuned and their parameters: RF power, nitrogen flow, distance between target and plasma, were modified to guarantee the highest quality of the deposited AlN. Material properties such as dielectric constant, measured by capacitance, and refractive index measured by ellipsometry, were carefully monitored to ensure the reproducibility of high quality aluminum nitride properties from run to run and, from sample to sample in the planetarium sample holder.

Multiple reflections of laser beam with the substrate affected the refractive index measurements in films less than 400 nanometer thick. It became evident that ellipsometry required thickness larger than 500 nanometer to render consistent results, which required thin film deposition for at least 4 hours. The refractive index measurements of the AlN thin films and their variation across different locations at the sample holder, are shown in Table 5.2.

These results were in close agreement with the refractive index value predicted by the Sellmeier equation of amorphous aluminum nitride of $n = 2.029$, at $\lambda = 632.8$ nanometer, discussed in Chapter 3. The refractive index was determined from the values of $\Delta$ and $\Psi$, a Fortran 95 program was written based on the "one film program" by McCrackin [122], which rendered satisfactory results.
5.5 Breakdown Voltage and Leakage Current

Dielectric quality of the material was established from the capacitance measurements; results are presented in Table 5.1. Figure 5.6 displays the circuit diagram of probing station used to perform CV measurements of each Aluminum Nitride dot.

A variable voltage was applied across the Aluminum Nitride film, and the current through was measured, to determine the film resistivity, the breakdown voltage, and the leakage current. Left hand side of circuit diagram (selected with the switch) of Figure 5.6, was used to measure such parameters of Aluminum Nitride.

Resistivity as a function of applied voltage, is plotted in Figure 5.7; was calculated form:

\[ \rho = \frac{Rd}{A} = \frac{vd}{iA} \]  

where \( d \) = film thickness, \( A \) = Aluminum dot area, \( \rho \) = resistivity

\[ (5.5.1) \]
Figure 5.7: DC Resistivity vs. Voltage

Figure 5.8: Breakdown Voltage
Figure 5.7 displays the resistivity of Aluminum Nitride, which is of the order $10^{14}\Omega\text{-cm}$, it reaches a maximum value around 20 Volts DC, and slightly drops after the applied voltage is increased. Similar results were reported in 2004 by Xie et. al [123]. Resistivity remains within the same order of magnitude even after the applied voltage was increased to 120 Volts DC.

The IV characteristic of leakage current vs. applied voltage across Aluminum nitride, displayed in Figure 5.8; shows a non linear interaction between the two parameters. Leakage current appears to be constant once the applied voltage is above 105 volts. Figures 5.7 and 5.8 indicate that the dielectric properties of the deposited material were in accordance to those of best quality Aluminum Nitride.

5.6 Characterization of Optical Instrumentation

The present section is devoted to describe how optical instrumentation is used to characterize the optical waveguides under study and accurately determine their performance.

5.6.1 Modulated Laser, Fibertech-105

Fibertech 105 was a dual wavelength modulated laser source built by Laser Precision, equipped with two lasers one at $\lambda = 1300$ nm and the other at $\lambda = 1550$ nm. The internal oscillator in the Fibertech 105 has a fixed frequency of 5 KHz and can modulate either laser separately or both simultaneously, see Figures 5.9 and 5.10.

Characterization of AF modulated output from Fibertech 105 lasers reference purposes. Prof. Kosel’s laser driver was calibrated against this source. Different sizes
Figure 5.9: Fibertech 105 Optical Power in dBm units at 1550 nm

Figure 5.10: Fibertech 105 Optical Power in µW units at 1550 nm
of optical fiber were chosen for this. The core and cladding size in µm are included in table. As expected larger core size fibers transmit more light and were chosen for laser source coupling in waveguide measurements.

Table 5.3 presents the optical power levels measured in dBm and µW for modulated (5 KHz) and CW modes from the Fibertech 105. The third column in table 5.3 includes the percentage of optical power drop between the modulated signal denoted with \textit{mod} in the first column, and with \textit{cw} for continuous wave. When modulation is enabled Optical power dropped to $= 50.2 \pm 0.7\%$. Optical power value is equal to 50.2% with a standard deviation of 0.7. The slightly higher value in optical power detected with green fiber was because ferrule may have been cleaner, it was a brand new one just taken out of the plastic bag.

The internal oscillator in Fibertech 105 produces a square wave modulation. To
Figure 5.11: Fibertech modulated signal

Figure 5.12: Fibertech modulated signal, 5 KHz
detect the modulated signal an opto-electronic circuit was set up using a TEK P6702 detector that operates in the 1550 nanometer regime. Figures 5.11, 5.12 and 5.13 show the equipment setup. The TEK Probe 1103, was an opto-electric converter and power supply that amplifies the signal from the TEK P6702 and ports it out through a BNC port. Waveforms were displayed on a Tektronix 5403 oscilloscope with a time base plugin TEK 5840 and an input differential amplifier plugin TEK 5A21N. Modulated signal was 50 mV$_{p-p}$ for the 1550 nm laser and 22.5 mV$_{p-p}$ for the 1300 nm laser.

### 5.6.2 Optical Power Meters

The first optical meter used was LP-5000 built by Laser Precision Corporation equipped with a Germanium detector, which reads in dBm only and provides sensitivity compensation for wavelengths $\lambda = 780, 850, 1300, 1550$ nm.
Figure 5.14: Fibertech and Opto-electric Detector
<table>
<thead>
<tr>
<th>Laser Source Fibertech 105 (\lambda(nm))</th>
<th>Optical Power Meter, LP-5000 (dBm)</th>
<th>200/230 (\mu)m Optical Fiber Blue</th>
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<tbody>
<tr>
<td>1550</td>
<td>-10.4</td>
<td>CW</td>
</tr>
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<td>1550</td>
<td>-13.9</td>
<td>mod</td>
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<tr>
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<td>-11.6</td>
<td>CW</td>
</tr>
<tr>
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<td>-14.7</td>
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<th>60/140 (\mu)m Optical Fiber Orange</th>
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<th>8/140 (\mu)m Optical Fiber Yellow</th>
</tr>
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<td>-15.2</td>
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</table>

<table>
<thead>
<tr>
<th>Laser Source Fibertech 105 (\lambda(nm))</th>
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<th>200/230 (\mu)m Optical Fiber Blue</th>
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<td>1300</td>
<td>-13.83</td>
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</table>

<table>
<thead>
<tr>
<th>Laser Source Fibertech 105 (\lambda(nm))</th>
<th>Optical Power Meter, AM-3500 (dBm)</th>
<th>100/140 (\mu)m Optical Fiber Green</th>
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</thead>
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<td>1300</td>
<td>-13.74</td>
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Table 5.4: Optical Power from Fibertech 105 Laser for various optical fibers measured with AM3500 and LP5000 power meters.
The second optical meter used was AM-3500 also built by Laser Precision Corporation and equipped with a Germanium detector that operates in a very wide wavelength range $820 \text{ nm} < \lambda < 1550 \text{ nm}$. Sensitivity compensation is provided for $\lambda = 820, 830, 840, 850, 860, 870, 880, 890, 1270, 1280, 1290, 1300, 1310, 1320, 1330, 1340, 1350, 1510, 1520, 1530, 1540, 1550 \text{ nm}$. Optical Meter AM-3500 is able to provide optical power readings in two different units dBm as in LP-5000, and in several watt units, i.e. nanowatt, microwatt, etc. Data recorded by both meters appears to be in agreement, as shown in Tables 5.4 and Table 5.5. Figures 5.9–5.10 show the AM-3500 reading in dBm and in $\mu$watt.

