AIP | Applied Physics Letters

Fabrication and optical studies of AlGaN/GaN quantum-well waveguides

T. N. Oder, J. Y. Lin, and H. X. Jiang

Citation: Applied Physics Letters **79**, 12 (2001); doi: 10.1063/1.1381037
View online: http://dx.doi.org/10.1063/1.1381037
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/79/1?ver=pdfcov
Published by the AIP Publishing

Fabrication and optical studies of AlGaN/GaN quantum-well waveguides

T. N. Oder, J. Y. Lin, and H. X. Jiang[a)]
Department of Physics, Kansas State University, Manhattan, Kansas 66506-2601

(Received 5 March 2001; accepted for publication 1 May 2001)

We report the successful fabrication and optical study of submicron waveguide structures based on AlGaN/GaN multiple-quantum wells (MQWs). The MQW structures were grown by metalorganic chemical vapor deposition on sapphire substrates and the waveguides were fabricated by electron-beam lithography and inductively coupled plasma dry etching. The waveguides were patterned with a fixed width of 0.5 μm but with orientations varying from $-30°$ to 60° relative to the *a* axis of GaN. Optical emission from these structures was studied by photoluminescence spectroscopy. The peak position and linewidth of the emission peak were found to vary systematically with the orientations of the waveguides and followed the sixfold symmetry of a wurtzite structure. This is most likely related to the anisotropy of the exciton/carrier diffusion coefficient along the different crystal orientations in the quasione-dimensional case. The implication from the results is that in proper designs of photonic and electronic devices where submicron structures are fabricated in III nitrides one must consider the orientations of the structures. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1381037]

III-nitride wide band gap semiconductors have been recognized as very important materials for fabricating optoelectronic devices operating in the blue/UV region as well as for high temperature/high power electronic devices. A great deal of research has been directed towards realizing these devices. However, one area that has not been studied widely is microstructures, such as microcavities. When structural dimensions are reduced to submicron sizes, there may also be concomitant effects in carrier dynamics that may translate into significant changes in the device characteristics. Our interest in studying low-dimensional optical and electronic systems such as waveguide structures arises due to the need to understand their photonic properties. There is also interest in investigating the potential of the III nitrides for waveguide materials.

Different methods have been used to obtain structures with lateral confinement and to study their properties.[1–3] Standard photolithography is not capable of achieving structures of dimensions less than 1 μm in III nitrides due to limitations in photoresists, the wavelength of the light used, and the need for appropriate masks. Our group has previously fabricated structures of a few μm in dimension using photolithography.[4–9]

In this letter, we report the fabrication and optical study of submicron waveguide patterns based on AlGaN/GaN multiple quantum wells (MQWs). Our results from the optical study of the waveguides reveal that the peak position and linewidth of the emission peak vary systematically with the waveguide orientations. This behavior is explained in terms of the anisotropy of the carrier or exciton diffusion coefficient in a quasi one-dimensional (1D) case.

The AlGaN/GaN MQWs were grown by metalorganic chemical vapor deposition (MOCVD). The sources used were trimethylgallium (TMG), trimethylaluminum (TMAl), and ammonia. A 300 Å low temperature GaN buffer layer was first deposited on the sapphire substrate, followed by deposition of 1.0 μm GaN layer. Thirty periods of $Al_{0.2}Ga_{0.8}N(50\,Å)/GaN(12\,Å)$ were then grown between a pair of 200 Å thick $Al_{0.2}Ga_{0.8}N$ cladding layers. To provide lateral confinement, the waveguides were defined by an electron-beam lithography technique using our Nanometer Pattern Generation System (NPGS). Following a standard degrease clean, two drops of negative resist (PN-114, a novalak-based polymer from Clariant Corporation) were spun at 8000 rpm for 30 s to yield an estimated resist thickness of about 1.2 μm. A pre-exposure oven bake was carried out at 120 °C for 30 min. The electron beam used during the pattern writing was accelerated at 35 kV with a probe current of 5 pA and an area dose of 5 $\mu C/cm^2$ using the LEO 440 scanning electron microscopy system. A postexposure hotplate bake was carried out at 105 °C for 5 min followed by developing for 90 sec in dilute aqueous alkaline solution (AZ 400K). The defined patterns were transferred to the sample by inductively coupled plasma (ICP) etching. Dry etching was done at 300 W for 1 min, which resulted in an etch depth of about 0.75 μm. The width of the waveguides was kept fixed at 0.5 μm but the orientation was varied from $-30°$ to 60° relative to the *a* axis of GaN. Each waveguide was 500 μm in length and spaced about 15 μm from each other. For comparison purposes, a region of 500 $\mu m \times 500\,\mu m$ was defined and left unetched in the sample.

