**Optical Quality ZnSe Films on Silicon for Mid-IR Waveguides**

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ZnSe films were deposited on silicon substrates by evaporation and RF-sputtering and compared for their structural, morphological and optical properties. The deposited films were tested as waveguide cladding and the evaporated films showed lower loss.

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1. Introduction

Zinc selenide (ZnSe) is a group II-VI compound and an important optoelectronic material. This metal-chalcogenide has useful semiconducting properties such as wide and direct bandgap, low electrical resistivity, n type conductivity, and good optical properties such as wide transparency over the visible to mid infrared region, high refractive index, low dispersion and high photosensitivity. It is also a non-hygroscopic and chemically stable compound. ZnSe has been widely studied and used in the form of thin films in various optoelectronic devices and applications such as LEDs, laser diodes, solar cells and anti-reflection coatings. We propose to use ZnSe films as lower claddings or isolation layers on silicon substrates for germanium telluride (GeTe4) waveguides, exploiting its high mid-IR transparency. As an isolation layer, the film must be thick enough to avoid significant penetration of light from the core (GeTe4) into the silicon substrate, as Si has a higher refractive index than GeTe4 and should exhibit low loss. The thickness of a ZnSe film needed as an isolation layer between the silicon substrate and the GeTe4 core has been estimated by numerical modelling to be ~2.5 μm, to achieve a loss below 0.01 dB/cm at λ = 3.7 μm [1]. At longer wavelengths, the thickness of the isolation layer needed increases, so we deposited 4.0-4.5 μm thick ZnSe films on Si to enable characterization of the waveguides at longer wavelengths (6-12 μm). Achieving micron thickness optical quality ZnSe films on silicon is challenging because of the difference in thermal expansion coefficient and the stresses built in the film as the thickness increases above a critical value, due to which the film can peel off [2]. The deposition and characterization of ZnSe films on Si of thickness ranging from 0.25-1 µm using thermal evaporation [3] and 0.7-2.3 µm using RF sputtering [4] have been reported. To the best of our knowledge, no attempt has yet been made to utilize ZnSe films on Si as a cladding layer to realize an optical waveguide. In this paper, we discuss deposition and characterization of ZnSe films deposited by thermal evaporation and RF magnetron sputtering and compare the films for their structural, morphological, compositional and optical properties by field emission scanning electron microscopy (FESEM), atomic force microscopy (AFM), energy dispersive X-ray spectroscopy (EDX) and Fourier transform infrared spectroscopy (FTIR). After optimizing the deposition of robust 4.0-4.5 μm thick ZnSe films on Si, two identical waveguide devices were fabricated with sputtered and evaporated films as lower claddings and were tested at the mid-infrared wavelength of 3.7 µm.

2. Experimental

Silicon (100) substrates were cleaned in H2SO4:H2O2 before ZnSe deposition. For sputtering, a 3 inch target of ZnSe made by CVD was used. The substrates were mounted on a platen facing down towards the target. The substrates were heated in argon atmosphere for 2 hours at 250°C before starting the deposition. A sputtering pressure of 5mTorr and an RF power of 50W were used to deposit the films in an argon flow of 15sccm. The samples were rotated and kept at 250°C throughout the deposition, and the deposition rate was maintained between 0.05 and 0.06 nm/s. The samples were annealed within the chamber in an argon atmosphere at 250°C for two hours before cooling them to room temperature and removing them. The final ZnSe film thickness by RF sputtering was 4.5 µm.

For thermal evaporation, ZnSe pieces made by CVD were placed in a tungsten boat. The substrates were mounted on a platen facing down towards the source and rotated. The substrates were heated in vacuum for 2 hours at 250°C before starting the deposition. After reaching a chamber pressure of 7 x 10-6 mbar, the ZnSe was evaporated at a rate of 0.5-0.7 nm/s to form the film. The deposition was performed in steps, depositing 1 µm thick film at a time and then leaving the samples inside the chamber at 250°C for an hour before starting the next deposition step. This is equivalent to vacuum annealing to release thermal stresses built during the formation of the film. Once the required thickness was achieved, the samples were annealed in the chamber at 250°C for two hours and then allowed to cool to room temperature before opening the chamber. The final ZnSe film thickness was 4.1 µm.

3. Results and discussion

Fig. 1 (a) and (b) show FESEM images of the surface and cross-section of the sputtered ZnSe film on Si. The microstructure and grains of the sputtered film can be seen clearly and the film cross-section reveals the columnar-void structure which can be explained by Thornton’s zone model [5]; a similar structure for sputtered chalcogenide films is reported in [6]. EDX revealed the presence of approximately 4.5% oxygen in the film which may be due to moisture absorption from the ambient in these columns. The atomic concentrations of Zn and Se were found to be 44.5 at% and 51.0 at% respectively. AFM measurements performed over a 1 µm x 1 µm area showed an average roughness of ~13 nm.

Fig. 1 (c) and (d) show FESEM images of the surface and cross-section of the evaporated ZnSe film on Si. The evaporated film is much denser than the sputtered film, but contains some random circular spots which were also observed in [3] and which may be due to “spitting”, where a sudden release of impurities such as carbon or oxygen trapped in the source material leads to bigger spitting of pieces of source material towards the samples. The average roughness of the evaporated film determined by AFM is ~4 nm over a 1 µm x 1 µm area. EDX gave the concentrations of Zn and Se to be 51.5 at% and 48.5 at% respectively, with no detectable oxygen.



Fig. 1 FESEM images of surface and cross-section of (a) and (b) sputtered and (c) and (d) evaporated ZnSe films on Si, respectively

FTIR measurements taken between 1.6 – 20.0 μm showed that both the films are transparent at wavelengths from 1.6 µm to16 μm.

Two identical GeTe4 channel waveguides of thickness 2.1 μm were fabricated by RF sputtering on the ZnSe films acting as isolation layers on silicon; the GeTe4 waveguide fabrication process is described in [1]. Light from a tunable OPO at λ = 3.7 μm was coupled into a 20 μm wide GeTe4 channel using a ZrF4 fiber and the guided light was recorded using a mid-infrared camera from above [7]. Fig. 2 (a) and (b) shows an infrared camera image of the guided light emerging from the waveguide fabricated on sputtered ZnSe film and evaporated ZnSe film, respectively. With the same input power, the sample with the RF sputtered ZnSe film as isolation layer was found to have an additional loss of ~15dB/cm.



Fig. 2 Infrared camera images of channel waveguides fabricated on (a) sputtered and (b) evaporated ZnSe films on Si

3. Conclusion

Thermally evaporated ZnSe films on Si were found to be denser, smoother and to have lower losses at mid-IR wavelengths than RF magnetron sputtered films, and have potential as mid-IR waveguide isolation layers.

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