Optical power measurements of a 650 nanometer laser diode is not fully appropriate with the Ge-based meters, their sensitivity is best at $\lambda > 800 \text{ nm}$ [124]. Characterization of the optical circuit took place under the assumption there is a constant attenuation factor in the measurements. The AM-3500 optical meter had a minimum
Laser Source
Fibertech 105
\( \lambda (\text{nm}) \)

<table>
<thead>
<tr>
<th>Laser Source Fibertech 105</th>
<th>Optical Power Meter, LP-5000 (dBm)</th>
<th>100/140 ( \mu \text{m} ) Optical Fiber Green</th>
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</thead>
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<tr>
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<td>-11.3</td>
<td>CW</td>
</tr>
<tr>
<td>1550</td>
<td>-14.3</td>
<td>mod</td>
</tr>
<tr>
<td>1550</td>
<td>-10.9</td>
<td>CW</td>
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<table>
<thead>
<tr>
<th>Laser Source Fibertech 105</th>
<th>Optical Power Meter, AM-3500 (dBm)</th>
<th>100/140 ( \mu \text{m} ) Optical Fiber Green</th>
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<td>-10.96</td>
<td>CW</td>
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Table 5.5: LP-5000 vs. AM-3500 under same conditions

wavelength setting of 820 nm. Laser diodes were driven by a circuit constructed by Professor Kosel which was connected to an external signal generator set to operate at \( f = 100 \text{ KHz} \) (maximum available frequency), \( V=1.2 \nu_{p-p} \).

Table 5.5 shows a maximum power reading for the 650 nm laser diode on the AM-3500 for the shortest wavelength setting of 820 nm.

5.6.3 Laser Driver

Prof. Kosel’s laser driver circuit was based on a BJT Schmitt trigger \([125]\), and a MOSFET amplifier stage to drive laser diodes, used for characterization. Two laser diodes were chosen for wavelengths: \( \lambda = 650 \text{ nm} \) and \( \lambda = 1550 \text{ nm} \).

The characteristic of the Schmitt trigger used here was that an input repetitive signal, of arbitrary shape, could be transformed into a periodic sequence of pulses of
<table>
<thead>
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<th>Wavelength $\lambda$(nm)</th>
<th>Optical Power, $\mu$/nwatt</th>
<th>Optical Power dBm</th>
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<td>820</td>
<td>1.573 $\mu$w</td>
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<td>850</td>
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<td>1540</td>
<td>525.6</td>
<td>-32.81</td>
</tr>
<tr>
<td>1550</td>
<td>522.3</td>
<td>-32.84</td>
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</tbody>
</table>

Table 5.6: Modulated Laser 650 nm vs $\lambda$, optical meter AM-3500.

identical shape. The input signal was supplied by a low output impedance (50 $\Omega$) frequency generator.

Q1 and Q2 are the Schmitt trigger transistors, the collector of Q1 is coupled to the base of Q2 by a resistive divider. Also Q2 and Q1 are coupled through a common emitter resistor. The circuit is driven into one of two stable states, depending on the voltage at the base of Q1. When the input is near 0 V, Q1 is cut off. The base of Q2
Figure 5.16: Pulsed Laser Driver

Figure 5.17: Laser Driver Simulation, Voltages
is supplied from voltage divider R2, R3 and R5. So Q2 is saturated, Vce=0. This puts Q3 in the OFF condition.

When V1 is raised to about 0.6 V higher than the emitter voltage established by the emitter current from Q2, Q1 begins to conduct and pulls collector current from R5 which lowers the voltage on R2, which suppresses the base current to Q2. Q2 comes out of saturation and soon turns off Q2, while Q1 goes into saturation; with Q2 off the base of Q3 is turned on.

Q3 is a high speed BJT used to drive the gate of a N-channel power MosFET by means of R10. The MosFET, in turn drives the laser diode at the frequency given by the external signal generator. The voltage at the drain of the power MosFET and the voltage signal at the laser diode are shown in figure 5.17. This shows that laser diode current is maxima when the drain current is minima and viceversa.

Laser driver shown in Figures 5.18, 5.19 allows laser diodes to be conveniently
Figure 5.19: Modulated Laser Driver Circuit in Aluminum box.

Figure 5.20: 1550 nm Laser Diode.
exchanged, from 650 nm to 1550 nm. The circuitry can drive lasers in CW mode or pulsed mode.

![Diagram of RF Generator, Optical Fiber, Laser, and Optical Meter]

Figure 5.21: Modulated Laser and Optical Meter

5.6.4 Laser Characteristics Curve

The minimum attenuation in silica optical fiber is 0.15 dB/km, happens at \( \lambda = 1550 \) nm,\(^{126}\) therefore optical characterization of waveguides was done at this wavelength. Unfortunately, at this wavelength is invisible to the naked eye. In order to perform optical alignment and assure that maximum coupling was achieved, a visible 650 nm single mode laser, with 5 mw of optical power, was used. Waveguide, optical fiber, rutile prism, photo-diode were all aligned first, using the 650 nm wavelength, visible laser to ensure maximum optical coupling, before switching to the invisible wavelength laser.
Figure 5.22: 650 nm laser, modulated and unmodulated

Output characteristic of the 650 nm laser shown in Figure 5.22, tables 5.6 and 5.7 list laser current vs. optical power measured using LP-5000 and AM-3500 optical power meters, respectively. When signal generator frequency was set to 100 KHz (maximum available frequency), the signal amplitude was $V = 1.2 \, V_{p-p}$.

The 1550 nm laser characteristic is shown in Figure 5.23. Similar characteristic curves were obtained with either optical meter. Tables 5.8 and 5.9 present data on optical power vs power supply current. Optical power was also measured using LP-5000 and AM-3500 power meters, respectively.
Figure 5.23: 1550 nm laser, modulated and unmodulated

Table 5.7: Optical meter LP-5000 on Laser Diode, 650 nm.

<table>
<thead>
<tr>
<th>Source Current mA</th>
<th>Optical Power, RF ≠ 0 dBm</th>
<th>Optical Power, RF = 0 dBm</th>
</tr>
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<tr>
<td>10.0</td>
<td>$-\infty$</td>
<td>-49</td>
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<tr>
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### Table 5.8: Optical meter AM-3500 on Red Laser Diode, 650 nm.

