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Prospective for Gallium Nitride-Based Optical Waveguide Modulators

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SUMMARY A complete analysis of GaN-based structures with very promising characteristics for future optical waveguide devices, such as modulators, is presented. First the material growth was optimized for low dislocation density and surface roughness. Optical measurements demonstrate excellent waveguide properties in terms of index and temperature dependence while planar propagation losses are below 1 dB/cm. Bias was applied on both sides of the epitaxially grown films to evaluate the refractive index dependence on reverse voltage and a variation of 2.10^{-3} was found for 30 V. These results support the possibility of using structures of this type for the fabrication of modulator devices such as Mach-Zehnder interferometers.

key words: *Gallium-nitride, electro-optic, optical waveguide, optoelectronics*

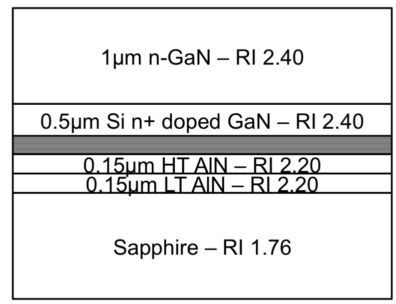

Fig. 1 Schematic of the waveguide structure.

1. Introduction

Electro-optic modulators are used for high-speed optical communication systems and ultra-fast information processing applications [1]. Bulk modulators using discrete electro-optic materials are possible, but operate with relatively high driving voltage (typically > 5 Volts) and narrow modulation bandwidth (f_{max}=30 GHz). To improve these properties, materials with good transparency and electro-optic coefficients, low optical losses, low dielectric constants and single mode waveguide formation are required. III-Nitride materials have already demonstrated good performance as power devices. Optical modulators made out of Gallium Nitride (GaN) and related alloys using an appropriate design open the way in producing a new generation of optical waveguides, useful for passive and active devices such as switches or modulators [2]–[4].

This paper describes the growth, processing and characterization of optical waveguides made on GaN and presents first results on their bias dependent properties.

2. Waveguide Structure Details

The gallium nitride materials have been grown on (0001) sapphire by an in-house MOVPE system using AlN/GaN Short Period Superlattices (SPS) [5], [6]. Trimethyl-aluminum and trimethyl-gallium were used as aluminum and gallium sources and ammonia was used as nitrogen source. After the cleaning of the substrate at high temperature, a low temperature (LT) 150 nm thick AlN layer was grown at 950°C. The temperature was subsequently elevated to a higher value (HT) of 1040°C and a 150 nm thick high temperature (HT) AlN layer was grown onto the LT-AlN. Finally, an interlayer consisting of 10 × GaN/AlN layers having a total thickness of 200 nm was grown under the same HT conditions. The first 500 nm of the GaN grown on top of the interlayer were doped by Silicon to 10^{-18} cm^{-3}. 1 μm thick n-doped GaN was then grown on top to complete the waveguide structure. Optical confinement is assumed to exist within the top GaN layer because of the higher refractive index (RI) of GaN (around 2.40 in the visible) compared to the buffer layer (between 2.20 for AlN and 2.25 for GaN/AlN SPS) and the substrate (around 1.76). Figure 1 presents a schematic of the complete stack together with the corresponding RI values.

3. Microstructure Analysis

First a Scanning Electron Microscopy (SEM) analysis was performed to evaluate the thickness of the waveguide and the results are shown in Fig. 2.

In this figure, the two GaN layers cannot be distinguished from each other. The total thickness of the waveguide made out of them is around 1.5 μm. Transmission Electron Microscopy of the GaN optical waveguide structure was performed to confirm the suitability of the buffer layer for obtaining a quasi-freestanding GaN film. Figure 3

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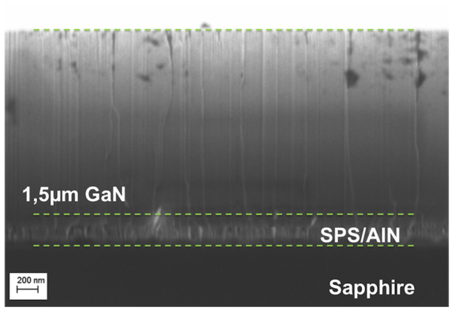

Fig. 2 SEM view of the structure.

