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ABSTRACT

Photonic integrated circuits (PICs) have experienced an exponential growth in a number of applications, including telecom/datacom, LiDAR, optical sensing/metrology and quantum technology. Most materials and platforms commonly used in integrated photonics, such as silicon-on-insulator (SOI), silicon nitride (Si_3N_4) and indium phosphide (InP) do not show transmission below ~400 nm, hindering the development of PICs operating in the ultraviolet wavelength range. Furthermore, devices in this wavelength range also require fast modulation and switching in order to enable complex emerging applications.

Aluminum nitride (AlN) is a material with a band gap of 6.2 eV, exhibiting a wide transparency window, from the ultraviolet to the mid-infrared. AlN has the capacity to achieve high electro-optic[1], non-linear[2] and piezo-electric[3,4] coefficients, which makes AlN an interesting material for PICs with operation down to the ultraviolet wavelength range. However, high losses have prevented PICs from benefiting from its excellent optical properties.

In this work, we present our work on the sputter deposition of low-loss AlN slab waveguides. The optical performance of AlN sputtered slab waveguides after annealing at different temperatures and their relation with the film morphology will be discussed. Preliminary slab propagation losses as low as 1.5 dB/cm at 633 nm of wavelength have been demonstrated.

Keywords: aluminum nitride, AlN, integrated photonics, propagation loss, reactive sputtering, thin film.

1. Introduction

Due to its unique characteristics, aluminum nitride (AlN) has a high potential to enable devices in different fields including quantum information processing, optical sensing/metrology, and bio/chemical sensing. AlN has one of the largest band gaps (6.2 eV) among all known semiconductors and therefore allows it to operate in a wide wavelength range, from UV to IR wavelengths[5]. Many applications require photonic integrated circuits (PICs) operating in a broad spectrum down to the UV and visible (UV-vis). A PIC platform in this wavelength range requires broadband materials that are optically transparent and have low propagation losses. Therefore, AlN is one of the most exciting semiconductors.

Among the existing deposition techniques, magnetron sputtering is a good candidate for industrial applications due to its high deposition rate, uniform coverage for large substrates, and low temperature deposition [6]. Provided that low optical propagation losses can be achieved, AlN layers deposited by this method are ideal candidates for integrated photonics.

Thermal annealing provides the energy for atoms to rearrange, and the grains in the polycrystalline material start to grow. Smaller grains can coalesce into larger grains. All of these have substantial effects on the quality and properties of the film[7,8]. Many groups have used different annealing treatments with different temperatures and times to change the film structure and improve performance. Then, the changes in chemical composition and crystallinity for AlN films before and after annealing were studied[9–11].

In this work, we show our advancements towards low-loss high-confinement sputter deposited AlN waveguides for PICs. First, a 147 nm thick AlN layer is deposited by reactive sputter deposition and its surface and optical properties are characterized. Next, different annealing temperatures are studied, again followed by surface, material and optical characterization. Slab losses ~1.5 dB/cm at 633 nm have been experimentally demonstrated.

2. Materials and Methods

The AlN layer is deposited using a RF reactive sputtering system on 10 cm diameter silicon wafers with 8 µm thick thermal oxide. The temperature of the substrate during deposition was set to 400ºC. A 3-inch Al target (99.999 % purity, 101.6 mm diameter) is powered with its own RF power source. The depositions are performed with a constant RF power of 500 W applied to the aluminum target. The base and processing pressures are 7E-7 and 5E-3 mbar, respectively. Argon is used as

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the sputtering gas and nitrogen as reactive gas with 40 and 4 sccm gas flow, respectively. A deposition rate of 7.7 nm/min was achieved with the applied deposition parameters. The thickness of the deposited layer was 147 nm.

The deposited layer is annealed at 400 °C, 500 °C, 600 °C, 700 °C, 800 °C and 1150 °C. After the wafer is introduced into the annealing oven, N_2 is delivered to the chamber at a flow rate of 2 slm. The standby temperature is 400°C and then increases at a rate of 8°C/min. We kept the wafer at the desired temperature for 3 hours each time.