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<th>Source Current mA</th>
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<th>Optical Power, RF ≠ 0 n/µ-watt</th>
<th>Optical Power, RF = 0 dBm</th>
<th>Optical Power, RF = 0 n/µ-watt</th>
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<td>776.8</td>
<td>-23.2</td>
<td>4.836</td>
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<td></td>
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<tr>
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<td>1.316</td>
<td></td>
<td></td>
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<td>65.5</td>
<td>-28.08</td>
<td>1.554</td>
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</table>

### Table 5.9: 1550 nm Laser Diode, Optical meter LP-5000

<table>
<thead>
<tr>
<th>Source Current mA</th>
<th>Optical Power, RF ≠ 0 dBm</th>
<th>Optical Power, RF = 0 dBm</th>
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</thead>
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<td>−∞</td>
</tr>
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<td>−∞</td>
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</tr>
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<td>10.4</td>
<td>-53.9</td>
<td>-41.1</td>
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<tr>
<td>15.2</td>
<td>-48.6</td>
<td>-38.9</td>
</tr>
<tr>
<td>20.2</td>
<td>-45.4</td>
<td>-37.1</td>
</tr>
<tr>
<td>24.9</td>
<td>-43.1</td>
<td>-35.8</td>
</tr>
<tr>
<td>30.7</td>
<td>-41.1</td>
<td>-34.6</td>
</tr>
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<td>35.2</td>
<td>-39.9</td>
<td>-33.7</td>
</tr>
<tr>
<td>40.1</td>
<td>-38.8</td>
<td>-32.8</td>
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<tr>
<td>45.5</td>
<td>-37.7</td>
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<td>50.6</td>
<td>-36.9</td>
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<td>65.2</td>
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<tr>
<td>Source Current (mA)</td>
<td>Optical Power, RF ≠ 0 dBm</td>
<td>Optical Power, RF ≠ 0 n/µ-watt</td>
</tr>
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<td>--------------------------</td>
<td>-------------------------------</td>
</tr>
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<td>0.0</td>
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<tr>
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<td>−∞</td>
<td>0.0</td>
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<td>10.4</td>
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<td>15.2</td>
<td>-47.72</td>
<td>17</td>
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<td>20.3</td>
<td>-44.65</td>
<td>34.7</td>
</tr>
<tr>
<td>25.5</td>
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<td>45.7</td>
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<tr>
<td>50.1</td>
<td>-36.3</td>
<td>234.8</td>
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<td>55.3</td>
<td>-35.55</td>
<td>278.6</td>
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<td>60.2</td>
<td>-34.92</td>
<td>322.4</td>
</tr>
<tr>
<td>65.1</td>
<td>-34.36</td>
<td>420.8</td>
</tr>
</tbody>
</table>

Table 5.10: 650 nm Laser Diode, Optical meter AM-3500

5.7 Waveguide Attenuation Measurement Setup

Optical characterization of the AlN waveguide required special test fixture to align optical fiber with waveguide. Multiple electronic instruments were setup to provide power to the laser driver, laser diode, opto-electronic converter and, photodiode. Silicon/germanium photodiodes voltages and laser diode currents were accurately monitored, during all the characterization process. Signal generator and oscilloscope were used to modulate the laser diode and monitor the signals. All the electronic instrumentation required to drive and the optical set up is shown in Figure 5.24.
Figure 5.24: Electronic instrumentation for driving and modulating laser diodes
Instrument Label Description on Figure 5.24

A: Power supply to drive the Si/Ge photodiode

B: Voltmeter to monitor photocurrent

C: Signal generator to modulate laser

D: Ammeter to monitor laser current

E: Voltmeter to monitor voltage in photodiode power supply

F: Power supply to drive laser diode

G: Power supply to drive modulator circuit in laser driver with \( \pm 5 \) and \( \pm 12 \) VDC

H: Laser driver

I: Microscope

J: Optical fiber coupling on waveguide;

K: Movement to adjust prism positioning

L: Oscilloscope

Laser light was launched into waveguide by means of optical fiber butt coupling, with a three dimensional micrometer equipped jig that allowed high accuracy adjustment to control waveguide position. Light was coupled out of the waveguide with a Rutile (Titanium Dioxide, TiO\(_2\)) prism, which has a refractive index much higher than Aluminum Nitride.
Figure 5.25: Butt-coupling Fiber to launch light into waveguide.

Figure 5.26: X-Y Movement for 2D Motion to Adjust Prism.
Figure 5.27: Rutile Prism for coupling out laser light from waveguides.

Figure 5.28: Microscope View of Rutile Prism Position.
<table>
<thead>
<tr>
<th>Wavelength nm</th>
<th>Ordinary Refractive Index</th>
<th>Extraordinary Refractive Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>2.5742</td>
<td>2.8599</td>
</tr>
<tr>
<td>1550</td>
<td>2.4532</td>
<td>2.7093</td>
</tr>
</tbody>
</table>

Table 5.11: Rutile Refractive Index

Rutile Sellmeier equations of ordinary and extraordinary optic axes respectively, with lambda in ångstroms, were reported by Devore, [127].

\[
n_o^2 = 5.913 + \frac{2.441 \times 10^7}{\lambda^2 - 0.803 \times 10^7} \quad (5.7.1)
\]

\[
n_e^2 = 7.197 + \frac{3.322 \times 10^7}{\lambda^2 - 0.843 \times 10^7} \quad (5.7.2)
\]

Maximum contact between photodiode and Rutile prism was ensured, by accurately controlling the photodiode position with a 2-D motion stage. Prism position was carefully manipulated to drastically reduced measurement errors. Photodiodes had a large square area to cover the prism surface. Figures 5.25, 5.26, 5.27, and 5.28 show prism-photodiode setup, as well as the ruler to measure prism position.

### 5.8 Photodiode Circuit

Light output from the prism was detected by two Ge/Si Photodiodes that were reverse biased or in photo-conductive mode, to increase the depletion layer width and
minimize junction capacitance, hence reducing the device time response, [109], [98].

Biasing circuit of the Silicon Photodiode is shown in Figure 5.30. A given reverse bias (12 V silicon PD case) produces a depletion layer at the photodiode junction, in which the width depends on the doping concentrations [128]. Photons are absorbed within the depletion layer where the EHP are separated by the electric field [109].

Any photon with energy higher than device’s bandgap will excite electron-hole pairs. The generated photocurrent through R1 was monitored by the voltmeter, Vm1, after a coupling capacitor C1, such that $V = I_{\text{photo}}R_1$. For the germanium photodiode case, the power supply voltage did not exceed 6 V and $R_1 = 2 \, \text{M}\Omega$ was chosen.
Silicon and germanium photodiodes responses to room ambient light, are shown in Figures 5.31 and 5.32. The Ge-PD seems to be fairly linear above 5 VDC, and in fact it was operated at 6 VDC. The voltage across R1 was 6.9 mv for a power supply setting of 8 VDC. The Si-PD response also showed nearly flat behavior vs. the power supply voltage with photo voltage of 50 mv across R1 for 12 V setting of the power supply voltage.

5.9 Optical Attenuation Measurements

Measurements were taken with both Si & Ge photodiodes, mounted directly on the Rutile prism, covering a very large surface to ensure maximum detection. Multiple out-coupling measurements were taken with a distance of one millimeter between each point, covering a span of 10 to 14 data points, i.e., millimeters. Attenuation of optical waveguide was determined in accordance with equation 3.10.7; which was discussed
Optical fiber-waveguide coupling loss was constant for each measurement taken. Optical losses due to waveguide-prism coupling were assumed essentially the same, at each point. Voltages detected by either (Si/Ge) photodiode were measured by detecting light on Rutile Prims, at one millimeter intervals, to establish waveguide losses.

