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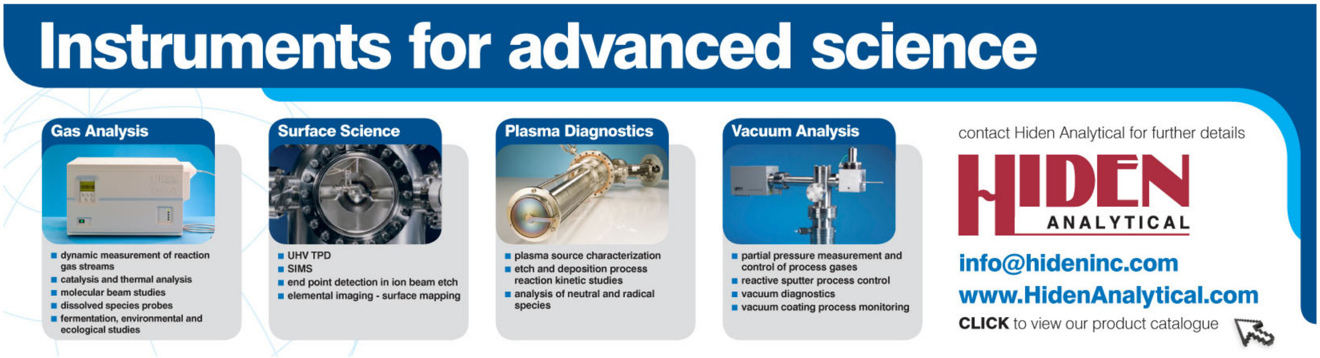

Optical properties of GaN/AlGaN multiple quantum well microdisks

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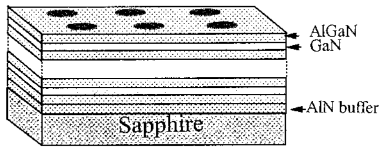
An array of microdisks with a diameter of about 9 μm and spacing of 50 μm has been fabricated by dry etching from a 50 Å/50 Å GaN/Al$_x$Ga$_{1-x}$N ($x \sim 0.07$) multiple quantum well (MQW) structure grown by reactive molecular beam epitaxy. Optical properties of these microdisks have been studied by picosecond time-resolved photoluminescence (PL) spectroscopy. Photoluminescence emission spectra and decay dynamics were measured at various temperatures and pump intensities. With respect to the original MQWs, we observe strong enhancement of the transition intensity and lifetime for both the intrinsic and barrier transitions. The intrinsic transition is excitonic at low temperatures and exhibits an approximate tenfold increase in both lifetime and PL intensity upon formation of the microdisks. This implies a significant enhancement of quantum efficiency in microdisks and a bright future for III-nitride microcavity lasers. © *1997 American Institute of Physics.* [S0003-6951(97)04746-3]

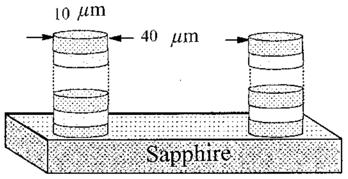
A great deal of research involving the group III-nitrides has been directed toward the realization of practical blue laser devices. Impressive successes such as the room temperature operation of an edge-emission InGaN/GaN multiple quantum well (MQW) blue lasers have already been reported.[1] Yet, there remains much to be investigated. One particularly promising area meriting study is the microstructure laser system. Structures such as micron-sized disks, or microcavities, can be fabricated from epitaxial layers, MQW structures, or vertical-cavity surface-emitting lasers (VCSELs). In VCSELs, these microdisks are expected to enhance the spontaneous emission coefficient of desired lasing modes, thus reducing the threshold current for lasing.[2,3] The fundamental change from a large area plane to small discrete structures may also significantly affect carrier dynamics in microdisks independently from the coupling effects to the radiation field. In this letter, we report the results of picosecond time-resolved photoluminescence (PL) emission studies carried out on a GaN/AlGaN MQW microdisk structure. The results are compared with data obtained for the MQW structure prior to microdisk formation and significant changes in the behavior of the various optical transitions are discussed. The implications of our results to future nitride VCSELs and microcavity lasers are also discussed.