Figure 1(a) shows a schematic diagram of a waveguide structure. Figure 1(b) is a scanning electron microscope (SEM) image of the waveguides. The width of the waveguides was about 0.5 μm as targeted. Figures 1(c) and 1(d) are atomic force microscope (AFM) images of the sample. From these images, we did not notice any preferred pattern in the edges of the etched steps of the waveguides for the different orientations. Low temperature (10 K) photoluminescence (PL) spectra were measured using a laser spectroscopy system with an average output power of about 20 mW, a tunable photon energy up to 4.5 eV, and a spectral

[a)]Electronic mail: jiang@phys.ksu.edu

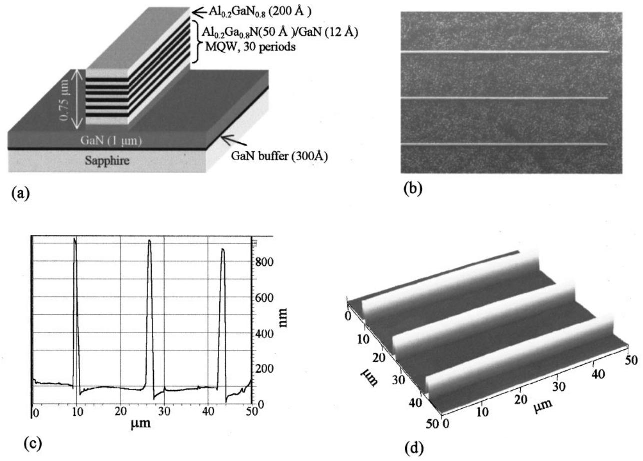

FIG. 1. (a) Schematic diagram showing the waveguide structure. (b) SEM image of the waveguide sample. The spacing between the waveguides is 15 μm. (c), (d) AFM images of the waveguides.

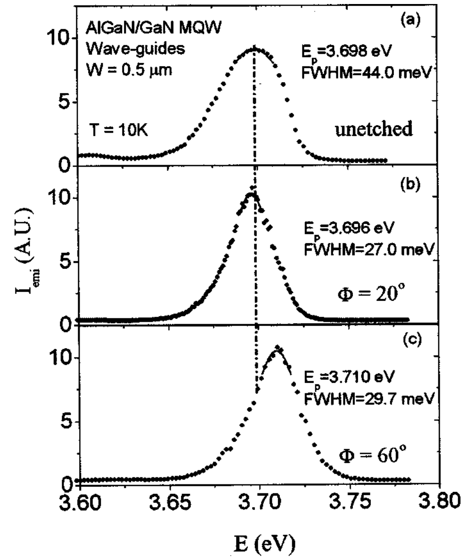

FIG. 2. Low temperature (10 K) continuous wave PL spectra from AlGaN/GaN MQW waveguides of different line orientations. For clarity, we only show (a) the PL spectrum from an unetched portion of the sample and the PL spectra from waveguides oriented at (b) 20° and (c) 60°.

resolution of about 0.2 meV. Details of the laser system setup are described elsewhere.[10]

Figure 2 shows the PL spectra of the waveguide sample. For clarity, we only show the spectra from an unetched portion of the sample, Fig. 2(a), and from two waveguides oriented at 20° and 60° in Figs. 2(b) and 2(c), respectively. The emission peaks in these spectra are attributed to localized exciton recombinations in the well regions of the waveguide structures. The linewidth of the spectrum from the unetched region is much broader than that of the spectrum from the waveguides. The peak position, E_p, and full width at half maximum (FWHM) versus the waveguide orientation (ϕ) relative to the *a* axis of GaN are shown in Figs. 3(a) and 3(b), respectively. As shown, there is a definite periodicity of 60° in E_p and the FWHM, both varying sinusoidally as $A\sin[6\pi(\Phi-C)/180]+B$, where A, B, and C are variables. E_p and the FWHM are both maximum for orientations roughly parallel to 0° and 60° and both are minimum for orientations roughly parallel to $-30°$ and 30°. Between the two extremes, E_p changes by about 11 meV while the FWHM changes by about 4.6 meV.

Kapolnek *et al.*[11] investigated the orientation of the morphology and growth rates of the lateral epitaxial overgrowth (LEO) of GaN. It was found that lines oriented parallel to 30° relative to the *a* axis of GaN had a low lateral to vertical growth rate and resulted in triangular wedge cross sections. Lines parallel to 0° or 60°, however, had high lateral to vertical growth rate ratios. A very similar trend in the anisotropy of lateral growth was also observed in GaAs by Asai.[12]

In semiconductor MQW systems, the major cause of variation in E_p and the FWHM is localization effects caused by fluctuations in the well width and alloy composition.[13,14] Since a binary semiconductor forms the well regions in AlGaN/GaN MQWs, localization effects in this system are only due to well width fluctuations. However, we expect well width fluctuations to be the same for waveguide structures of the same width with orientations along different crystal line orientations. The diffusion process in the unetched region can be regarded as two-dimensional while that in each waveguide as quasione-dimensional. An unetched region of the sample whose PL spectrum is shown in Fig. 2(a) will have more low energy sites compared to the waveguide structures, since a much larger area is involved for the unetched region compared with the waveguides. From the PL spectra of another set of waveguides with different widths but fixed orientations, the spectral peak position E_p of the emission line was observed to shift towards lower energy as the waveguide width was increased (not shown). This behavior is consistent with our interpretation that more low energy sites are available in wider waveguides.

