Optical constants of thin film gallium sulfide layers

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ABSTRACT

Gallium sulfide (GaS) deposited by chemical vapor deposition (CVD) is known to passivate GaAs surfaces. In this paper we examine the thin film optical properties of GaS as they relate to the fabrication of optical waveguides. Spectroscopic ellipsometry was use to determine the index of refraction of GaS films deposited on various substrates. Results indicate that GaS has a high index of refraction suitable for waveguide structures. A gallium sulfide waveguide could provide both the optical interconnect and the passivating layer of GaAs integrated circuits. Progress toward fabricating GaS waveguides is also discussed. Keywords: gallium sulfide, optical waveguide, ellipsometry, optical constants, gallium arsenide

1. INTRODUCTION

Gallium arsenide devices are important components in opto-electronic circuits. Both lasers and photodetectors are commonly fabricated from the GaAs/AlGaAs material system. However, the performance of GaAs devices is often limited by poor surface passivation of GaAs interfaces. High surface recombination velocity and large interface state density can limit lifetime and device miniaturization. For laser devices, a poorly passivated laser facet creates nonradiative recombination centers lowering laser light output and heating up laser facets. For detectors that make use of minority carrier transport or rely on high conductivity of thin GaAs layers, poor surface passivation will limit quantum efficiency and increase joule heating losses. Miniaturization of devices creates high surface-to-volume ratios, increasing the importance of surface quality in device performance.

In recent years sulfur has been studied as a passivating layer for GaAs.[1-5] The improvement in surface recombination by the application of free sulfur on the GaAs surface is well documented.[6-9] What is equally well documented is the short lifetime of sulfur passivation. The decay in passivation is attributed to photo-oxidation of the sulfur-GaAs interface.[10] In several recent reports, a stable, passivated, GaAs interface has been obtained using cubic-GaS.[9,11,12] Cubic-GaS is a metastable phase of GaS created using a molecularly designed single-source CVD precursor.[13] The passivation mechanism of cubic-GaS on GaAs is not fully understood, but appears to be either epitaxial growth of a lattice matched GaS/GaAs interface or a sulfur passivated layer that is environmentally stable.

Cubic GaS exhibits properties that make it suitable for waveguide applications as well. Its high index of refraction ($n>2.5$) makes it compatible with a wide variety of cladding layers. High quality GaS can be deposited via a low temperature (390°C) CVD process. A waveguide that can passivate the light source or detector and provide an optical guiding layer would make a very useful building block for integrated optical circuits. Figure 1 shows a schematic diagram of two GaAs devices passivated and optically coupled using GaS. In this paper we report on the optical constants of cubic GaS and progress towards fabricating GaS waveguides.

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2. CVD DEPOSITION OF GaS

Gallium sulfide films were deposited using the single source precursor: $[(t\text{-Bu})GaS]_4$. The resulting GaS films are thought to have a cubic crystal structure when deposited on GaAs substrates. The crystalline structure degenerates as the layer grows away from the GaAs interface and becomes amorphous after a few atomic layers. Films deposited on amorphous substrates such as thermally grown SiO_2 on silicon are completely amorphous.

GaS was deposited using low pressure MOCVD on both n-type GaAs layers implanted on semi-insulating GaAs substrates and on SiO_2 coated silicon wafers. The single source precursor was sublimed at 245°C and carried to the substrate by a pressure differential from inlet to outlet in the CVD chamber. The substrates were held at 390°C during deposition and the growth rate was approximately 0.5Å/second. The GaS layers averaged about 360Å thick and appeared featureless under a Nomarski optical microscope. The passivation of the GaS/GaAs interface was monitored using contactless sheet resistance measurements of the GaAs n-type layer. Typical sheet resistance measurement of 1260 ohms/square is reduced to 950 ohms/square after GaS passivation. Films for waveguide use were grown ~700Å thick, on 1.5 microns of thermally oxidized SiO_2 on silicon.