The optical waveguide attenuation in dB/centimeter is given by:

\[
\text{Attenuation} = 20 \log_{10} \left( \frac{V_2}{V_1} \right) \quad \text{(dB/cm)}
\]  

(5.9.1)
5.9.1 Slab Waveguide

Optical attenuation on the AlN slab waveguide, was performed using a visible at 650 nm to optically align optical fiber, waveguide, prism and photodiode. A near infrared laser at 1550 nm, was also used to characterize waveguide attenuation at that wavelength.

At 1550 nm the slab waveguide attenuation is slightly lower than at 650 nm, and it appears to have smaller variation. Attenuation at the two different wavelengths is plotted in Figure 5.33.
Slab Waveguide Attenuation

Figure 5.33: Slab WG Att. (dB/cm)
<table>
<thead>
<tr>
<th>Prism Position (cm)</th>
<th>Voltage (mV)</th>
<th>Attenuation (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>9.9</td>
<td>-</td>
</tr>
<tr>
<td>0.1</td>
<td>9.8</td>
<td>0.44</td>
</tr>
<tr>
<td>0.2</td>
<td>9.6</td>
<td>0.9</td>
</tr>
<tr>
<td>0.3</td>
<td>9.4</td>
<td>0.91</td>
</tr>
<tr>
<td>0.4</td>
<td>9.3</td>
<td>0.46</td>
</tr>
<tr>
<td>0.5</td>
<td>9.2</td>
<td>0.47</td>
</tr>
<tr>
<td>0.6</td>
<td>9.15</td>
<td>0.24</td>
</tr>
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<td>0.7</td>
<td>9.1</td>
<td>0.24</td>
</tr>
<tr>
<td>0.8</td>
<td>9.05</td>
<td>0.24</td>
</tr>
<tr>
<td>0.9</td>
<td>9.0</td>
<td>0.24</td>
</tr>
<tr>
<td>1.0</td>
<td>8.95</td>
<td>0.24</td>
</tr>
<tr>
<td>1.1</td>
<td>8.9</td>
<td>0.24</td>
</tr>
<tr>
<td>1.2</td>
<td>8.85</td>
<td>0.24</td>
</tr>
<tr>
<td>1.3</td>
<td>8.8</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 5.12: Slab Waveguide Attenuation, 650 nm Laser
<table>
<thead>
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<th>Prism Position (cm)</th>
<th>Voltage (mV)</th>
<th>Attenuation (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>8.68</td>
<td>-</td>
</tr>
<tr>
<td>0.1</td>
<td>8.64</td>
<td>0.2</td>
</tr>
<tr>
<td>0.2</td>
<td>8.6</td>
<td>0.2</td>
</tr>
<tr>
<td>0.3</td>
<td>8.58</td>
<td>0.1</td>
</tr>
<tr>
<td>0.4</td>
<td>8.54</td>
<td>0.2</td>
</tr>
<tr>
<td>0.5</td>
<td>8.5</td>
<td>0.2</td>
</tr>
<tr>
<td>0.6</td>
<td>8.48</td>
<td>0.1</td>
</tr>
<tr>
<td>0.7</td>
<td>8.46</td>
<td>0.1</td>
</tr>
<tr>
<td>0.8</td>
<td>8.42</td>
<td>0.21</td>
</tr>
<tr>
<td>0.9</td>
<td>8.4</td>
<td>0.1</td>
</tr>
<tr>
<td>1.0</td>
<td>8.35</td>
<td>0.26</td>
</tr>
<tr>
<td>1.1</td>
<td>8.3</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Table 5.13: Slab Waveguide Att., at 1550 nm Laser

Table 5.12 displays the voltage measurements across R1 on the Silicon photodiode circuit. Data taken every 1 millimeter and $\lambda$ is 650 nm. Attenuation was the median of 14 data points listed on Table 5.12 ± the standard deviation.

Table 5.13 shows voltage measurements and attenuation data, taken with the Germanium photodiode, and laser light was 1550 nm. Attenuation was the median of 12 data points listed on Table 5.13 ± the standard deviation.
Figure 5.34: Prism and Slab WG
5.9.2 Straight Ridge Waveguides

Optical attenuation on patterned waveguides, was also performed with 650 nm and 1550 nm lasers respectively, as shown in Tables 5.14 and 5.15, which is compared in Figure 5.35. Optical attenuation was performed by coupling light into structures etched on AlN waveguide. Results are consistent at $\lambda = 1550$ nm for both cases of etched and slab waveguides, whereas for the case where $\lambda = 650$ nm, attenuation on the etched structure is much higher than that of the slab case. Probably because of the light source wavelength used in photolithography.

<table>
<thead>
<tr>
<th>Prism Position (cm)</th>
<th>Voltage (mV)</th>
<th>Attenuation (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>11.9</td>
<td>-</td>
</tr>
<tr>
<td>0.1</td>
<td>11.7</td>
<td>0.74</td>
</tr>
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<td>11.5</td>
<td>0.75</td>
</tr>
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<td>11.1</td>
<td>1.54</td>
</tr>
<tr>
<td>0.4</td>
<td>11.0</td>
<td>0.39</td>
</tr>
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<td>10.5</td>
<td>0.41</td>
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<tr>
<td>0.9</td>
<td>10.45</td>
<td>0.21</td>
</tr>
<tr>
<td>1.0</td>
<td>10.4</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Table 5.14: Pattern Etched Waveguide Attenuation A, 650 nm Laser

Tang et. al. in 1997 reported attenuation ranging from 5.4 - 7.6 dB/cm of slab AlN grown by MOCVD on Saphire substrates, for $488 \text{ nm} < \lambda < 632 \text{ nm}$ [129]. Similar results were reported by Dogheche et. al in 1999 who found attenuation equal to 7.3 dB/cm [130].
<table>
<thead>
<tr>
<th>Prism Position (cm)</th>
<th>Voltage (mV)</th>
<th>Attenuation (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>8.55</td>
<td>-</td>
</tr>
<tr>
<td>0.1</td>
<td>8.5</td>
<td>0.25</td>
</tr>
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<td>8.48</td>
<td>0.1</td>
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<td>0.3</td>
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</tr>
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<td>8.44</td>
<td>0.1</td>
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<tr>
<td>0.5</td>
<td>8.42</td>
<td>0.1</td>
</tr>
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<td>0.1</td>
</tr>
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<td>8.38</td>
<td>0.1</td>
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<tr>
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<td>8.34</td>
<td>0.21</td>
</tr>
<tr>
<td>0.9</td>
<td>8.3</td>
<td>0.21</td>
</tr>
<tr>
<td>1.0</td>
<td>8.28</td>
<td>0.1</td>
</tr>
<tr>
<td>1.1</td>
<td>8.24</td>
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</tr>
<tr>
<td>1.2</td>
<td>8.2</td>
<td>0.21</td>
</tr>
<tr>
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<td>8.1</td>
<td>0.53</td>
</tr>
</tbody>
</table>

