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# The effect of inserting strain-compensated GaNAs layers on the luminescence properties of GaInNAs/GaAs quantum well

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## Abstract

Photoluminescence (PL) properties of GaInNAs/GaAs quantum wells (QWs) with strain-compensated GaNAs layers grown by molecular beam epitaxy are investigated. The temperature-dependent PL spectra of GaInNAs/GaAs QW with and without GaNAs layers are compared and carefully studied. It is shown that the introduction of GaNAs layers between well and barrier can effectively extend the emission wavelength, mainly due to the reduction of the barrier potential. The PL peak position up to 1.41  $\mu\text{m}$  is observed at the room temperature. After adding the GaNAs layers into QW structures, there is no essential deterioration of luminescence efficiency. N-induced localization states are also not remarkably influenced. It implies that with optimized growth condition, high-quality GaInNAs/GaAs QWs with strain-compensated GaNAs layers can be achieved.

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## 1. Introduction

Semiconductor lasers at 1.3 or 1.55  $\mu\text{m}$  wavelengths are very important light sources for optical fiber communication. Recently, a novel material system GaInNAs/GaAs was proposed for this application [1]. It has many advantages compared with the conventional GaInAsP/InP system. Ac-

tually, adding nitrogen into the compressively strained GaInAs/GaAs quantum well can reduce the strain, lower the band gap, and increase the conduction band offset. Moreover, it is easy to grow a good GaAs/AlAs DBR structure for vertical-cavity surface-emitting lasers (VCSEL) using GaInNAs in the active region [2–4]. However, with increasing N mole fraction, the optical quality of the material may be deteriorated significantly, resulting in a higher threshold current density of GaInNAs/GaAs lasers. In order

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to improve the performance of 1.3–1.55  $\mu\text{m}$  GaInNAs/GaAs QW lasers, the nitrogen composition of GaInNAs well should be considerably small, commonly no more than 1%, although this will lead to an increased strain for getting corresponding wavelength [5]. In order to solve this problem, it was proposed to introduce strain-compensated layers to this GaInNAs/GaAs QW structure, which is able to extend the emission wavelength and reduce the average strain in system, hence increasing the number of multi-quantum wells (MQWs) in the laser structures [6–8]. However, the effect on the PL properties of GaInNAs/GaAs QW system by inserting strain-compensated GaNAs barrier layers is not well elucidated now. Especially, the existence of high strain accumulated at the compressive/tensile strain surfaces induced by inserting GaNAs layers between GaInNAs QW and GaAs barriers might deteriorate the crystalline quality.

In this paper, we have reported detailed investigations on the PL properties of GaInNAs layers with strain-compensated GaNAs layers grown by molecular beam epitaxy (MBE). The temperature-dependent PL spectra of GaInNAs/GaAs QW are carefully studied. It is shown that with the introduction of GaNAs layers between well and barrier, the wavelength is effectively extended up to 1.41  $\mu\text{m}$  without remarkably affecting the quality of material. The theoretical calculation shows that the redshift of the emission wavelength is caused by the reduction of the barrier potential. The N-induced localization states are also not remarkably influenced after adding the GaNAs layers into QW structures. The results imply that with optimized growth conditions, high-quality GaInNAs/GaAs QWs with a strain-compensated GaNAs layer emitting at 1.3 or 1.55  $\mu\text{m}$  may be achieved.

## 2. Experimental details

Both GaInNAs/GaAs QW with strain-compensated GaNAs layers (marked as sample B) and reference GaInNAs/GaAs sample (marked as sample A) investigated here were grown at the same condition by molecular-beam epitaxy

(MBE). The structure of the sample B consists of a GaAs(100) substrate, 4-nm-thick GaNAs, 8-nm-thick GaInNAs layer, then 4-nm-thick GaNAs, 150-nm-thick GaAs, and 25-nm-thick GaAs cap layer. The band gap structure of sample B is a double step (DS) QW, as shown in Fig. 1(b), while that of sample A is a single step (SS) QW not shown here. The In and N concentration of samples B and A is the same, which is 36% and 1.6%, respectively. The N percentage incorporated into the strain-compensated GaNAs layers was assumed to be a little higher than the GaInNAs

