Optical waveguiding properties into porous gallium nitride structures investigated by prism coupling technique

Bandar Alshehri, Seung-Min Lee, Jin-Ho Kang, Su-Hyun Gong, Sang-Wan Ryu, Yong-Hoon Cho, El Hadj Dogheche

Applied Physics Letters

Optical waveguiding properties into porous gallium nitride structures investigated by prism coupling technique

Cite as: Appl. Phys. Lett. **105**, 051906 (2014); https://doi.org/10.1063/1.4892528
Submitted: 02 April 2014 • Accepted: 23 July 2014 • Published Online: 06 August 2014

Bandar Alshehri, Seung-Min Lee, Jin-Ho Kang, et al.

ARTICLES YOU MAY BE INTERESTED IN

Nanoporous distributed Bragg reflectors on free-standing nonpolar m-plane GaN
Applied Physics Letters **112**, 041109 (2018); https://doi.org/10.1063/1.5016083

Thermal transport of nanoporous gallium nitride for photonic applications
Journal of Applied Physics **125**, 155106 (2019); https://doi.org/10.1063/1.5083151

Dislocations as channels for the fabrication of sub-surface porous GaN by electrochemical etching
APL Materials **8**, 031115 (2020); https://doi.org/10.1063/1.5142491

APPLIED PHYSICS LETTERS **105**, 051906 (2014)

Optical waveguiding properties into porous gallium nitride structures investigated by prism coupling technique

Bandar Alshehri,[1] Seung-Min Lee,[2] Jin-Ho Kang,[2] Su-Hyun Gong,[3] Sang-Wan Ryu,[2,a)] Yong-Hoon Cho,[3] and Elhadj Dogheche[1,b)]

[1]*Institute Electronics, Microelectronics and Nanotechnology (IEMN CNRS), University of Valenciennes, Villeneuve d'Ascq, France*
[2]*Department of Physics, Chonnam National University, Gwangju 500-757, South Korea*
[3]*Department of Physics and KI for the NanoCentury, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 305-701, South Korea*
[4]*Advanced Institute of Science Technology (KAIST), Daejeon 305-701, South Korea*

(Received 2 April 2014; accepted 23 July 2014; published online 6 August 2014)

In order to modulate the refractive index and the birefringence of Gallium Nitride (GaN), we have developed a chemical etching method to perform porous structures. The aim of this research is to demonstrate that optical properties of GaN can be tuned by controlling the pores density. GaN films are prepared on sapphire by metal organic chemical vapor deposition and the microstructure is characterized by transmission electron microscopy, and scanning electron microscope analysis. Optical waveguide experiment is demonstrated here to determine the key properties as the ordinary (n_0) and extraordinary (n_e) refractive indices of etched structures. We report here the dispersion of refractive index for porous GaN and compare it to the bulk material. We observe that the refractive index decreases when the porous density p is increased: results obtained at 0.975 μm have shown that the ordinary index n_0 is 2.293 for a bulk layer and n_0 is 2.285 for a pores density of 20%. This value corresponds to GaN layer with a pore size of 30 nm and inter-distance of 100 nm. The control of the refractive index into GaN is therefore fundamental for the design of active and passive optical devices. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4892528]

III-nitride semiconductors as gallium nitride and related alloys are actually the well-known wide band gap materials which are key materials for the fabrication of efficient laser and light emitting diodes (LED). However, in order to expand their field of applications, device performances have still to be improved and a class of active and passive devices should be targeted. One important step towards the demonstration of GaN-based optoelectronic devices is the ability to control the light emission by an increased coupling of the active material with optical modes. Much effort has already been done with other material systems using cavities such as photonic crystal, micropillars, etc. The development of optical devices encountered a lot of processing technique that enabled the realization of original structures. Particularly, the possibility to realize nanostructures based on GaN is a major concern in the community. Different techniques to nanostructure the GaN have been reported by authors as for photonic crystals and surface gratings in solar cells resulting in the enhancement of the collection efficiency.[1–4] Up to date, many researchers have reported optical properties of GaN, AlGaN, and InGaN this films.[7–11] This family of semiconductors has become popular due to porous structures; reducing the dimensions of these structures to nanoscale can extend the range of properties of nitride materials. By controlling the pores in GaN with suitable geometries, one can control various optical functions such as spectral selection, polarization, and nonlinear action. Recently, considerable effort has been directed towards the nanostructuration of GaN.[2–4] The possibility to extract electro-optic effects within porous structures offers an alternative for active SPR plasmonics.[5,6] This study reports the progress into porous GaN and the demonstration of optical waveguiding into similar configurations.