**Table 5.15:** Pattern Etched Waveguide Attenuation, 1550 nm Laser

<table>
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<tr>
<th>Prism Position (cm)</th>
<th>Voltage (mV)</th>
<th>Attenuation (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>10.25</td>
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</tr>
<tr>
<td>0.1</td>
<td>10.2</td>
<td>0.21</td>
</tr>
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<td>0.2</td>
<td>10.1</td>
<td>0.43</td>
</tr>
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<td>0.3</td>
<td>10</td>
<td>0.43</td>
</tr>
<tr>
<td>0.4</td>
<td>9.95</td>
<td>0.22</td>
</tr>
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<td>0.5</td>
<td>9.9</td>
<td>0.22</td>
</tr>
<tr>
<td>0.6</td>
<td>9.85</td>
<td>0.22</td>
</tr>
<tr>
<td>0.7</td>
<td>9.8</td>
<td>0.22</td>
</tr>
<tr>
<td>0.8</td>
<td>9.78</td>
<td>0.09</td>
</tr>
<tr>
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<td>9.74</td>
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</tr>
<tr>
<td>1.0</td>
<td>9.7</td>
<td>0.18</td>
</tr>
</tbody>
</table>

**Table 5.16:** Modulated Ridge Pattern Waveguide Attenuation, 650 nm Laser
Figure 5.35: Straight Ridge Pattern Waveguide Attenuation (dB/cm)
Figure 5.36: Straight Ridge WG Attenuation, Modulated Light. (dB/cm)

Modulated Ridge Patterned Waveguide

$0.22 \text{ dB/cm, } \lambda = 650\text{nm}$

$0.09 \text{ dB/cm, } \lambda = 1550\text{nm}$
<table>
<thead>
<tr>
<th>Prism Position (cm)</th>
<th>Voltage (mV)</th>
<th>Attenuation (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>9.78</td>
<td>-</td>
</tr>
<tr>
<td>0.1</td>
<td>9.75</td>
<td>0.13</td>
</tr>
<tr>
<td>0.2</td>
<td>9.72</td>
<td>0.13</td>
</tr>
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<td>0.3</td>
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<td>0.09</td>
</tr>
<tr>
<td>0.4</td>
<td>9.68</td>
<td>0.09</td>
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<td>9.66</td>
<td>0.09</td>
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<td>9.64</td>
<td>0.09</td>
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<td>0.7</td>
<td>9.62</td>
<td>0.09</td>
</tr>
<tr>
<td>0.8</td>
<td>9.6</td>
<td>0.09</td>
</tr>
<tr>
<td>0.9</td>
<td>9.55</td>
<td>0.23</td>
</tr>
<tr>
<td>1.0</td>
<td>9.5</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.09 ± 0.06</td>
</tr>
</tbody>
</table>

Table 5.17: Modulated Ridge Pattern Waveguide Attenuation, 1550 nm Laser

Figure 5.37: Straight Ridge Waveguide
5.9.3 Meander Waveguides

Optical attenuation of meander waveguides was measured in a similar fashion as in the previous case. Meander line I corresponds to the long curvy line located at the center of the waveguide and Meander line II corresponds the short curvy line at the edge of the optical waveguide.

![Microscope View of Meander Line WG on Glass](image)

Figure 5.38: Microscope View of Meander Line WG on Glass

Due to the curvy nature of the meander waveguide the optical losses are expected to be higher than in the case of a slab or ridge waveguide. A curvy waveguide inherently present higher attenuation. A formula for curvature loss in optical fiber was proposed by D. Marcuse [131].
<table>
<thead>
<tr>
<th>Prism Position (cm)</th>
<th>Voltage (mV)</th>
<th>Attenuation (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>14.5</td>
<td>-</td>
</tr>
<tr>
<td>0.1</td>
<td>13.4</td>
<td>3.43</td>
</tr>
<tr>
<td>0.2</td>
<td>12.3</td>
<td>3.72</td>
</tr>
<tr>
<td>0.3</td>
<td>11.0</td>
<td>4.85</td>
</tr>
<tr>
<td>0.4</td>
<td>10.2</td>
<td>3.28</td>
</tr>
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<td>9.1</td>
<td>4.96</td>
</tr>
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<td>8.2</td>
<td>4.52</td>
</tr>
<tr>
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<td>7.4</td>
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<td>0.8</td>
<td>76.8</td>
<td>3.67</td>
</tr>
</tbody>
</table>

### Table 5.18: Meander I Waveguide Attenuation, 650 nm Laser

<table>
<thead>
<tr>
<th>Prism Position (cm)</th>
<th>Voltage (mV)</th>
<th>Attenuation (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>14.3</td>
<td>-</td>
</tr>
<tr>
<td>0.1</td>
<td>13.1</td>
<td>3.81</td>
</tr>
<tr>
<td>0.2</td>
<td>12.2</td>
<td>3.09</td>
</tr>
<tr>
<td>0.3</td>
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<td>2.95</td>
</tr>
<tr>
<td>0.4</td>
<td>10.5</td>
<td>3.57</td>
</tr>
<tr>
<td>0.5</td>
<td>9.8</td>
<td>3</td>
</tr>
<tr>
<td>0.6</td>
<td>9.1</td>
<td>3.22</td>
</tr>
<tr>
<td>0.7</td>
<td>8.4</td>
<td>3.48</td>
</tr>
<tr>
<td>0.8</td>
<td>8</td>
<td>2.12</td>
</tr>
</tbody>
</table>

### Table 5.19: Meander I Waveguide Attenuation, 1550 nm Laser

Attenuation $= 4.09 \pm 0.66$

Attenuation $= 3.04 \pm 0.49$
Meander I Waveguide

\[ 4.09 \text{ dB/cm}, \lambda = 650\text{nm} \]

\[ 3.04 \text{ dB/cm}, \lambda = 1550\text{nm} \]

Figure 5.39: Meander I attenuation

Figure 5.40: Meander I Line WG
<table>
<thead>
<tr>
<th>Prism Position (cm)</th>
<th>Voltage (mV)</th>
<th>Attenuation (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
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<td>-</td>
</tr>
<tr>
<td>0.1</td>
<td>13</td>
<td>3.22</td>
</tr>
<tr>
<td>0.2</td>
<td>12.1</td>
<td>3.12</td>
</tr>
<tr>
<td>0.3</td>
<td>11</td>
<td>4.14</td>
</tr>
<tr>
<td>0.4</td>
<td>9.9</td>
<td>4.58</td>
</tr>
<tr>
<td>0.5</td>
<td>9</td>
<td>4.14</td>
</tr>
<tr>
<td>0.6</td>
<td>8.3</td>
<td>3.52</td>
</tr>
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<td>0.7</td>
<td>7.4</td>
<td>4.98</td>
</tr>
<tr>
<td>0.8</td>
<td>6.7</td>
<td>4.32</td>
</tr>
</tbody>
</table>

Attenuation: 4.14 ± 0.66

Table 5.20: Meander II Waveguide Attenuation, 650 nm Laser

<table>
<thead>
<tr>
<th>Prism Position (cm)</th>
<th>Voltage (mV)</th>
<th>Attenuation (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
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<td>13.1</td>
<td>2.89</td>
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<td>2.95</td>
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<td>0.4</td>
<td>10.6</td>
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<td>0.5</td>
<td>9.8</td>
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<td>9</td>
<td>3.70</td>
</tr>
<tr>
<td>0.7</td>
<td>8.3</td>
<td>3.52</td>
</tr>
<tr>
<td>0.8</td>
<td>7.8</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Attenuation: 3.13 ± 0.34

Table 5.21: Meander II Waveguide Attenuation, 1550 nm Laser
Figure 5.41: Meander II attenuation

Figure 5.42: Meander II Line WG
An arbitrary curvature in the waveguide introduces losses that are due to radiation, these losses are due to the transition at entering or exiting a curve and bending losses, [132]. Analysis and simulation methods have been devised to accurately determine the losses that occur in curved optical waveguide structures. [133].