3. OPTICAL CONSTANTS OF CVD DEPOSITED GaS FILMS

The complex index of refraction ($n\text{-}ik$) for GaS films was determined using a reflection ellipsometer. Ellipsometry is a well know analytic technique and will not be described here in detail. The reader is referred to reference [14] for a thorough treatment of ellipsometry. Figure 2 shows a block diagram of the ellipsometer. A plane polarized probe beam is reflected off the sample at a known angle of incidence. A polarization analyzer and photodetector measure the reflected beam's intensity and polarization state. The measured quantities are Ψ and Δ where :

$$\tan(\Psi) = \frac{|rp|}{|rs|} \tag{1}$$

and

$$\Delta = \delta p - \delta s \tag{2}$$

rp is the intensity of the parallel polarized beam reflection.
rs is the intensity of the perpendicular polarized beam reflection.

δp and δs are the parallel and perpendicular phase shifts of the E-field vector upon reflection.

From these data the optical constants n and k are deduce via a computer modeling routine. The ellipsometer uses a 75W xenon arc lamp and a scanning monochrometer as a light source from 250nm to 1000nm. The angle of incidence of the probe beam was varied from 55° to 75° in 5° increments with Ψ and Δ being recorded for at least 3 different angles.

All gallium sulfide layers exhibited very low absorption for all wavelengths longer than 500nm. A good fit for the psi and delta data was obtained by fixing k to zero for wavelengths longer than 500nm. Figures 3a and 3b show psi and delta for a $GaS/SiO_2/Si$ waveguide structure. The solid lines in figures 3a and 3b are the modeling result assuming k fixed at zero. The model is in excellent agreement with the experimental data. Figure 4 plots the real part of the index of refraction vs. wavelength for the GaS layer grown on GaAs. GaS has a high index compared to other waveguide materials such as SiO_2, Si_3N_4 and Ta_2O_5. The high index of GaS allows for a wide variety of cladding layer materials for GaS waveguides. The index of refraction of GaS shows relatively high dispersion compared to other waveguide materials. This may limit gallium sulfide's ultimate bandwidth performance but is acceptable for many applications.

Films grown on GaAs substrates generally show higher dispersion compared to films grown on SiO_2 (figure 5). At this time it is not clear whether the variation is due to the thin crystalline layer near the GaAs interface or run to run process variations in film quality. To this point the quality of GaS films has been monitored by electronic properties and not optical properties. Further process optimization will be required for the best optical films.

4. GaS WAVEGUIDES

GaS deposited on thermally grown layers of SiO_2 on silicon were used as test waveguide structures. Attempts were made to couple to the waveguides using the prism coupling method and by end firing. For prism coupling, a rutile prism and a HeNe laser were used. For end firing, the wafer was cleaved to expose a smooth face of the GaS. A 40X microscope objective focused the laser on to the cleaved face of the waveguide. Neither method produced observable coupling. The most likely cause of the poor coupling is non-zero absorption in the GaS film. This conclusion does not run counter to the ellipsometry findings however. The ellipsometer used in this study was not sensitive enough to measure the small values of absorption that determine whether a waveguide will have acceptable transmission losses or not. This first attempt to fabricate a GaS waveguide clearly illustrates the need to optimize GaS optical quality before viable waveguide structures are realized.

5. SUMMARY

We have measured the index of refraction of CVD deposited GaS and found it to be compatible with other waveguide materials. Optical absorption was undetectable between 500nm and 1000nm using ellipsometry. However, absorption was apparently high enough to limit waveguide coupling. Future work will include optimizing GaS deposition for optical properties and a continued effort to fabricate GaS waveguides.

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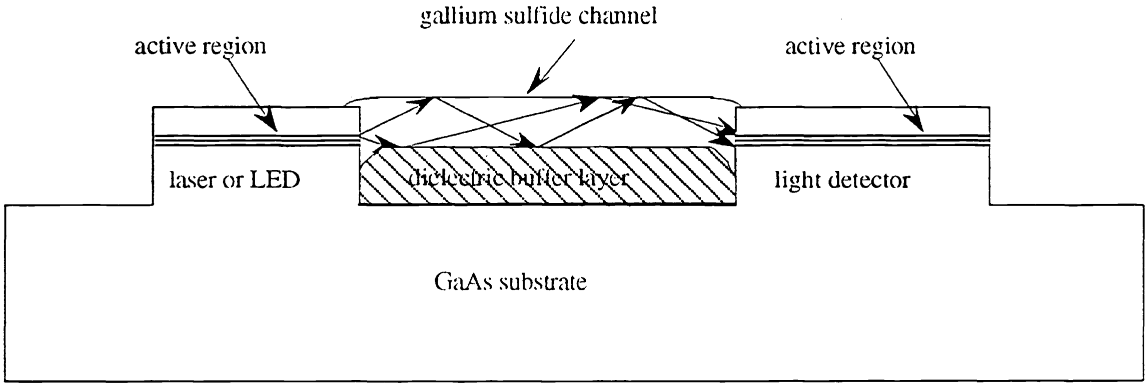


Figure 1. Schematic of a GaS waveguide coupling and passivating two GaAs devices.