The wurtzite MQW structure used for this study was grown by reactive molecular beam epitaxy (MBE) on a (0001) sapphire substrate. It consists of a 50 nm AlN buffer layer followed by growth of a 10 period MQW consisting of 50 Å/50 Å GaN/Al$_x$Ga$_{1-x}$N ($x \sim 0.07$) and a 200 Å AlN cap layer. All layers were grown nominally undoped. Dry etching was used to pattern an array of microdisks of approximate 9 μm diameter and 50 μm spacing. The sample was etched to an approximate depth of 250 nm and thus into the sapphire substrate so that no III-nitride material is present between microdisks. Figure 1 shows schematics of (a) the MQW structure, (b) MQW microdisks, and (c) a scanning electron microscopy (SEM) image obtained after microdisk fabrication. As depicted in Fig. 1(b), each microdisk is comprised of a 10 period MQW with the confinement direction along the axis of the disk. The SEM image presented in Fig. 1(c) clearly shows the array of disks with a measured diameter of 8–9 μm which is in good agreement with the target diameter of 9 μm. The regularity of the array and the quality

(a) GaN/AlGaN MQWs



(b) GaN/AlGaN Micro-disk



(c)

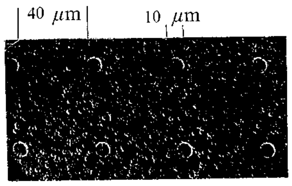


FIG. 1. Schematics of (a) the MQW structure and (b) the MQW microdisks. A top view SEM image of the microdisk structure is shown in (c).

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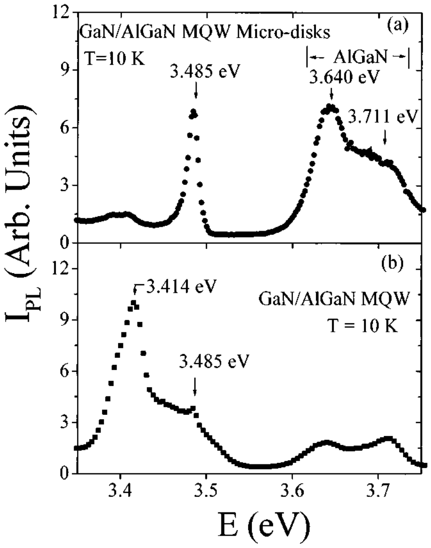

FIG. 2. The cw spectra at 10 K from (a) the MQW microdisk structure and (b) the MQW structure. Peak energies of various optical transitions are labeled for clarity within the text. The spectra were obtained under identical excitation intensities and pump geometries with an excitation wavelength of 288 nm.

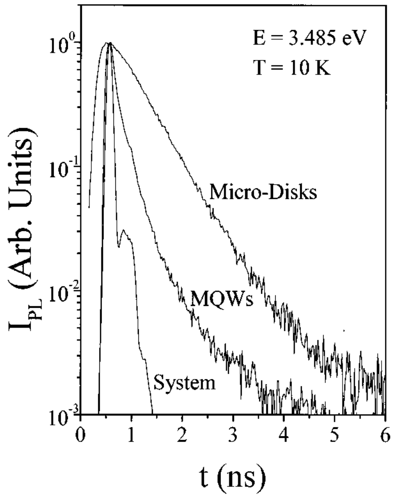

FIG. 3. Temporal response of the intrinsic exciton recombination measured at 10 K for a PL energy of 3.485 eV. Decays are shown for the sample prior to and after formation of the microdisks. System response is about 25 ps and is shown as indicated.

of the disk shape are also evident in the SEM image. Time-resolved PL emission spectroscopy measurements were conducted both prior to and after microdisk fabrication. The overall response of the PL detection system is approximately 25 ps. The excitation laser wavelength is 288 nm and the pulse width is about 7 ps. A more detailed description of the laser and PL detection systems may be found elsewhere.[4,5]

