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Propagation properties of light in AlGaN/GaN quantum-well waveguides

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The dynamic properties of light propagation in AlGaN/GaN-based multiple-quantum-well waveguides have been investigated by time-resolved photoluminescence (PL) spectroscopy. The waveguides were patterned with a fixed width of 0.5 μm and length 500 μm using electron-beam lithography and inductively coupled plasma dry etching. Our results reveal a remarkable decrease in the PL intensity as well as an increase in time delay of the temporal response as the location of the laser excitation spot on the waveguide is varied. These results can be understood in terms of polariton propagation in the waveguides. From the time delay of the temporal response, it has been determined that the speed of generated polaritons, with energy corresponding to the well transitions in the waveguides, is approximately $(1.26\pm0.16)\times10^7$ m/s. The implications of these results to waveguiding in optical devices based on the group III-nitride semiconductors are discussed. [DOI: 10.1063/1.1410359]

Group III-nitride wide band gap semiconductors have been intensively studied recently for applications in optical devices operating in the blue/UV region as well as high temperature/high power electronic devices. However, not so many studies have been done on submicron structures due to the difficulties involved in fabrication and characterization. There is still a need to elucidate the basic physics governing the optical properties in submicron size structures. These may open doors for new applications as well as contribute to the improvement of the design of existing devices where such structures are used. When structural dimensions are reduced to submicron sizes, significant changes in properties such as carrier and photon dynamics of the semiconductor structures will result. In our previous letter, we reported the fabrication and optical study of submicron waveguide patterns based on AlGaN/GaN multiple-quantum wells (MQW).[1] In this letter, we report the dynamic properties of light propagation in AlGaN/GaN MQW waveguides. Our results reveal that the emission intensity systematically decreases as the location of the incident laser spot on the waveguide is moved further away from one end of the waveguide. From the temporal response, we have determined the propagation speed of light in the waveguide, with energy corresponding to the well transitions in the MQW, to be $(1.26\pm0.16)\times10^7$ m/s. These results are explained in terms of the propagation properties of polaritons in the waveguides.

The AlGaN/GaN MQWs were grown by metalorganic chemical vapor deposition. The sources used were trimethylgallium, trimethylaluminum, 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 (24 Å) were then grown between a pair of 200-Å-thick $Al_{0.2}Ga_{0.8}N$ cladding layers. The waveguides were fabricated using electron-beam lithography technique and dry etching by inductively coupled plasma system as previously reported.[1] Arrays of waveguide patterns occupying 500 μm$\times$500 μm field with a center-to-center separation of 1 mm were defined. The width and length of each waveguide were fixed at 0.5 and 500 μm, respectively, with a spacing of 15 μm from each other. Figures 1(a) and 1(b) show the schematic of the waveguide structure and the atomic force microscopy (AFM) picture of the waveguides, respectively.

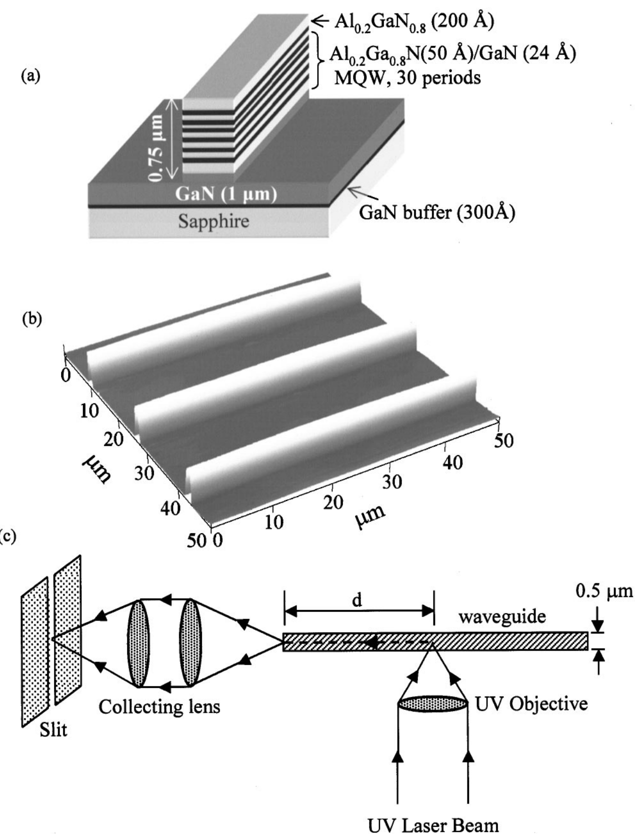

FIG. 1. (a) Schematic diagram showing the waveguide structure fabricated from AlGaN/GaN MQWs. (b) Atomic force microscope (AFM) image of the waveguide sample. Each waveguide has length 500 μm and width 0.5 μm and the spacing between them is 15 μm. (c) The schematic diagram for the time-resolved PL measurement setup. The value *d*, measured from the edge of the waveguide closest to the slit, defines the position of the focused laser spot on the waveguide.