The observed anisotropic optical properties with sixfold symmetry in the nitride quantum well plane can be understood by the anisotropic diffusion of photoexcited carriers and excitons for waveguides along different orientations. For fixed excitation laser intensity, due to the band filling effect,

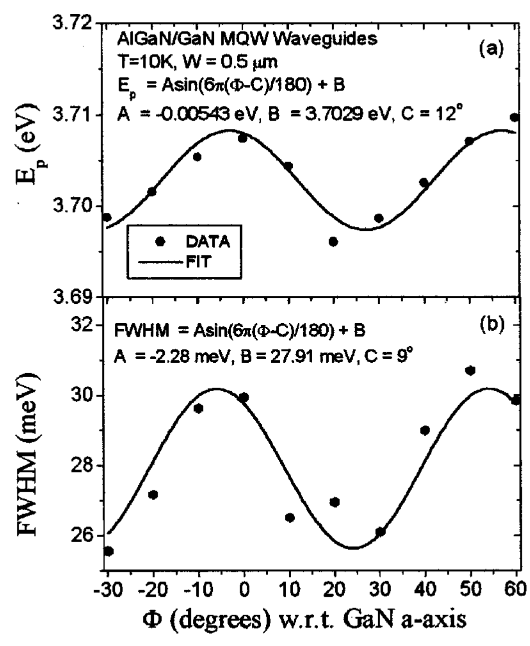

FIG. 3. Variation of (a) the spectral peak positions (E_p) and (b) FWHM of the PL emission line at 10 K. The solid line is the sinusoidal fit of the data with six fold symmetry of the hexagonal structure.

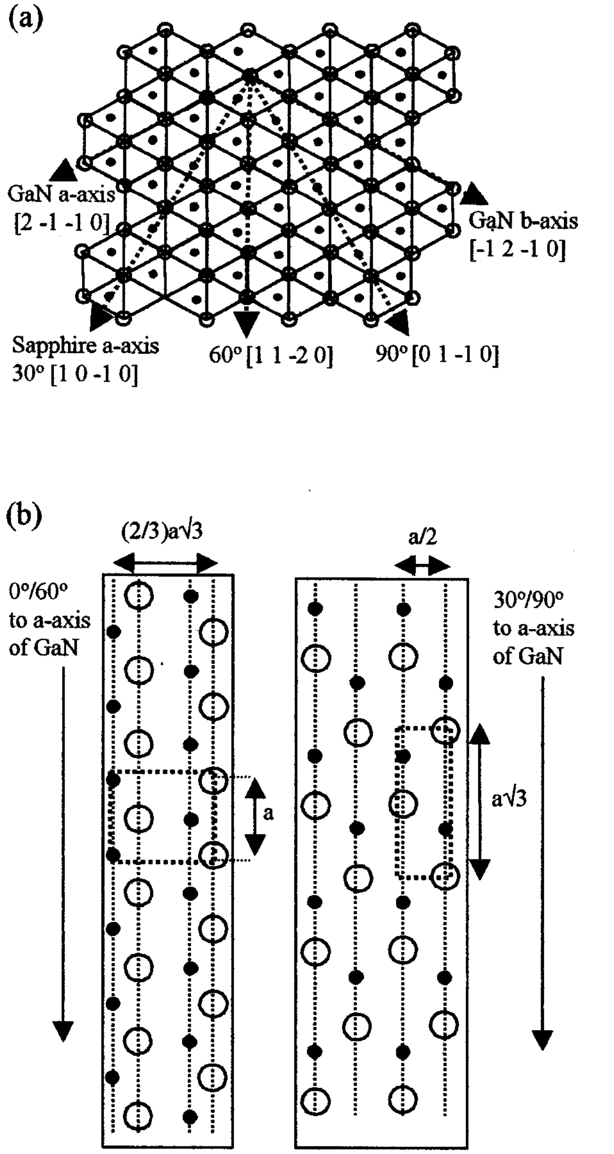

FIG. 4. (a) Crystal arrangement of Ga^{3+} (●) and N^{3-} (○) ions in a GaN hexagonal crystal structure. (b) detailed arrangements of the ions along the directions parallel to 0°/60° (left) and 30°/90° (right) relative to the *a* axis of the GaN crystal.

the carrier or exciton density will be higher for the case of either a lower diffusion coefficient or less potential fluctuation.