Meander optical waveguides presented higher attenuation than those of either the ridge or slab waveguide. These results were certainly expected, nevertheless it is certainly promising that, the losses of the curvy waveguide are in fact smaller than what has been reported by Tang et. al. [129]

Optical attenuation measurements on meander I waveguide were recorded in tables 5.18 and 5.19. Attenuation measurements of the meander II waveguide are displayed in tables 5.20, and 5.21, at a laser emission of 650 nm and 1550 nm respectively. It is evident that losses for both meander I and II waveguides are lower at 1550 nm.
5.9.4 Optical Couplings Loss

Laser light was coupled to the waveguide with optical fiber and coupled out of the waveguide with the rutile prism. Optical attenuation of due to the coupling of optical fiber and optical waveguide and the optical losses due to the coupling between optical waveguide and rutile, TiO$_2$, prism are inherent to the characterization setup.

Figure 5.43: Signal Generator Waveform HP239A

Figure 5.43 displays the oscillator electrical signal used to modulate a 1550 nm laser. Figure 5.44 displays the laser modulated optical signal that was detected with a optoelectronic converter, and transduced into an electric signal to be displayed on the oscilloscope.
Figure 5.44: 1550 nm Laser Diode Modulated Output.

Figure 5.45: Opto-electronic Converter TEK P6702
Figure 5.46: Opto-electronic signal, 1550 nm

<table>
<thead>
<tr>
<th>Input (mV)</th>
<th>Output (mV)</th>
<th>Attenuation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>120</td>
<td>-9.3</td>
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<tr>
<td>400</td>
<td>150</td>
<td>-8.5</td>
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<tr>
<td>375</td>
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<td>-9.5</td>
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<tr>
<td>425</td>
<td>160</td>
<td>-8.5</td>
</tr>
<tr>
<td>380</td>
<td>130</td>
<td>-9.3</td>
</tr>
<tr>
<td>420</td>
<td>160</td>
<td>-8.4</td>
</tr>
</tbody>
</table>

| Attenuation | 8.9 ± 0.5 |

Table 5.22: Waveguide-Prism-PD Attenuation, 650 nm Laser
The electronic converter TEK P6702 shown in Figure 5.45 was used to detect the modulated laser signal, before the signal was coupled into the waveguide with optical fiber connector, and after it was out coupled. The waveform in Figure 5.46 shows the optical signal detected out of the rutile prism after opto-electronic conversion took place.

The output signal showed attenuation consequence of the two inherent coupling losses: optical attenuation due to optical fiber connector-waveguide coupling, and prism-waveguide-optical fiber out coupling. The prism position for this measurement is at $x = 0$ mm from the optical fiber coupling. The total attenuation is the product of the two individual losses, and each attenuation can not be isolated, data is presented in Table 5.22.

### 5.10 Conclusions

Dispersion analysis of amorphous aluminum nitride, based on the Sellmeier equation showed that the material dispersion suffers a cross over zero at a wavelength of 1.52 µm, which suggest the existence of solitons at wavelengths longer than the crossover point. Dispersion analysis of the ridge waveguide effective index predicted a crossover at 1.42 µm, which allows solitons to exist for $\lambda > 1.42$ µm. Both results fit the standard wavelength in optical communications 1.55 µm.

The existence of solitons was simulated on amorphous aluminum nitride as well as in silica fiber; it was also predicted that for the same applied optical power, soliton pulses in amorphous aluminum nitride would be shorter than optical solitons in silica fiber.
Waveguide confinement due to structure such as the ridge waveguide, improves device performance, lower attenuation and longer transmission range than in slab waveguide. Optical attenuation at 1550 nm wavelength laser light was reported, lower than at 650 nm wavelengths, as expected.

Meander waveguide showed the highest attenuation, as predicted in the theory of curvy waveguides, but in agreement with reported data. Attenuation of 4.7 dB/cm was reported by Fraaga et al. in 2014 [134]. Results in this study are much smaller, than the large propagation loss of 27 dB/cm at $\lambda = 1.5\mu m$ reported by Liu, 2015 [135].

The waveguide losses of amorphous aluminum nitride found in this research, are among the best results reported so far, 0.1 dB/cm. Pernice et al reported attenuation of AlN deposited by sputtering to be 0.8 dB/cm, at wavelength of 766 - 780 nm [136]. Lin reported AlN attenuation to be 0.83 dB/cm $\lambda = 2.5\mu m$, [137]. Aluminum nitride remains a very promising optical material.

Waveguide scattering losses can be substantially improved by the use of a thick upper cladding of of SiO$_2$, as reported by Bauters et al. in 2011, on Si$_3$N$_4$ [138]. Waveguide losses, might be also reduced with using lithography with a shorter wavelength, such as extreme ultra violet.
Appendix

Soliton Background

Solitons were first reported in 1844, Report on Waves [139], by a Scottish hydrodynamic engineer John Scott Russell, [140] who witnessed a solitary water wave in August 1834, that propagated over two miles along the Union Canal linking Edinburgh with Glasgow, with no change of shape or diminution of speed, [141], [142].

Since its first observation in 1834, the soliton initiated controversy and scientific debate; for it contradicted the prevalent ideas about nonlinear phenomena in shallow waters (which in fact neglected dispersion). It was necessary to wait until 1895 for a theory that could describe solitons, namely the Korteweg-De Vries equation or KdV equation for short:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \delta^2 \frac{\partial^3 u}{\partial x^3} = 0 
\]  

(5.10.1)

Fermi, Pasta and Ulam in 1955 [143], tried to model heat transfer in one dimensional lattice, under nonlinear interactions, and obtained results that contradicted thermodynamics since their model was not reaching thermal equilibrium [144]. Their results motivated Zabusky and Kruskal in 1965 [20], [25], to further explore this problem [33]. Using numerical modeling they solved the well known Korteweg de Vries equation, which solution they called solitons, the term was in fact coined by them, in
reference to a “solitary-wave pulse” that focuses in space-time as observed in numerical solutions. Their work is certainly and landmark in soliton research. They observed that solitons, preserved their shapes after collisions with only a small change in their phases.

**Equipment List**

1. 169 Keithley Multimeter (2)
2. 239A Hewlett Packard Oscillator
3. Power Supply Model IP-18, 0 - 15 VDC, 500 mA.
4. 8000 A Fluke, Digital Multimeter
5. 4005 Power Designer Inc., Power Supply, 0 - 40 VDC, 100-500 mA
6. Model TC371 Video Camera
7. 300 A Amdek Video (Monitor)
8. Mic 931 Mica Power Supply ± 5 VDC, ± 12 VDC, 1.2 A
9. TEK P6702, Tektronix O/E Detector
10. 5403 Tektronix Oscilloscope, Time base 5840, Input Differential Amplifier 5A21N,
11. Fibertech 105 Laser Source
12. Schmitt Trigger Based Laser Driver (Section 5.5.3)
13. AM-3500 Laser Precision, Optical Power Meter
Fabrication Methods

Lengthy processing methods relevant to material from chapter 4, are described in detail in present section.