Using a simple and cheap manufacturing process, it is also easy to control the size of the pores, the distance between the pores, and the thickness by adjusting fabrication conditions.[12] Note that an alternative, low cost approach to produce nano-patterned surfaces with uniform features is to etch GaN films using nanoporous anodic aluminum oxide (AAO) films as etch masks.[13] Authors report that nanopore arrays with pore diameters of approximately 75 nm can be fabricated in GaN films by inductively coupled plasma.[14]

In terms of materials quality, the nanostructured GaN has a reduced defect density and strain relaxation as compared to epitaxial GaN films, and the optical properties of such materials can be tailored to suit various device requirements. Few studies on porous III–V compound semiconductors have been carried out using the spectroscopic ellipsometry technique.[12] Exploiting the properties of porous GaN requires fabrication of porous structures with control over morphology, surface chemistry, and optoelectronic properties. Here, the fabrication and the full characterization of nanoporous structures by electrochemical etching on n-GaN layer grown by MOCVD are reported.[15]

GaN samples used in the experiments are grown on c-plane sapphire substrates by metal organic chemical vapor deposition (MOCVD). The first step is the growth of a 0.4 μm thick undoped GaN film which is followed by the growth of 0.8 μm thick n-type GaN ($n \sim 1 \times 10^{18}\,cm^{-3}$). The

a)Electronic mail: sangwan@chonnam.ac.kr
b)Electronic mail: elhadj.dogheche@univ-valenciennes.fr

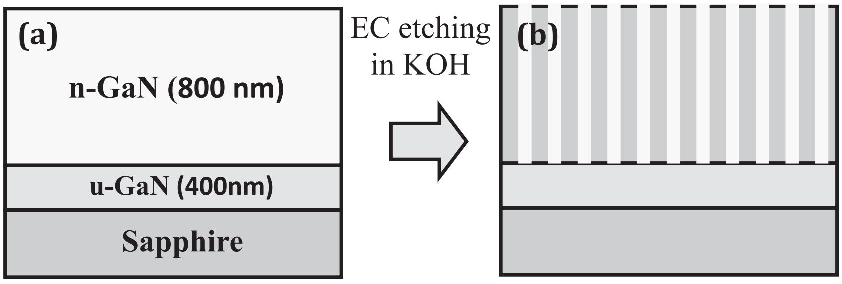

FIG. 1. Sample structure for bulk GaN (a) and low porous (20%) GaN (b).

bulk GaN sample is considered as a reference for the following study. The electrochemical etching sample configuration is given in Figs. 1(a) and 1(b). GaN sample and Pt electrode are connected to the positive and negative terminals of a voltage source. Both were immersed in KOH at room temperature and a constant DC voltage was applied. During the etching, no UV light is intentionally illuminated onto the sample surface. It should be noted that the electrochemical etching is very sensitive to the doping concentration and only n-type GaN is etched during the process. Upon completion of the electrochemical etching, the sample is rinsed in de-ionized water and in methanol sequentially and then dried. We have used a field emission scanning electron microscope (SEM, JEOL) at the operating voltage of 10 kV to examine the etching profile and formation of nanoporous structure.[14]

The pore size, etching depth, or the transverse dimension of the pores is controlled by varying the etching conditions (applied bias, etching time). The pores density is ranging from 0% to 40% in this work. Figs. 2(a) and 2(b) shows the SEM surface image and cross section of nanoporous GaN formed by electrochemical etching at 100 V and analyzed by transmission electron microscopy (TEM): in this case, the porosity value is 20%. Figure 1 shows the top surface of GaN films with different pore sizes. During the pore widening process, only the pore radius changes while the distance between the pores remains fixed. The average pore radius and the spacing between the pores are extracted from the observed area ratio between pores and alumina. The average spacing between the pores is ~100 nm and the average pore radiuses are ~13, 25, and 37.5 nm for different pore widening process times of 0, 50, and 70 mn, respectively. In this example, we have estimated the porosity p of 20%.The surface roughness measured by atomic force microscopy (AFM) is estimated to $r_{ms} = 0.34$ nm for the bulk GaN material and it is $r_{ms} = 1.34$ nm for the porous GaN material.