In Fig. 4(a), we show schematic arrangements of Ga^{3+} and N^{3-} ions in a hexagonal GaN crystal, described earlier more fully by Kung *et al.*[15] The crystal arrangements along the directions parallel to 0°/60° and −30°/30° are shown in Fig. 4(b). The *a* axis of GaN is shifted 30° with respect to the *a* axis of sapphire. Waveguides prepared along −30°/30° (where E_p and the FWHM are minimum) and 0°/60° (where E_p and FWHM are maximum) have the following differences in crystal arrangements:

(1) the number of ions per unit length in the −30°/30° line is greater than that along the 0°/60° line by a factor of 10:9;
(2) the lateral termination of the waveguides for the −30°/30° line is composed of both Ga and N ions while that of the 0°/60° line is either Ga or N;
(3) the width covered by four columns of ions is larger in the −30°/30° direction than in the 0°/60° direction.

These differences could be the source of the anisotropy of the exciton/carrier diffusion coefficient in the quasi-1D waveguide structures. At 0°/60° orientations, there is slow carrier or exciton diffusion leading to the band-filling effect with the result that E_p and the FWHM are both maximum. Faster diffusion occurs along the −30°/30°, resulting in E_p and the FWHM both being minimum.

The most intriguing result we obtained above is that there is a difference in optical property of the submicron structures, shown by the periodic variation in the peak energy E_p and the FWHM of the spectra from MQW waveguides at different crystal orientations. This difference is more pronounced in smaller structures. The major implication of this result is that in photonic and electronic devices where structures of submicron sizes are involved, there will be differences in exciton or carrier dynamics. The differences arising from the choice of orientation will result in significant effects in the associated devices. Such devices include field effect transistors (FETs), optical waveguides, photodetectors, and ridge-guide laser diodes. Therefore in the design of these devices, proper attention must be paid to the choice of orientation of the associated submicron structures.

In conclusion, we have fabricated submicron waveguide structures based on AlGaN/GaN MQWs. The spectral peak and linewidth of the PL emission line for waveguides fabricated with fixed widths and different orientations were found to have sixfold symmetry. This variation is most likely due to the anisotropy in the carrier or exciton diffusion rates. The 60° periodic variation is expected to be due to the hexagonal crystal structure of the nitride materials.

The authors wish to acknowledge support by grants from the NSF (Grant Nos. DMR-9902431 and INT-9729582), DOE (Grant No. 96ER45604/A000), ARO, and ONR.

[1] C. Weisbuch, M. Nishioka, A. Ishikawa, and Y. Arakawa, Phys. Rev. Lett. **69**, 3314 (1992).
[2] D. Baxter, M. S. Skolnick, A. Armitage, V. N. Ashtratov, D. M. Wittaker, T. A. Fisher, J. S. Roberts, D. J. Mowbery, and M. A. Kaliteevski, Phys. Rev. B **56**, 10032 (1997).
[3] A. Kuther, M. Bayer, T. Gutbrod, and A. Forchel, Phys. Rev. B **58**, 15744 (1998).
[4] S. X. Jin, J. Li, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **77**, 3236 (2000).
[5] S. X. Jin, J. Li, J. Z. Li, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **76**, 631 (2000).
[6] K. C. Zeng, L. Dai, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **75**, 2563 (1999).
[7] H. X. Jiang, J. Y. Lin, K. C. Zeng, and W. Yang, Appl. Phys. Lett. **75**, 763 (1999).
[8] K. C. Zeng, J. Y. Lin, H. X. Jiang, and W. Yang, Appl. Phys. Lett. **74**, 1227 (1999).
[9] R. A. Mair, K. C. Zeng, J. Y. Lin, H. X. Jiang, B. Zang, L. Dai, H. Tang, A. Botchkarev, W. Kim, and H. Morkoç, Appl. Phys. Lett. **75**, 2563 (2000).
[10] http://www.phys.ksu.edu/area/GaNgroup.
[11] D. Kapolnek, S. Keller, R. Vetury, R. D. Underwood, P. Kozodoy, S. P. Den Baars, and U. K. Mishra, Appl. Phys. Lett. **71**, 1204 (1997).
[12] H. Asai, J. Cryst. Growth **80**, 425 (1987).
[13] K. C. Zeng, J. Li, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **76**, 3040 (2000).
[14] K. C. Zeng, M. Smith, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **73**, 1724 (1998).
[15] P. Kung, C. J. Sun, A. Saxler, H. Ohsato, and M. Razeghi, J. Appl. Phys. **75**, 4515 (1994).