Surface and optical analysis are performed before and after annealing. First, the thickness and refractive index are measured using a Woollam M-2000UI ellipsometer. Given the 8 µm oxide layer a fitting range from 600 to 1600 nm is used to determine the layer properties with a Cauchy model of the layer. The surface roughness of the layers is measured using a Bruker Fast Scan AFM. The propagation loss of the layer is measured using a Metricon 2010/M prism coupler with a propagation loss module. The propagation loss is determined at 636 nm, 521 nm, 451 nm and 403 nm of wavelength.

3. Results and Discussion

Figure 1 shows changes in thickness and refractive index after different annealing temperatures. At 1150 °C, the ellipsometer measurement shows a significant increase of the layer thickness. The increase in thickness means a decrease in the layer density, which leads to a reduction in the refractive index. Further experiments are currently being carried out to determine the origin of this sudden variation and to verify whether it is simply an artifact of the fitting to the ellipsometer data using a simplified model or whether the changes are real and caused by a change in the stoichiometry and crystallography of the thin film.

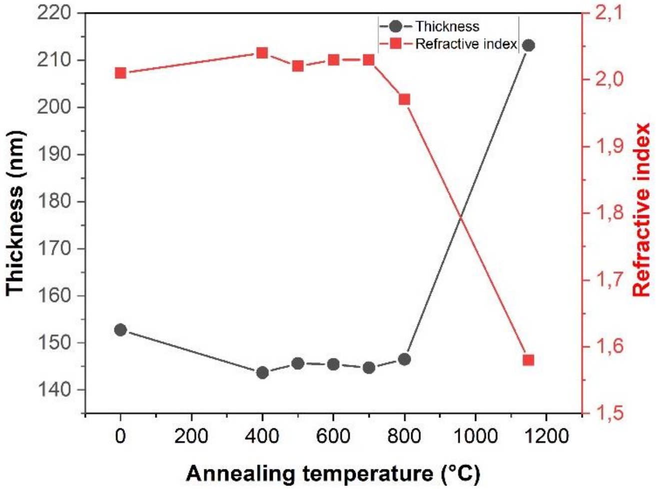
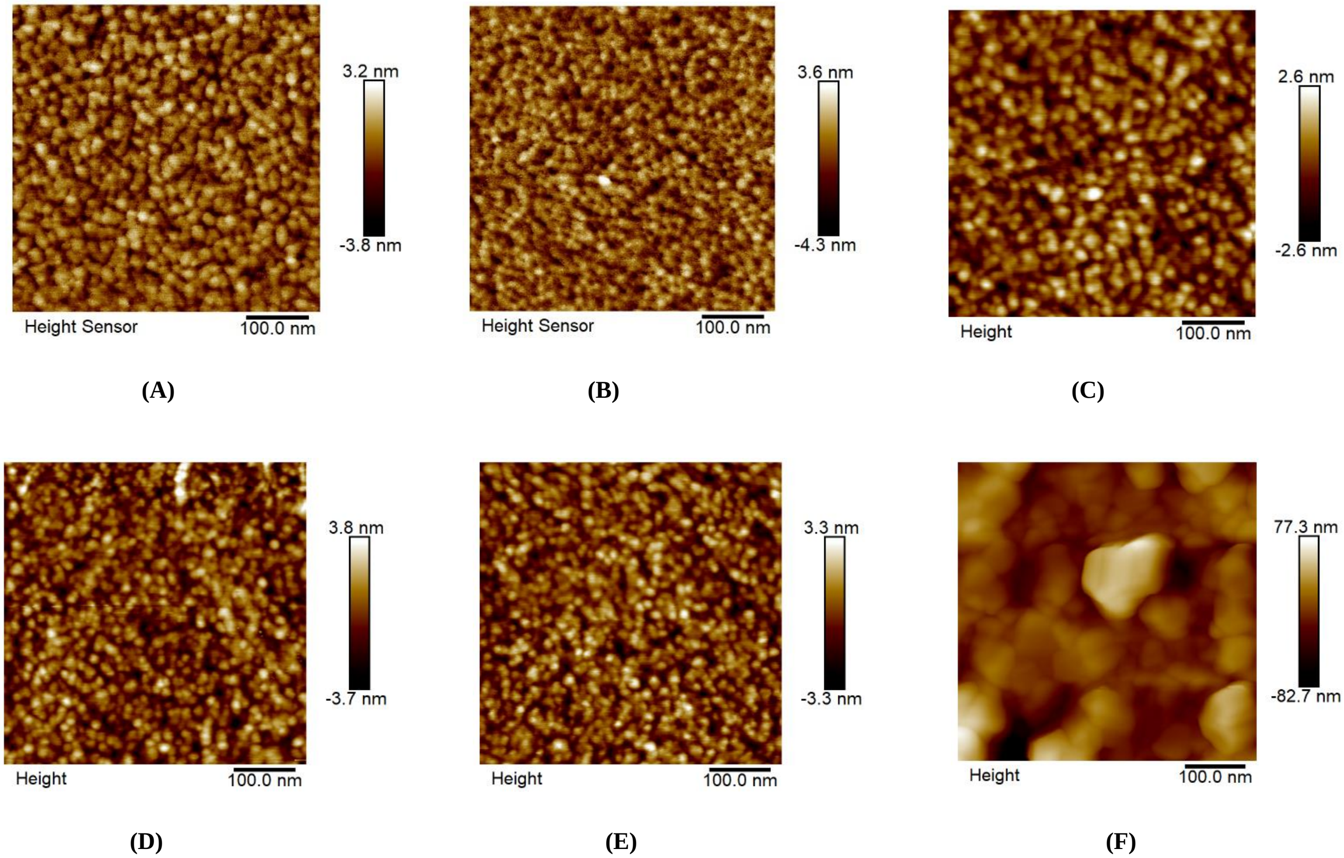