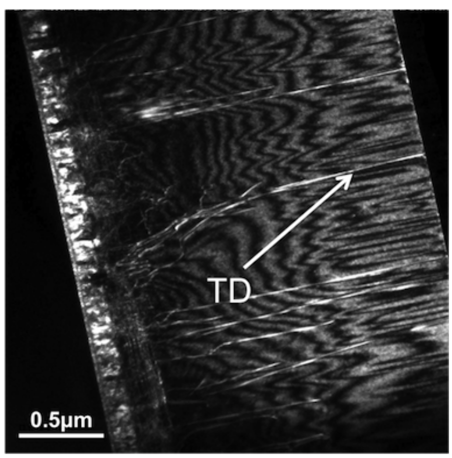

Fig. 3 Cross-sectional analysis of the threading dislocation (TD) density in the GaN thin film.

presents a large-scale cross-sectional weak-beam view of the layers used with the g vector in the [0002] direction.

The buffer layer had a strong influence on the threading dislocation density within the 1.5 μm-thick GaN film. The threading dislocation density within the GaN waveguide layer was estimated to be $\approx 0.5 \times 10^{-9}\,\mathrm{cm}^{-3}$. The suppression of dislocation propagation is to a large extent due to the AlN/GaN SPS acting as a barrier layer and resulting in a small only presence of them in the active GaN epilayer. This finding correlates well to Atomic Force Microscopy analysis, which shows a small RMS roughness of around 0.7 nm on a 5 μm × 5 μm area.

4. Optical Characterizations

Optical studies were performed on a commercial Metricon M2010 model ATR prism-coupling setup. A schematic of the heart of the system is given in Fig. 4.

In this setup, a laser beam is focused on the edge of the equilateral TiO_2 prism (n=2.867 for 633 nm wavelength) which is fixed on a 360°-rotating plate carrying a large InGaAs photodetector. For each incident angle (θ), the intensity reflected out of the prism was monitored using a software program developed for this purpose. When the light is coupled into the GaN bulk planar waveguide, the reflected intensity drops to a minimum. For each wavelength and polarization, the corresponding incident angle (θ) is also related to the m-th effective index of the propagation waveguide mode Nm through the following equation [7],

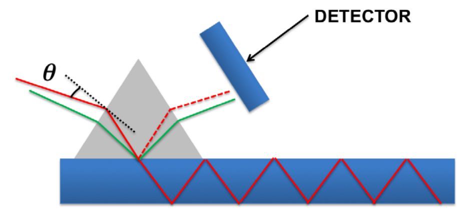

Fig. 4 Schematic of the prism-coupling technique used in the Metricon setup.

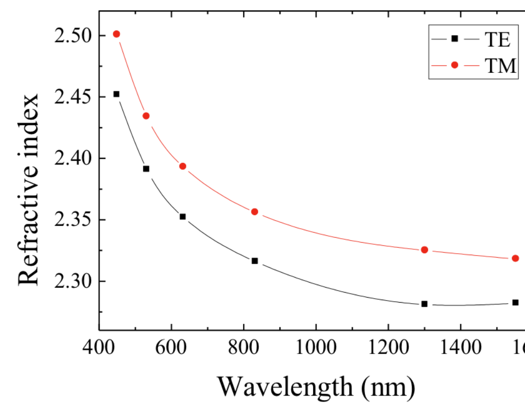

Fig. 5 Refractive index dispersion in both TE and TM polarizations.

$$N_m = n_{prism} \sin\left(A_{prism} + \arcsin\left(\frac{\sin\theta}{n_{prism}}\right)\right), \qquad (1)$$

where n_{prism} and A_{prism} are the index and angle of the prism (here 60°).

Computation of the all-effective modes by the software based on solving Maxwells propagation equation, allows one to obtain the refractive index of the GaN waveguide as a function of the wavelength and polarization.