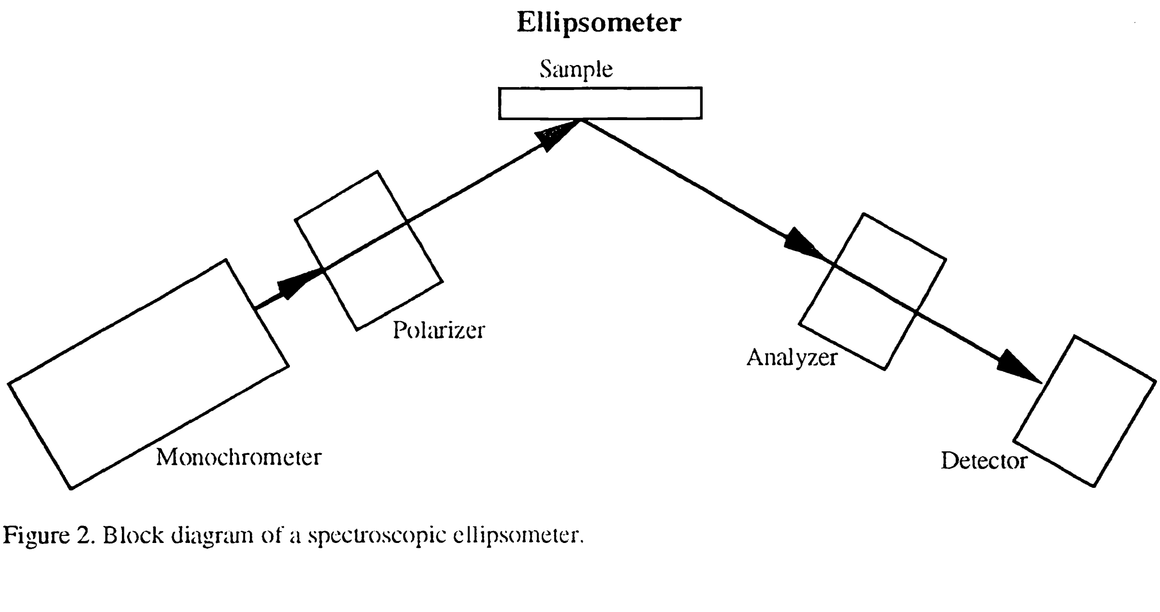
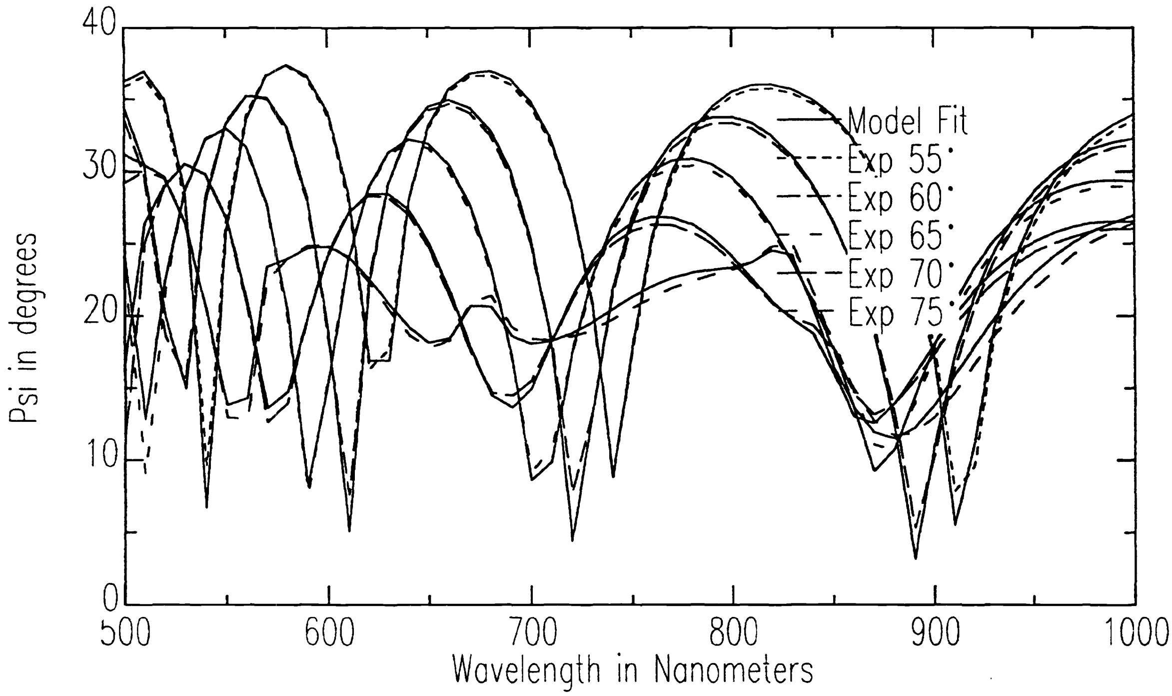