We have applied these structures to optical waveguide applications. In the literature, most of III-nitride structures have been optically characterized by prism coupling; this technique has been widely used to measure the refractive index, the thickness, the optical losses, and more recently the static-dynamic electrooptic effects.[15] We demonstrate here that it is possible to couple optical signal into a nanostructured GaN sample. Laser beams of different wavelengths (from 450 to 1539 nm) are coupled into the GaN film planar waveguide using a rutile prism (TiO_2) through the evanescent field in the air-films gap. Reflectivity spectra are measured, depending on angles using rotation stage mounted below the prism and the film (Fig. 3).

From optical point of view, the so-called "*nanostructured*" GaN films consist of a bulk GaN and air inside the pores. Since the wavelength of light is much larger than the pore size and their inter-distance, we can consider it as a uniform layer exhibiting an effective refractive index using effective medium approximations. The effective refractive index of porous GaN is lower than that of the reference bulk GaN but higher than that of air when the volume ratio of pores is considered. To measure the effective refractive index, we plot the guided modes spectrum at different wavelengths and for TE or TM polarizations. The ordinary and extraordinary modes are excited, respectively, using TE and TM polarized light with the optical axis normal to the surface. As example, we report in Fig. 4, the TE guided-mode reflectivity spectrum excited at a wavelength of 975 nm.

Seven sharp reflectivity dips for bulk material and three dips for porous material are observed at certain angles θ and correspond to the excitation of guided modes. These can be identified as the modes TE_0–TE_6 for bulk and TE_0–TE_2 for the porous GaN. Note that six modes have been excited with the TM polarized light. For the angular positions of the guided modes, we computed the corresponding effective refractive indices Nm given by

$$n_{m.ode} = n_{prism}.\sin\left(A_{prism} + \arcsin\left(\sin\left(\frac{\theta}{n_{prism}}\right)\right)\right),$$

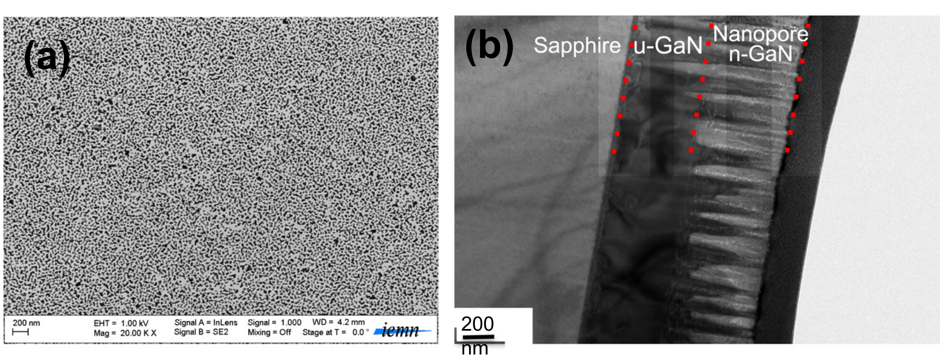

FIG. 2. SEM surface image of nanoporous GaN (a) and cross-section (b).

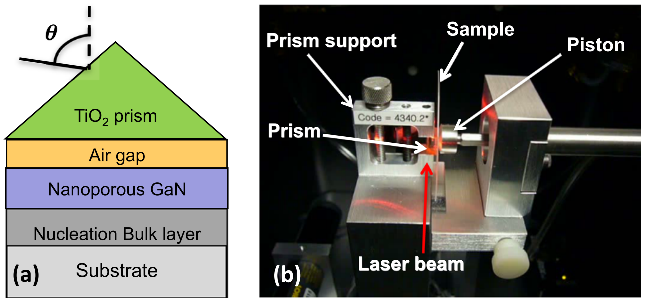

FIG. 3. Schematic and illustration of prism coupling configuration.