Procedure I

1. Prepare a fresh mixture of deionized water (H$_2$O), hydrogen peroxide (H$_2$O$_2$) and HN$_4$O$_4$, by:
   - heating a mixture of 50 ml of HN$_4$O$_4$ and 200 ml of DI water in a beaker to 90°C on a hot plate [this takes about 9 minutes],
   - remove beaker from hot plate and add 50 ml of H$_2$O$_2$ the solution is ready after 1 minute when vigorous bubbling begins

2. Immerse and hold substrates in the ammonia-peroxide solution for 15 minutes (900 seconds on kwikset chronometer) and let the bubbles do their cleaning action

3. Rinse the substrates in succession in 3 different beakers, of DI water for 3 minutes in each beaker

4. Perform the water break test by:
   - removing the substrate from the last DI water beaker and identify the substrate side intended for deposition
- observe the water edge downward flow with a smooth border until the surface is completely dry. A sudden breakup of the water edge means contamination is present and the washing must be repeated.

5. Blow dry the substrate completely with nitrogen. Remember to shut valve when done.

6. Prepare a mixture of DI water, Hydrogen peroxide and Hydrochloric acid by

- heating a mixture of 50 ml of Hydrochloric Acid (HCL) and 200 ml of DI water in a beaker to 90°C [this takes about 9 minutes]
- Remove beaker from hot plate and add 50 ml of DI water, the solution this time will bubble instantly.

7. Soak substrates for 15 minutes (900 seconds on kwikset chronometer) and let the bubbles work.

8. Repeat the rinsing as described above.

9. Repeat the water break test and if it fails repeat this second part

Procedure II

1. Substrates were mounted right after RCA washing. Pressure in the chamber was then reduced with the roughing pump to $3 \times 10^{-3}$ Torr in the following steps:

   (a) All pneumatic valves were initially closed (foreline and roughing valve), then the manual valve on the roughing pump was opened very slowly to
start pumping of the vacuum line while vibration is minimized at the pump,
than the valve was closed when line has been fully pumped.

(b) With the manual valve closed, the foreline pneumatic valve was opened
slowly followed by opening the manual valve until the foreline pressure
was about 50 mTorr. Then the manual valve was closed again.

(c) Foreline valve closed, the roughing valve was opened followed by slightly
opening the manual valve to pump the chamber. After a few minutes the
roughing valve was closed followed by the manual valve in that sequence.

(d) With all pneumatic valves closed the gate valve was opened when the
pressure in the diffusion pump (foreline) was much lower than that in the
chamber. This forced the chamber lid to be *sucked in* by the vacuum in the
foreline, sealing the chamber lid as it compresses the o-ring sealing the
lid.

(e) Since the foreline pressure increased during lid sealing step b was re-
peated. Then step d was repeated to reduce chamber pressure. These
steps were alternately repeated until minimum pressure of $3 \times 10^{-3}$ Torr
was achieved.

(f) Finally the foreline valve was closed and the roughing valve was opened
while, keeping the gate closed to pump down the chamber, ready for the
next step.

2. The chamber was outgassed to eliminate any residual humidity. This was
achieved by means of a heating lamp that raised the temperature inside the
chamber up to 250 °F. After 60 minutes the lamp was turned off and two fans
were placed over the chamber and by the side wall to cool it down quickly. Since there was an O-ring in the chamber lid the temperature was limited to 200 °C. A J-type thermocouple was mounted inside the chamber to monitor the temperature in °F.

3. Open foreline valve and close roughing valve, once the temperature in the chamber is brought down to about 80 °F and keeping the gate valve closed. Chamber pressure should stay low at 3×10⁻³ Torr while the ultra low vacuum is achieved with diffusion pump.

4. Diffusion pump heater is now turned on, while pumping the foreline. A Deionized water recirculation system for cooling the walls of the diffusion pump, must be enabled before turning the D.P. heater on, otherwise there will not be power available to operate diffusion pump heater since it is interlocked. Power delivered to the diffusion pump heater is also controlled with the variac above described. Such heater was modified in order to facilitate maintenance and repair of the system in case of failure; so far the heating element has been replaced 3 times. Experience has shown that it is inadvisable to use voltages larger than 90 volts it is very liable to burn the heating element. The oil for the diffusion pump used is a Kurt Lesker 704 which boiling point is 215 °C and flash point is 221 °C. The oil temperature can not be directly measured; a thermocouple is mounted at the bottom of the diffusion pump to monitor its temperature closely, which is usually around 180 °C after the diffusion pump heater has been on for one hour and 30 minutes.

5. Cold cathode (ionization) pressure gauge located in the chamber can be turned
on now, its response takes a few moments depending on the vacuum level the higher the slower.

6. Foreline valve is kept open, and once the temperature at the bottom of the diffusion pump is about 185 °C, now open the gate valve so the ultra high vacuum in the diffusion pump sucks in the contents of the chamber reducing its pressure down to $4 \times 10^{-6}$ Torr.

7. System should be kept pumping chamber for a period of time before diffusion pump is turned off. 30 minutes (when system is being used frequently) or 60 minutes (when system has not been used for a while). Turn diffusion pump off, keep running the water cooling on the D.P. walls and observe pressure at chamber start to raise slowly.

8. Gate valve is closed when chamber pressure is at $1 \times 10^{-4}$ Torr. High purity nitrogen valve is carefully open and chamber pressure increases to $5 \times 10^{-3}$ Torr, the system is ready to start the plasma.

9. Start the water cooling re-circulation system on the sputtering gun, this is a crucial step. Its purpose is to cool the gun from heat generated by the power delivered from the RF generator, i.e. it exchanges heat from the s-gun by means of water recirculating through a heat radiator. There is a simple water sensor that indicates the water is flowing throughout the gun and radiator. Copper pipes in radiator can be touched with bare hands to make sure the cooling water is not overheating. This is a very important step, for it will provide the plasma a lot of stability but if neglected the system’s health will be compromised. Last time a failure occurred, the cooling system stopped running for it was clogged,
the sputtering gun overheated and all of the sealing o-rings melted allowing cooling water to leak into chamber. Sputtering gun needed to be dismounted and completely rebuilt, chamber then must be sealed and all leaks fixed, all that takes unfortunately a lot of time.

10. RF generator power can now be safely turned on. Plasma will now ignite if all conditions above described are satisfied. A matching network has to be adjusted in order to maximize delivered RF power to the sputtering gun and ultimately the plasma and minimize the reflected power back to the generator. Matching network available in the Lab has a primary capacitor for coarse control and secondary capacitor for fine control. The maximum power must not exceed 500 W. due to the maximum capacity of generator and the reflected power is kept at all times about 20%, certainly no more than 30 % of maximum power. Figure 4.7 shows the RF power meter, built by VCI Vectronics model PM-30 that monitors both forward and reflected power.