Figure 5 presents the refractive index dispersion for the GaN waveguide. Fitting of the obtained refractive index dispersion values with the following Snellmeier equation

$$n_o^2(\lambda) = 1 + \left(\frac{A_1\lambda^2}{\lambda^2 - C_1}\right) + \left(\frac{A_2\lambda^2}{\lambda^2 - C_2}\right), \qquad (2)$$

$$n_e^2(\lambda) = 1 + \left(\frac{B_1\lambda^2}{\lambda^2 - D_1}\right) + \left(\frac{B_2\lambda^2}{\lambda^2 - D_2}\right) \qquad (3)$$

where A_1=0.2, A_2=3.95, B_1=0.118, B_2=4.195, and C_1=D_1=122,500, C_2=23,409 and D_2=31,152.25 for both polarizations demonstrated good agreement with values reported from [8].

Additional measurements allowed evaluation of the waveguide planar loss. This was possible using a Silicon photodiode, which monitors the decreasing intensity of the light propagation into the GaN planar waveguide. In Fig. 6, loss values are plotted as a function of the wavelength for the TE polarization. In particular, the planar optical waveguide loss measured at telecom wavelength (1.55 μm) was found to be $\approx$ 0.5 dB/cm (for bulk material), which confirms the presence of relatively low losses at larger wavelengths [6]. In comparison, InP ridge waveguide based devices possess optical waveguide loss of around 1 dB/cm [9].

The temperature dependence of the waveguide properties (such as refractive index) in both polarizations is plotted in Fig. 7. For these measurements, we used a flexible hotplate to apply a heating on the back of the substrate and a Pt100 thermocouple to monitor the temperature on the waveguide side. The results indicate that GaN possesses a relatively stable behavior with only 3×10^{-5} K^{-1} and 7×10^{-5} K^{-1} refractive index variations for temperatures from 300 to 400 K in TE and TM optical polarization respectively. The observed temperature dependence is consequently relatively low compared with standard semiconductors such as InP, which presents an at least one order of magnitude stronger temperature dependence around 2×10^{-4} K^{-1} [10].

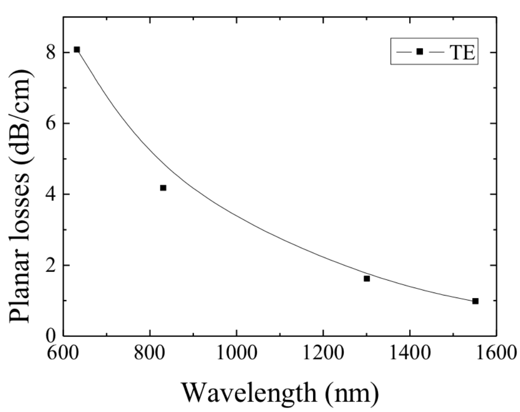

Fig. 6 Waveguide loss measurement spectrum (TE polarization).

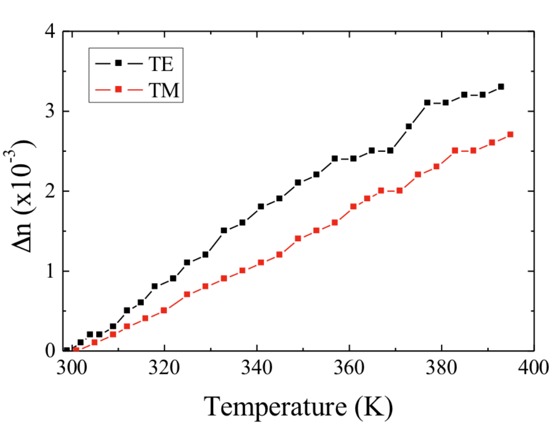

Fig. 7 Temperature dependence of the refractive index of GaN thin film in both TE and TM optical polarization.