Figure 2. Block diagram of a spectroscopic ellipsometer.



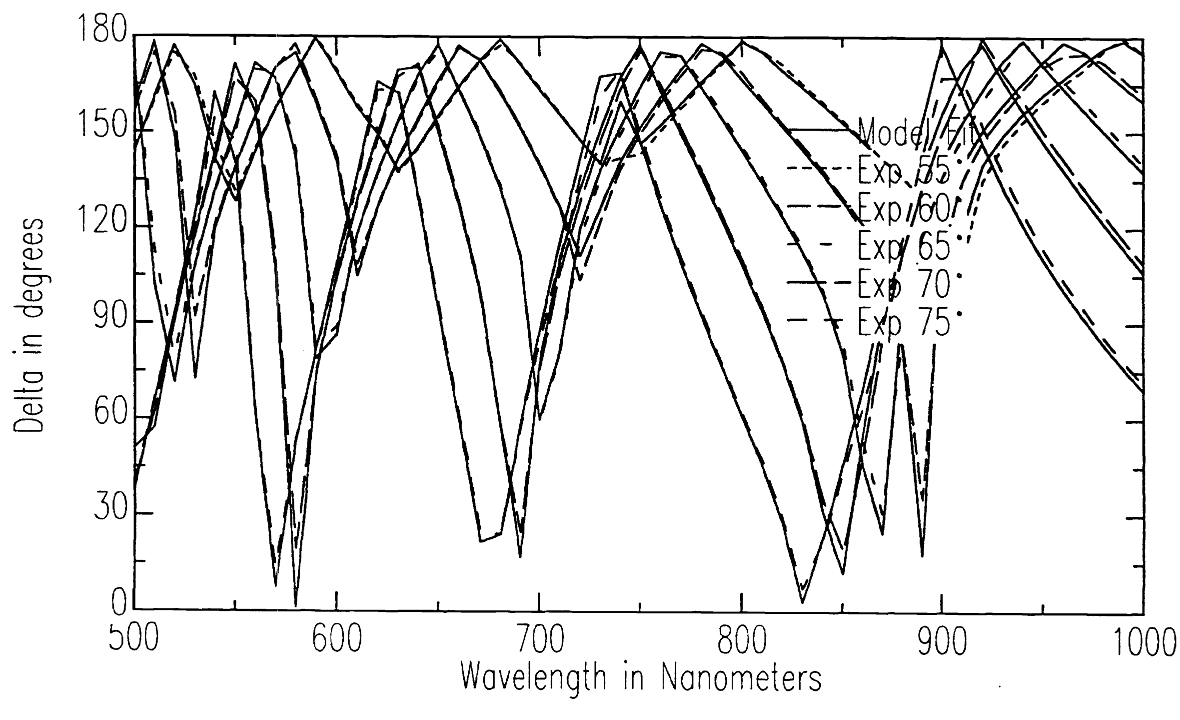


Figure 3a (top), and 3b (above) show ellipsometry data, psi and delta, for a $GaS/SiO_2/Si$ structure at five different angles of incidence. The solid line represents the modeling fit assuming no absorption in the GaS film.