Figure 2 shows cw spectra for the GaN/AlGaN MQWs at 10 K after (a) and prior to (b) formation of microdisks. Experimental conditions such as excitation energy, excitation intensity, and geometry are the same for both cases. The 3.485 eV emission line has been previously identified for GaN epilayers as the recombination of the ground state *A* exciton.[5–8] No quantum confinement related blue shift of the *A*-exciton transition is expected for this MQW sample because its well width exceeds the empirical critical thickness of the GaN/$Al_{0.07}Ga_{0.93}N$ MQW system.[9] Therefore, the 3.485 eV optical transition for this MQW microdisk sample shown in Fig. 2(a) is identified as the *A* exciton. The 3.640 eV optical transition originates from within the $Al_xGa_{1-x}N$ ($x \sim 0.07$) barrier layer. We believe the impurity transition at 3.414 eV, which is dominant within the MQW [Fig. 2(b)], originates from misfit dislocations that are generated at the lattice-mismatched interface of the GaN/$Al_{0.07}Ga_{0.93}N$ system.[9] Comparison of the spectra in Figs. 2(a) and 2(b) reveals a large enhancement of the *A* exciton (3.485 eV) and barrier (3.640 eV) transitions in the MQW microdisks relative to the dominant transition (3.414 eV) prior to patterning. Furthermore, the intensity of each of these transitions in the microdisks was found to vary linearly or super linearly with pump intensity. This is an indication that the enhancement of the *A* exciton (3.485 eV) and barrier (3.640 eV) transitions is not the result of a saturation of the lower energy (or impurity) optical processes. The obvious difference between the cw spectra seen here is very interesting because it suggests that the carrier dynamics and quantum efficiency within the MQW structure change upon formation of the microdisks. It should be noted however, that the dimensions of the microdisks are far too large to result in carrier quantum confinement effects within the growth plane.

In order to elucidate the nature of the observed excitonic transition quantum efficiency enhancement, decay lifetimes were measured at various temperatures. Figure 3 shows the temporal response of the *A*-exciton (3.485 eV) transition at 10 K both prior to and after microdisk fabrication. The overall system response, which is about 25 ps, is also shown as indicated by ''system.'' Both decays in Fig. 3 are almost simple exponential, but the exciton decay measured at 3.485 eV in the MQW (prior to microdisks) has a slow decay tail at longer delay times due to a PL contribution from the dominant band-to-impurity transition at 3.414 eV. The major component of the decay in the MQW represents the *A*-exciton lifetime which is dominated by nonradiative transfer to the impurity states induced by misfit dislocations. However, the *A*-exciton decay lifetime in the microdisks ($\tau = 593\,\mathrm{ps}$) is much longer than that for the MQW ($\tau = 53\,\mathrm{ps}$) and is more representative of a true radiative lifetime. The significantly longer lifetime observed for the *A* exciton in the microdisks sample is consistent with the enhancement of the *A*-exciton transition intensity seen in Fig. 2(a).

Figure 4 shows the temperature dependence from 10 to 100 K of the *A*-exciton lifetime. The lifetimes measured for the microdisks are comparable to the *A*-exciton lifetime found previously for high quality GaN layers and GaN/AlGaN MQWs in which impurity transitions are absent.[8,9] It is clearly seen in Fig. 4 that the enhancement of the transition lifetime for the microdisks is present up to a temperature of at least 100 K. Although the lifetime of the exciton transition remains fairly long, the integrated PL intensity was observed to decrease rapidly with increased temperature. We observed an approximate one order of magnitude decrease in PL intensity for the *A*-exciton transition in the microdisks (not shown) as the sample temperature was raised from 10 to