5. Electro-Optic Characterization

Part of the n-GaN top layer was etched by RIE-ICP in order to allow bias application on both sides of the GaN thin film. A Si_3N_4 optical mask was used for this purpose and a combination of Ar and Cl_2 gases were employed for etching in an Oxford Plasmalab100 chamber. A standard Ti/Al/Ni/Au (12/200/40/100 nm) metallization was deposited with a Plassys thermal evaporator system on the etched n+ GaN for ohmic contacts and was flash-annealed at 900°C for 30 s. Schottky-type 100 μm $\times$ 100 μm Au pad contacts were deposited on top of the n-GaN film by thermal evaporation. The thickness of the Au metallization was about 40 nm when the ATR system configuration was used, allowing therefore light to penetrate into the waveguide. Both front and bottom contacts were connected to a static voltage generator for electro-optic characterization through soldered wires. The details of the structure used are shown in Fig. 8.

The reflected intensity was measured as a function of the applied voltage in the 0 to 35 V range. The results in Fig. 9 show that the index modulation Δn of the n-GaN waveguide is about 2×10^{-3}. This indicates for the first time the active behavior of the GaN material and the suitability of such a structure for optical modulation. To exclude the possibility of the results being impacted by thermal effects, the temperature of the top electrode was measured with a thermal camera upon application of a voltage. No significant heating was obtained, supporting the fact that the observed index variation cannot be explained by a temperature increase of the GaN film.

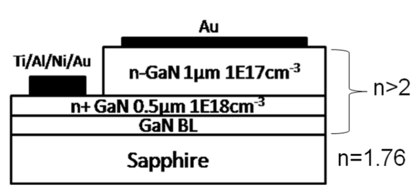

Fig. 8 Description of the electro-optic configuration on GaN/sapphire.

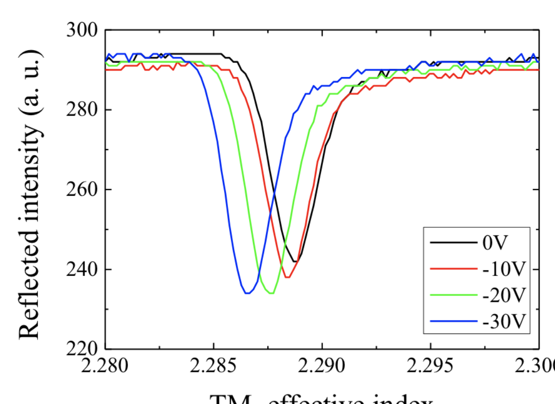

Fig. 9 Electrical driven displacement of the TM fundamental waveguide mode.

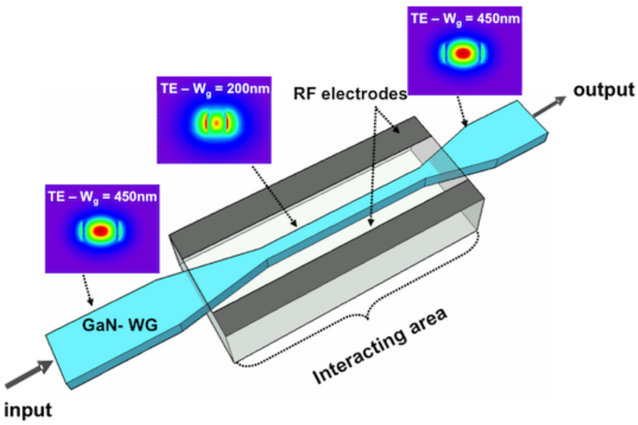

Fig. 10 Schematic of the modeled structure for high frequency optical waveguide modulator application.

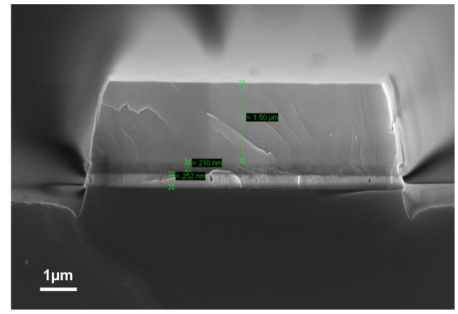

Fig. 11 GaN ridge etched by RIE-ICP technique.