where Np is the refractive index of the prism, θ is the angle of incidence, and A_{prism} is the prism angle with respect to the normal. With the measured TE mode data and the dispersion equations for a planar waveguide, the ordinary and extraordinary refractive index (n_0 and n_e) of GaN have been determined as reported by Ulrich and Torge.[16] As the index is modified with equivalent film thickness, the mode angles are also changed. The sharpness of the reflectivity dips indicates a good confinement of the light into both the bulk and the porous GaN films. This is an indication of the good microstructural quality of the porous films. We also could obtain the guided modes with other different wavelength. For a porous GaN (20%), the ordinary refractive index is $n_0 = 2.285$ and the extra-ordinary index is $n_e = 2.315$. In comparison, the indices are $n_0 = 2.291$ and $n_e = 2.328$. The anisotropy Δn is equivalent to 0.03 for a porosity 20% and $\Delta n = 0.033$ for a bulk material. This is an indication that the properties are maintained in the film after etching. These results agree well with the reported values measured by ellipsometry.[17]

Fig. 5 shows the index dispersion curves obtained for bulk GaN and the porous one. For both TE and TM polarizations, the ordinary and extra-ordinary indices are decreasing with the wavelength. The difference between porous and bulk structures remains similar whatever the wavelength is: this is a good indication of the index stability versus the laser source. A same behavior is observed for different values of porosities p. We can observe that GaN structures with larger pore sizes exhibit lower refractive indices due to the large volume fraction of air. It is therefore possible to establish a calibration curve giving the index as a function of pores size Birefringence also largely increased in function of pore sizes.

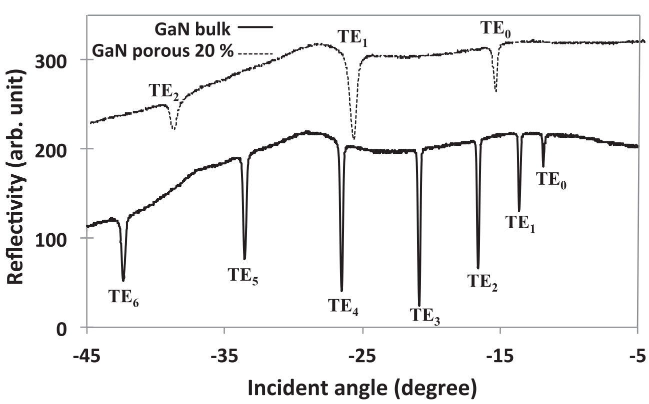

FIG. 4. Ordinary guided-mode reflectivity spectra obtained at 975 nm for bulk GaN and porous GaN (porosity of 20%) using prism coupler.

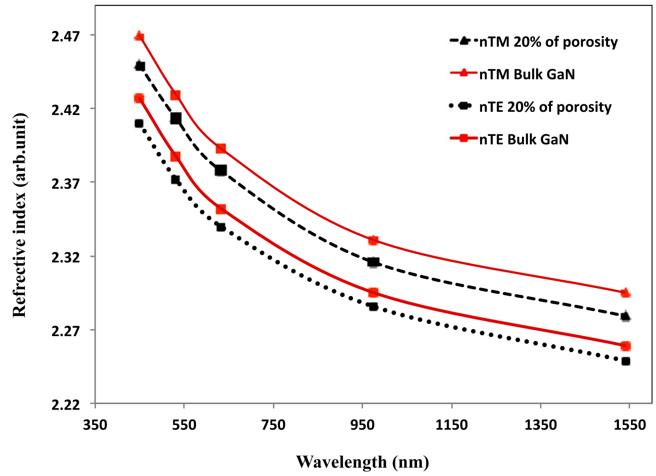

FIG. 5. Ordinary and extraordinary refractive indices dispersion for bulk and porous (20%) GaN samples.

Owing to the cylindrical structure of porous GaN, the thickness of porous GaN has no relation with the volume ratio of the pore. It is also denoted that no significant changes in the refractive index are measured when the film thickness is changed.