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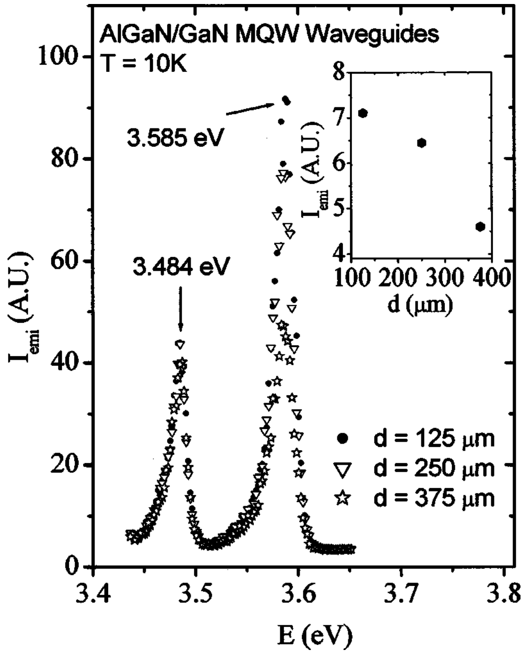

FIG. 2. Low temperature (10 K) continuous wave PL spectra from three different positions d on the AlGaN/GaN MQW waveguides lined perpendicular to the collecting slit of the monochromator. The peak at 3.484 eV is from the surrounding GaN exposed by etching and the peak at 3.585 eV is from the exciton recombination in the well regions of the waveguide structure. The inset shows the dependence of integrated intensity with the position d.

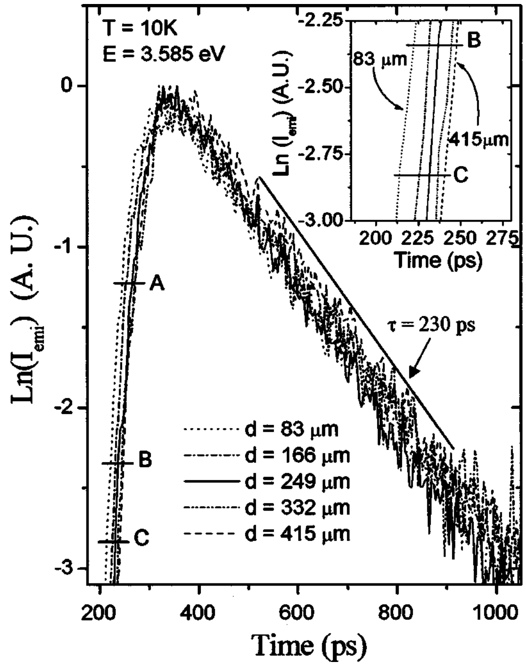

FIG. 3. The temporal responses of the PL emission measured at the spectral peak position (3.585 eV) of a waveguide lined perpendicular to the collecting slit. The responses were collected from five different positions d of the same waveguide with fixed excitation conditions. The inset shows more clearly the time delay observed in the rise part of the temporal response for the five different values of d, with $d = 83\ \mu$m on the left and $d = 415\ \mu$m on the right.

Low temperature time-resolved PL spectra were measured using a picosecond laser spectroscopy system with an average output power of about 20 mW, tunable photon energy up to 4.5 eV, and a spectral resolution of about 0.2 meV. Details of the laser system are described elsewhere.[2] The sample was placed normal to the incident light and the emitted photons were collected from a direction parallel to the sample surface, as schematically shown in Fig. 1(c). The incident laser beam was focused to a spot size of about 2 μm on a single waveguide using a UV transmitting objective lens of focal length 3 mm. The distance d (μm), from the edge of the waveguide closest to the collecting slit of the monochromator, defines the position of the incident excitation laser spot focused on the waveguide. The emitted photons were collected by a vertical slit of a 1.3 m monochromator with a photomultiplier tube detection system. For time-resolved measurements, a streak camera detection system with a time resolution of 2 ps was used.

Figure 2 shows the PL spectra collected from three positions of a waveguide lined perpendicular to the collecting slit of the monochromator. The emission line at 3.484 eV is from the underlying GaN epilayer exposed after dry etching as shown schematically in Fig. 1(a). The integrated intensity at this emission line is approximately the same for the different values of d. The emission line at 3.585 eV is attributed to the localized exciton recombinations in the quantum well regions of the waveguide structure.[1,3] The integrated intensity at this emission line, shown more clearly in the inset, decreases with increase in d. The peak position shows a slight decrease with increase in d. The decrease in PL emission intensity with increase in d can be understood in terms of light propagation loss in the waveguides that occurs in many different forms including scattering at the walls of the waveguides and reabsorption. At the spot on the waveguide where initial excitation occurs, carriers and excitons are generated. They recombine and emit light that is laterally confined to propagate along the waveguide. PL emitted at the excitation spot will traverse the distance d along the waveguide before being detected. The longer the distance the photons have to travel, the more the chance of loss through scattering or reabsorption leading to a decrease in the integrated emission intensity, as seen in Fig. 2. For comparison, we studied waveguides oriented parallel to the collecting slit (not shown) and found that the integrated emission intensity was consistently equal for different laser excitation positions on the waveguide. This is in agreement with the explanation given above.