Figure 1. Changing in thickness and refractive index after annealing at different temperatures.

The surface morphologies of the AlN thin film before and after annealing for each temperature are presented in Figure 2 and table 1. The scanned area was 500x500 nm^2. The surface roughness before annealing was 0.57 nm RMS. After annealing, the determined RMS increased step by step with increasing temperature. The increase in surface roughness is likely caused by a change in the morphology of the thin film. After the annealing step at 1150 °C, the surface roughness increased significantly, which can explain a failure in the fit to the ellipsometer data, as discussed above.



(A) **(B)** **(C)**

(D) **(E)** **(F)**

Figure 2 Surfaces of AlN thin films (A) As deposited, annealed at (B) 400°C, (C) 600°C, (D) 700°C, (E) 800°C, (F) 1150°C

Table 1. RMS for all annealing conditions

Annealing temperature (°C)	**As deposited**	**400**	**600**	**700**	**800**	**1150**
Roughness RMS (nm)	0.57	0.62	0.76	1.11	0.97	20.40

Figures 3 (A), (B), (C), (D), (E), and (F) show the effect of the annealing process on the propagation losses as determined by the prism coupling measurements.

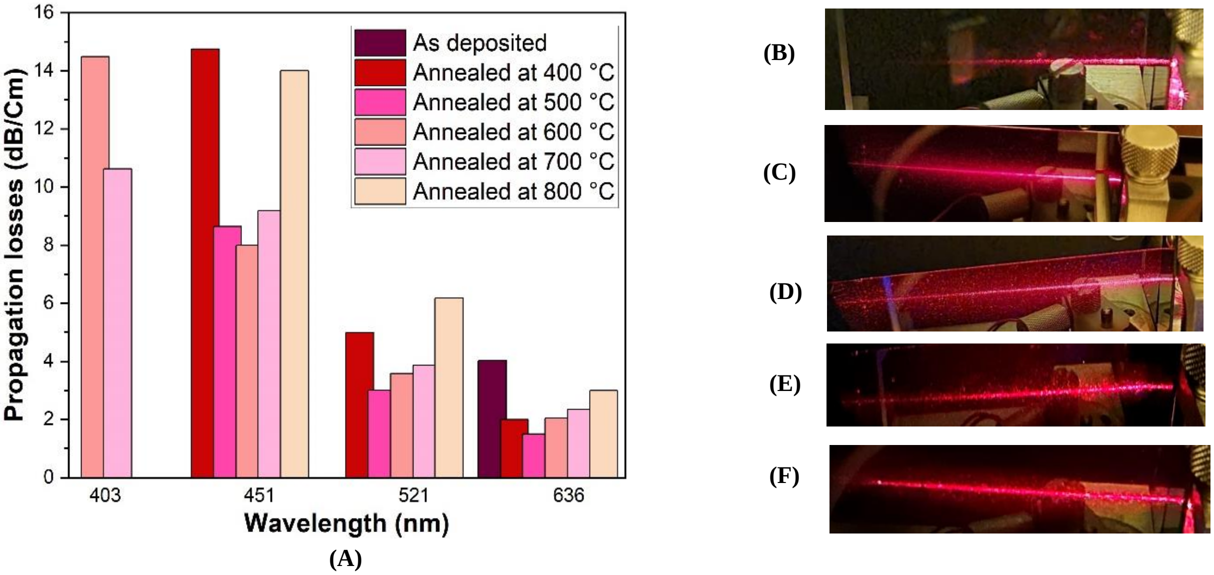


Figure 3 (A) Propagation losses at different wavelengths before and after annealing, Picture of the guided red light (636 nm) for (B) as deposited (4.03 dB/cm), (C) annealed at 400°C (2.02 dB/cm), (D) annealed at 600°C (2.06 dB/cm), (E) annealed at 700°C (2.35 dB/cm), (F) annealed at 800°C (2.99 dB/cm).

Before the annealing process, the AlN layer had high losses and we just measured 4.03 dB/Cm at 636 nm wavelength. The annealing process helped reduce the propagation losses of the layer and enabled optical propagation for shorter wavelengths. Recently, Dong et al. and Wu et al. showed that the annealing process could effectively reduce the propagation loss of AlN waveguides[10,12]. The absorption of materials due to hydrogen bonds formed during the deposition process is one of the reasons for the high propagation losses in the layer. The remaining H_2O and O_2 in the deposition chamber cause these bonds to form[13]. High temperature annealing reduces propagation losses by removing some impurities.