In this Letter, we report the control of the refractive index of GaN films and its birefringence by adjusting the pore sizes and film density. To investigate the influence of density on film indices, we have optimized the process fabrication in order to get porosities from 0% to 40%: a pore widening process is proposed in this paper for the sample with porosity value of 20%. This is systematically investigated by prism coupling. We demonstrate here that it is possible to excite guided wave modes into porous GaN. We have demonstrated that the refractive index and the film birefringence can be easily tuned with various pore sizes. The ordinary n_0 and extraordinary n_e indices are found to be lower compared to bulk GaN; the dispersion curves are reported for both configurations. This study demonstrates that nanostructures can open a promising perspective for III-nitride semiconductors. The refractive index and other optical properties of GaN films can be selected to design specific configurations of optical devices.

Authors would like to thank Dr. Ibrahim Albalawi, Cultural Counselor from Saudi Embassy in Paris for his support. The authors also would like to acknowledge Eng. Nasser Alsubaie, Director of General Directorate of Science and Technology (GDST) at Riyadh and Dr. Hamad Alyoussefi, consultant at King Abdulaziz City of Science and Technology (KACST) in Riyadh for their continuous encouragements.

[1]J. Park, J.-H. Kang, and S.-W. Ryu, Appl. Phys. Express **6**, 072201 (2013).
[2]L. Zhang, J. H. Teng, S. J. Chua, and E. A. Fitzgerald, Appl. Phys. A **103**, 827–830 (2011).
[3]O. V. Bilousov, H. Geaney, J. J. Carvajal, V. Z. Zubialevich, P. J. Parbrook, A. Giguère, D. Drouin, F. Diaz, M. Aguilo, and C. O'Dwyer, Appl. Phys. Lett. **103**, 112103 (2013).
[4]C. B. Soh, C. B. Tay, R. J. N. Tan, A. P. Vajpeyi, I. P. Seetoh, K. K. Ansah-Antwi, and S. J. Chua, J. Phys. D: Appl. Phys. **46**, 365102 (2013).
[5]M. Cuniot-Ponsard, I. Saraswati, S.-M. Ko, M. Halbwax, Y. H. Cho, and E. Dogheche, Appl. Phys. Lett. **104**, 101908 (2014).

[6]A. Stolz, S.-M. Ko, G. Patriarche, E. Dogheche, Y.-H. Cho, and D. Decoster, Appl. Phys. Lett. **102**, 021905 (2013).

[7]N. A. Sanford, A. Munkholm, M. Krames, A. Shapiro, I. Levin, A. Davydov, S. Sayan, L. Wielunski, and T. Madey, Phys. Status Solidi C **2**, 2783–2786 (2005).

[8]A. Gokarna, A. Gauthier-Brun, W. Liu, Y. Androussi, E. Dumont, E. Dogheche, J. H. Teng, S. J. Chua, and D. Decoster, Appl. Phys. Lett. **96**, 191909 (2010).

[9]T. L. Williamson, X. Guo, A. Zukoski, A. Sood, D. J. Diaz, and P. W. Bohn, J. Phys. Chem. B **109**, 20186–20191 (2005).

[10]A. H. Park, K. J. Lee, T. S. Oh, Y. S. Lee, H. Jeong, T. H. Seo, H. Kim, and E. K. Suh, J. Electrochem. Soc. **158**(2), D119–D122 (2011).

[11]L. S. Chuah, Z. Hassan, and H. Abu Hassan, Mater. Sci. **26**(3), 609 (2008).

[12]J.-H. Lee, B. Lee, J.-H. Kang, J. K. Lee, and S.-W. Ryu, Thin Solid Films **525**, 84–87 (2012).

[13]S.-H. Gong, A. Stolz, G.-H. Myeong, E. Dogheche, A. Gokarna, S.-W. Ryu, D. Decoster, and Y.-H. Cho, Opt. Lett. **36**(21), 4272–4274 (2011).

[14]Y. Wang, S. J. Chua, M. Sander, P. Chen, and C. G. Fonstad, Appl. Phys. Lett. **85**, 816 (2004).

[15]A. Stolz, E. Cho, E. Dogheche, Y. Androussi, D. Troadec, D. Pavlidis, and D. Decoster, Appl. Phys. Lett. **98**(16), 161903 (2011).

[16]R. Ulrich and R. Torge, Appl. Opt. **12**, 2901 (1973).

[17]Y.-H. Lee, J.-H. Kang, and S.-W. Ryu, Thin Solid Films **540**, 150–153 (2013).