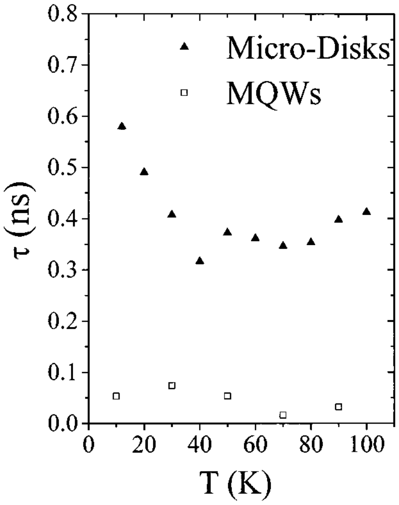

FIG. 4. Temperature dependence of the *A*-exciton decay lifetime (τ) up to 100 K. Open squares represent the MQWs and closed triangles represent the microdisks.

40 K. The radiative recombination efficiency (η) for an optical transition may be expressed as $\eta = \tau_L / \tau_R$ where τ_L and τ_R are the total transition lifetime and the radiative lifetime, respectively. Within the microdisks, the transition lifetime exhibited less than a factor of two decrease from 10 to 40 K and the radiative lifetime is not expected to vary significantly. Therefore, the pronounced decrease in PL intensity cannot be attributed to a large change in the radiative recombination efficiency (η) of the transition. Rather, we believe it suggests the rate of exciton formation from photogenerated carriers may have a strong temperature dependence within the microdisk structure.

Considering the observed PL emission behavior before and after fabrication of microdisks, the following interesting points may be expressed. Both the cw spectra and recombination lifetime measurements indicate a pronounced increase in the quantum efficiency of the *A*-exciton (intrinsic) transition. In the microdisks, an observed decrease in transition intensity with increased temperature appears to be attributable to a decrease in the efficiency of exciton formation from photogenerated carriers. The enhanced quantum efficiency of the *A*-exciton transition in conjunction with a suppression of the impurity transition at 3.414 eV implies a suppression of transfer from the exciton state to the impurity state in the microdisks. This phenomenon may be related to a change in exciton localization within the microdisk structure. For example, it is understood that unavoidable fluctuations in well thickness may result in exciton localization within MQWs.[10] Energy fluctuations may also exist due to variations in local lattice strain or strain relaxation. Whatever the source of energy fluctuation is, if one randomly removes 97% (as is the case for our microdisk sample) of the material from the MQW structure, the probability of significant fluctuations existing within a microdisk of the remaining material is greatly reduced. This of course assumes that such fluctuations are comparable in dimension to the microdisks. In other words, within this model, the MQWs inside the microdisks are more uniform on average than the MQW structure prior to microdisk fabrication. Therefore, there will be a reduced likelihood of coupling between low energy exciton states and impurity states within the microdisks. As a consequence, the recombination lifetime and quantum efficiency of the intrinsic exciton transition are greatly enhanced and the impurity transition is suppressed. We note that the previous is a suggested mechanism at this point, and more comprehensive studies of the optical transitions are underway to make more certain statements regarding the nature of the quantum efficiency enhancement.

In conclusion, we have studied the optical transitions within GaN/AlGaN MQW microdisk structures fabricated by dry etching. Comparison of the optical transition behavior with data acquired prior to microdisk fabrication reveals a strong enhancement of the intrinsic exciton transition quantum efficiency in the microdisks. The enhancement is related to a suppression of the impurity transition at 3.414 eV and is explained as a reduction in coupling between exciton and impurity transitions within the MQW microdisks and a corresponding cutoff of transfer from the excitonic state to the impurity state. The observed enhancement of the intrinsic transition quantum efficiency in the microdisk structure is a very encouraging result for future III-nitride laser devices, particularly microcavity lasers and VCSELs. The importance of this enhancement is more emphasized when one considers that it is not due to a cavity-modified spontaneous emission coefficient, but rather it is in addition to this expected effect. Perhaps real microcavity VCSEL devices will benefit from both effects. Further studies on this and other microdisk samples are currently in progress with particular emphasis on carrier dynamics under excitation intensities approaching laser injection level.

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