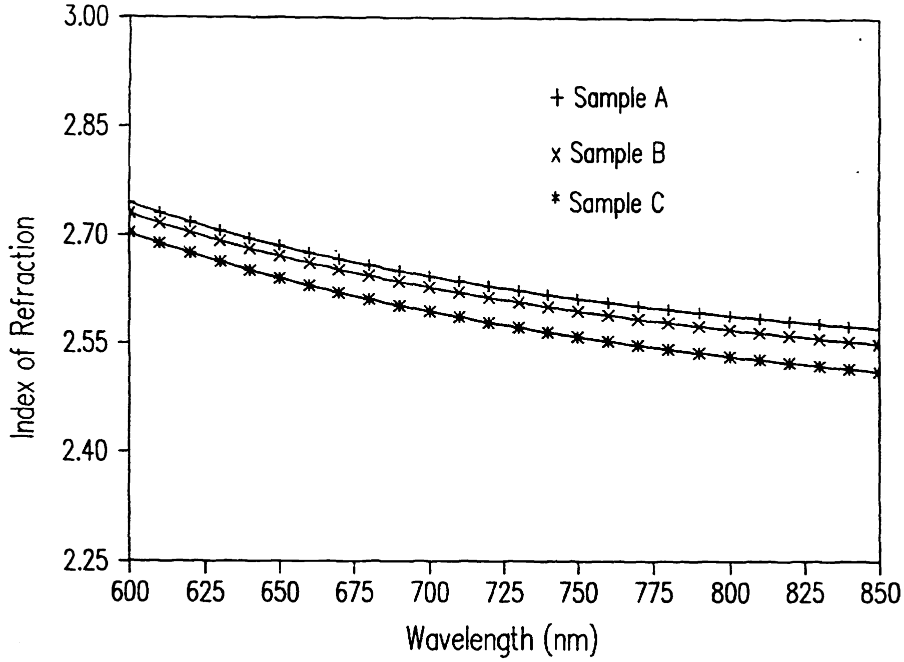


Figure 4. Index of refraction for three samples of GaS/GaAs.

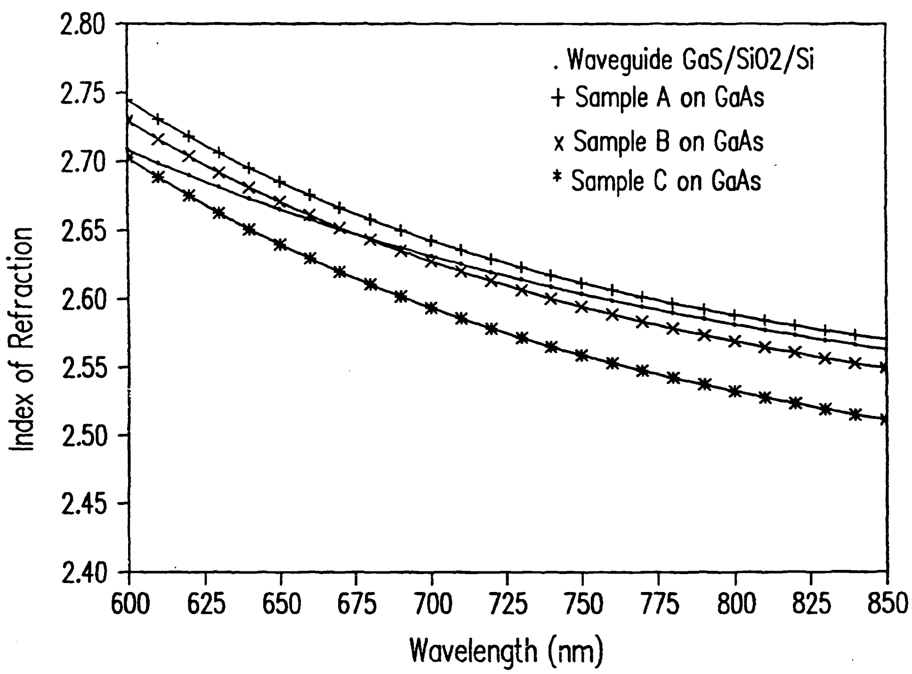


Figure 5. Index of refraction of GaS/SiO2 compared to the GaS/GaAs films of figure 4.