Figure 3 shows the temporal response of the PL emission at 3.585 eV, corresponding to the spectral peak position for the waveguide lined perpendicular to the collecting slit. The temporal PL responses were collected from five different positions d on the same waveguide with fixed excitation conditions. The responses for different d values are similar in slope both in the rise part and the decay part. The decay can be fitted quite well with a single exponential giving a lifetime of 230 ± 2 ps. However, there is a systematic increase in time delay in the initial PL signal buildup as d is increased. This is shown more clearly in the inset of Fig. 3. The arrival times at three different locations labeled A, B, C in Fig. 3 for five excitation spot positions d are plotted in Fig. 4. The inverse of the slopes from each of these locations A, B, and C yields an average velocity of $(1.26 \pm 0.16) \times 10^7$ m/s, which is the propagation speed of generated photons, with energy corresponding to the well transitions in the MQW.

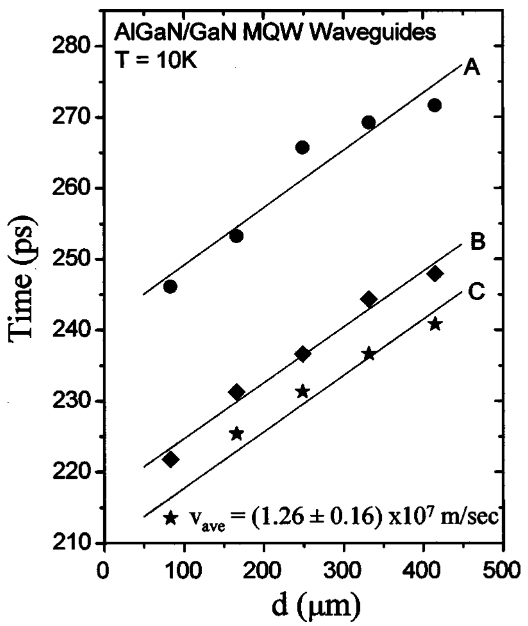

FIG. 4. The variation in time delay with laser excitation spot position *d*. These delay times were extracted from three locations labeled A, B, C in Fig. 3. Data points are shown in symbols and the lines are the least-square fits of the data points with a linear relation. From these, an average propagation speed of $(1.26\pm 0.16)\times 10^7$ m/s of light in the waveguide was determined.

Using an approximate value of refractive index $n=2.67$ for GaN,[4] the speed of light in the waveguide is estimated to be $c/n=1.12\times 10^8$ m/s. This is an order of magnitude greater than the velocity of the generated photons in the waveguides that we have determined.

In direct band gap semiconductors including the group III nitrides, polaritons, the coupled mode of photons and excitons, is the normal mode of propagation of light in semiconductors in the neighborhood of exciton resonant energy.[5] In a quantum well system, the coupling between excitons and photons to form excitonic polaritons is further enhanced due to the quantum confinement effect.[6,7] A quasi-one-dimensional structure such as the waveguide structure we have studied is expected to show even more stable excitonic polaritons because of the increased oscillator strength of excitons.[7,8] We therefore expect that the generated light in the waveguides propagate in excitonic polariton mode. In this mode, the propagation velocity has strong energy dependence, particularly in the knee region of the polariton dispersion curve, and is typically much smaller than the speed of light in the semiconductors. The reduced propagation speed of the polaritons in the waveguide is expected since the coupling between the excitons and photons occurs at the energy corresponding to exciton transitions in the MQW. The average speed obtained is a measure of the propagation speed of polaritons inside the waveguide. Polaritons with speeds three or four orders of magnitude slower than the speed of light in different semiconductors in the bottleneck region have been previously observed.[5,9–11]

Our results shed light towards the fundamental physics behind propagation of light in III-nitride semiconductors. This information is important for many device applications. For example, when the ridge-guide laser diode is used as a read/write laser source in digital versatile disks, the ridge width has to be reduced to micron dimensions in order to obtain fundamental transverse modes necessary to collimate the laser light to a small spot.[12,13] The knowledge of the speed at which light is propagated along such a device is basic to its design for improved operation.

In conclusion, we have studied the dynamic properties of light propagation in submicron waveguide structures based on AlGaN/GaN MQWs. The integrated emission intensity systematically decreases when detected from one end of the waveguide as the position of the laser spot on the waveguide is varied. The temporal response also shows a systematic increase in time delay. These changes in integrated intensity as well as time delay have been explained in terms of propagation of excitonic polaritons in the MQW waveguides of the III-nitride materials. The propagation speed of the polaritons in the waveguide was determined to be $(1.26\pm 0.16)\times 10^7$ m/s.

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