6. Future Opto-RF Characterization

The results obtained are very promising and could lead in a new way for designing GaN high-speed optical modulators. Modeling and design of devices such as high-frequency active GaN waveguides were possible using Advanced Design System (ADS) and Optiwave OptiBPM commercial software. The geometry of the coplanar transmission line and the optical-geometrical parameters of the active waveguide were both determined. The selected design is a GaN ridge with a W=10 μm width and h = 1 μm height, in order to maintain a mono-modal propagation. The investigated waveguide was 5mm long and light was coupled-in and out from it through tapered lines converging to a line of 100 μm width and 40 μm signal-ground spacing line. Optical signal modulation was possible through the use of a high-frequency signal applied across the coplanar line terminals.

Optical mode confinement in the designed structure is presented in Fig. 10 for TE polarization at the wide (input) and narrow (center transmission line) regions of the waveguide.

First experiments were conducted to investigate the possibility of fabricating the proposed design. The fabrication starts by a Cl_2/Ar RIE-ICP GaN etching to define the ridge structure. Etching can be extended down to the sapphire substrate but in this study only 300 nm of the GaN layer thickness (1 μm) were removed for process simplicity. A SEM view of the GaN ridge waveguide is presented in Fig. 11. This can be used on future GaN-based optical modulators.

7. Discussion

The physical reason for low losses in GaN lies on the bandgap properties at 1.55 μm: in this wavelength range, light energy is very far from the bandgap (nearly 370 nm). Lowering of the optical losses would require an appropriate thickness for the GaN film to assure a (TE/TM) monomode structure and guarantee an adequate film quality away from the substrate interface. If the film thickness is increased, the number of modes increases in the waveguide structure and as a result, the total optical loss decreases. The final goal is to maintain a monomode configuration. Doping also affects the losses through changes of the light-semiconductor interaction. Further studies are planned for a better understanding of these effects.

In performing the optical waveguide characterization reported in the paper, monomode waveguide features were aimed. To achieve this the TE0 mode was coupled by evanescent way from the prism to the GaN-based waveguide. In case of multimode waveguides, one couples each mode (TE0, TE1, etc) from the prism to the nitride film as a function of the incidence angle at the prism input face.

In the Metricon setup, the laser beam illuminates the GaN sample with an incidence angle through a macroscopic prism. For excitation of small waveguide structures, the used characterization setup is limited by the prism size and therefore an integrated micro-prism configuration is required.

The RIE process used for waveguide fabrication resulted in relatively small surface roughness. This is required to be as small as possible to ensure small optical losses. For a roughness of 2 to 5 nm the optical loss was estimated to be around 1 dB/cm.

It should be noted that the fabricated waveguides were metalized on the top. The impact of this metal is very important for optimum performance due to the fact that it may lead in multiple internal reflections in the waveguide. While reflectivity in the TE0 mode increases, the optical loss also increases.

Measurement of losses for different modes is possible by the prism coupling experiment through variation of the incident angle and selection of the mode for which the losses are evaluated. An increase of loss through the semiconductor waveguide roughness leads in additional loss that can be evaluated separately for each mode. The total loss was found to be less than 1 dB/cm for the first TE0 mode, around 5 dB/cm for the TE1 mode and 8 dB/cm for the TE2 mode. Optical losses increased with the mode number due to the optical field configuration inside the waveguide.

8. Conclusion

The prospective of a GaN-based structure for optical waveguide modulators was investigated. GaN optical waveguides were experimentally investigated through refractive index dispersion, low propagation losses and temperature sensitivity studies. The obtained results suggest the possibility of designing Mach-Zehnder interferometers based on such a structure and open the way for future optoelectronic applications.

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Arnaud Stolz received an Engineer degree in Material Science and a M.S. degree in Electronics in 2008 and a Ph.D. in Electronics in 2011 in IEMN, France. During 2008–2011, he worked on optical waveguide properties of nitride materials as gallium-nitride and on plasmonics on semiconductor for telecoms applications. In 2012, he joined the Laboratoire Interdisciplinaire Carnot de Bourgogne from University of Burgundy in France. His research topic is now on the plasmon-assisted photo-electric tranduction in metallic nanojunctions.

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