As the temperature increases, the propagation losses increase again. Losses are affected by various parameters such as impurities, roughness and crystalline morphology. During sputtering, atomic mismatches are created in the AlN film structure. Annealing, by reducing the stress in the layer and its effect on the crystal lattice, reduces threading dislocations and defects in the AlN layer and the crystalline morphology and impurities can be improved[7]. Also, we can see that the annealing process has increased the surface roughness, as a result of which the propagation losses increase[14]. In Figure 2(A), we can see that up to a temperature of 500°C, the impact of the reduction of threading dislocations and defects in the layer may be more obvious. Thus, the losses are significantly reduced. After that, as the annealing temperature increases, the losses due to scattering plays the main role and causes an increase in propagation losses. After 1150 °C, we have a high losses layer. As we saw in the AFM results, the surface roughness also increased significantly, about 20 times at this temperature. This is the main reason for the increase in scattering losses. Also, changes might be caused by a difference in the stoichiometry and crystallography of the thin film due to the high temperature step. Experiments are currently under way to further understand the mechanisms that relate structural changes, surface roughness variations and propagation losses in the annealed films.

Figure 3(B-F) shows a picture of the fundamental 636 nm mode propagating through the layer before and after annealing at different temperatures. Although much more work still needs to be completed, these experimental results confirm the ability of sputter deposition and annealing process to produce and develop a low-loss AlN optical layer for waveguide fabrication.

4. Summary

In summary, we report the fabrication, annealing and characterization of AlN layers with low propagation losses in the 633 nm and visible wavelength range. Silicon wafers with 8 µm thick thermal oxide buffer were sputter coated with an AlN layer of thickness 147 nm. The measured propagation losses show that the annealing process can reduce the propagation losses for the AlN layer.

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