11. Attention must be paid to the nitrogen valve such that chamber pressure does not raise too much above $7 \times 10^{-3}$ Torr in chamber. RF power conditions, as above described, must be continuously monitored. If the water recirculation cooling system on the sputtering gun is working efficiently the plasma will be very stable. Two external fans are normally placed around the chamber, one directly next to the sputtering gun, they operate as long as the RF generator is On and sputtering takes place.

12. Diffusion pump cooling system has been kept running and diffusion pump will be totally cooled. It is safe to shut D.P. cooling system.
13. After about 2 or 2.5 hours of continuous sputtering deposition; the nitrogen gas line can now be closed, there is enough gas remanent in the gas line to feed the plasma for at least 10 minutes. RF generator can now be turned off.

14. Pump chamber a short while then close roughing valve, finally close the manual valve on roughing pump finally shut the roughing pump down.

15. Final step is to shut down the diffusion pump water recirculation cooling system.

**Method III**

1. Both aluminum deposition and plasma sputtering chambers must be vented with nitrogen. Once pressure reaches 1 atm (760 Torr) the lid at the sputtering deposition chamber can be lifted, and substrates removed.

2. Substrates are mounted on the thick aluminum slab to hold substrates, as thoroughly described in section 3.3. Two filaments were loaded with five hooks of high purity aluminum, to ensure good contact when probing the material properties.

3. Roughing pump on the aluminum deposition system is of a rather large capacity that is able to reduce the chamber pressure with very little effort. The chamber is a *Bell Jar* made of glass, that keeps a very good sealing against the supporting surface. Alternate pumping of foreline and main chamber is necessary to quickly bring pressure down from $1 \times 10^{-3}$ Torr to $5 \times 10^{-3}$ Torr.

4. Diffusion pump is started, in a very similar fashion to the one described in section 3.4 step 4. It is unnecessary to repeat description here. Only this time
the heater on the diffusion pump is powered at full voltage, for at least one hour before opening the gate. There has been no need to reduce the voltage or to monitor temperature at the D.P. heater.

5. After the diffusion pump has been on for over one hour. Gate valve is manually opened and pressure at chamber will rapidly drop until it reaches \(5 \times 10^{-6}\) Torr. System must be pumped for 15 to 20 minutes to make sure chamber is very clean and ready for deposition.

6. Keeping diffusion pump on, evaporate one aluminum loaded filament at a time with 15 to 20 amperes for 15 to 20 seconds. Dark safety glasses are needed to observe and control the aluminum melting to avoid dropping of metal blobs due to the sudden melting of aluminum. This will naturally show a pressure increase in the chamber, due to the aluminum vapor.

7. Keep the diffusion pump operating for 10 to 20 minutes, to make sure the the chamber is completely vapor free, until the pressure is the same as before evaporation took place. Once that pressure has been reached, the diffusion pump can now be shut down. The gate is again closed once it reaches \(1 \times 10^{-4}\) Torr. Chamber will be able to keep that pressure for several days until re-opened.

8. Water cooling of diffusion pump walls must be kept running as well as the roughing pump with the foreline valve open. A fan is placed on the diffusion pump heater to cool it down; the heater reaches a temperature tolerable to the bare hand touch, after about 1 hour (2 hours without cooling fan) pumping the foreline and keeping roughing valve closed.
9. Finally, if the diffusion pump heater is cool, close the foreline valve and the roughing pump can now be safely turned off.

Ellipsometry

Electromagnetic waves when reflected on a material surface, suffer a change in their phase and amplitude. Such change of parameters depend upon the angle of incidence $\phi$, the refractive index $n$, the extinction coefficient $k$ and the polarization of the incident beam. Light linearly polarized parallel to the plane of incidence is called $p$-polarized light. Light linearly polarized perpendicular to the plane of incidence is called $s$-polarized light [145], [146].

Although it is not possible to determine the absolute values of phase shift $\delta$ and amplitude change $r$ by ellipsometry. It is possible to determine the relative phase shift and amplitude change:

$$\Delta = \delta_p - \delta_s$$

$$\tan \psi = \frac{|r_p|}{|r_s|}$$

$\Delta$ and $\psi$ can be used to calculate the refractive index and the extinction coefficient if the angle of incidence is known, a parameter that can be easily set up.

The Gaertner L117 Null Ellipsometer whose optical diagram is displayed in figure 5.47 is a manually operated null ellipsometer. Equipped with a HeNe laser emitting at 632.8 nm (L), a polarizer that can be rotated 360° (P), a fixed quarter wave plate
compensator (Q), an analyzer that can be rotated $180^\circ$ (A), an optical detector (D), and a substrate holder for the sample under study. Polarizer and Analyzer are rotated in order to null the signal at the detector.

Gaertner L117 was the instrument used to measure $\Delta$ and $\psi$ on AlN, glass, Si, and GaAs. The Standard Operation Procedure is the following:

Preparation

- Instrument is turned on and laser is allowed to warm up for at least 15 minutes.

- Specimen is placed on sample holder (supporting table). Table raised or lowered to direct reflected laser beam into analyzer pinhole.

- Meter must be observed and table height changed to get maximum reading on meter; if meter exceeds 110 gain control is adjusted so a reading below 100 is obtained. Table clamp screw is tightened at maximum reading.
Measurement Procedure

1. Gain control is adjusted until meter reads below 100.

2. Analyzer (right hand drum) is slowly rotated in the red numbered segment
   \(0^\circ - 90^\circ\) this drum is set to give the lowest reading on the meter.

3. Polarizer (left hand drum) is slowly rotated within the red numbered segment
   \(315^\circ - 135^\circ\) this drum is set to give a new even lower meter reading. If the
   meter exceeds 110, gain must be readjusted to bring maximum reading below
   100.

4. Steps 2 and 3 are repeated to minimize the meter reading. If it falls below 25,
   gain control is adjusted to bring indicator reading up to 100. If the meter can
   no longer be lowered the first analyzer \(A_1\) and first polarizer \(P_1\) are recorded.

5. 90 degrees are added to the first polarizer reading \(P_1 + 90^\circ\). Polarizer is then
   rotated to this new angle.

6. The first analyzer is subtracted from 180 degrees. \(180 - A_1\). Polarizer is now
   rotated to this new angle.

7. Polarizer is slowly rotated, a few degrees, to obtain the lowest reading on the
   meter.

8. Analyzer is slowly rotated to obtain the lowest reading. Gain is adjusted when
   necessary.

9. Steps 7 and 8 are repeated until lowest measurement is obtained. Analyzer and
   Polarizer readings are \(A_2, P_2\) respectively.
10. $\Delta$ and $\Psi$ can now be calculated using the following equations, if $P_1 + P_2 \geq 360^\circ$, $360^\circ$ are subtracted from $P_1 + P_2$.

$$\Delta = 360 - (P_1 + P_2)$$  \hspace{1cm} (5.10.2)

$$\Psi = \frac{180 - (A_2 - A_1)}{2}$$  \hspace{1cm} (5.10.3)
Bibliography


[113] Shallow Junction Silicon Photodiode. minority carrier generated at position x will cross the junction before recombination. in the bulk region, the doping concentration and minority carrier diffusion length are both independent of position, and analytic solutions for the contribution of this region to the. *Applied optics*, 18(6/15), 1979.