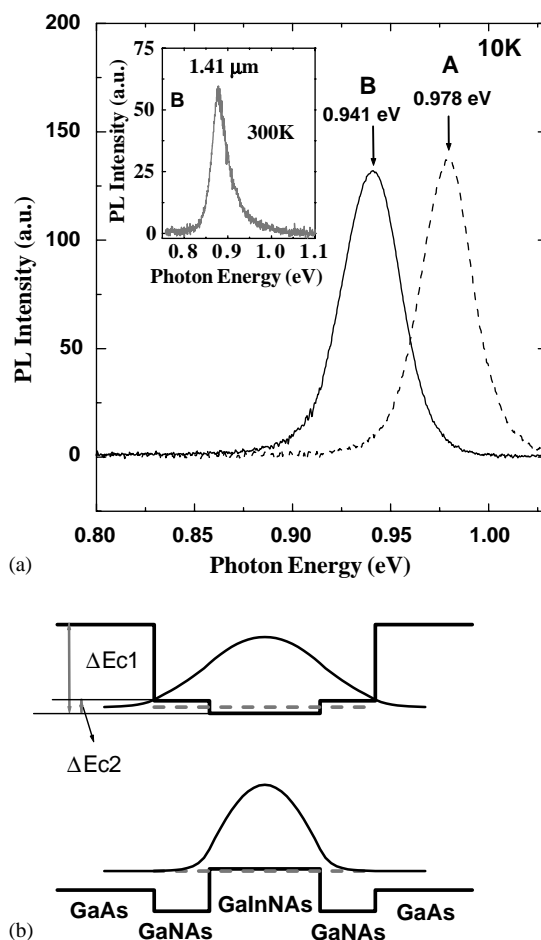


Fig. 1. (a) PL spectra from 8 nm  $\text{Ga}_{0.64}\text{In}_{0.36}\text{N}_{0.016}\text{As}_{0.984}/\text{GaAs}$  QW structures at 10 K: A—without GaNAs layer; B—with GaNAs layers. In the inset, PL spectrum from sample B at room temperature. (b) Schematic band gap of GaInNAs QW for with GaNAs layers and the result of theoretical calculation.

well layer due to the decrease of the growth rate of GaNAs layers.

The PL measurement was performed by using a variable-temperature (10–300 K) close-cycle cryostat under the excitation of a 632.8 nm line from an He–Ne laser. The PL signal was collected by a Nicolet FTIR760 Fourier spectrometer and detected by a cooled Ge detector.

### 3. Results and discussions

Fig. 1(a) shows the typical photoluminescence (PL) spectra at 10 K from samples A and B. The sample B shifts the spectrum towards longer wavelength, that is, to lower energy relative to the reference sample A, and their energy difference is about 37 meV. The PL peak wavelength at room temperature of sample B is extended up to 1.41  $\mu\text{m}$ , as shown in the inset of Fig. 1(a). We confirm here that introducing GaNAs layers can effectively extend the QW emission to longer wavelength. The reason is that insertion of GaNAs layers has effectively reduced the barrier potential. We have made a calculation of the quantized electron and hole energy levels in the SS and DS structures assuming that the epilayers are not relaxed, and a type-II band offset exists between GaNAs and GaAs [9,10]. As shown in Fig. 1(b), the barrier height  $\Delta E_{c2}$  at the GaInNAs/GaNAs interface is about 50 meV, which is much reduced in comparison with  $\Delta E_{c1}$  at the GaInNAs/GaAs interface. It is found that the ground states of electron and hole wave functions are still mainly distributed in the GaInNAs layer region in the DS structure. Compared with the wave function in the valence band, the spatial distribution of the wave function in the conduction band is more dispersed due to the reduction of barrier height caused by the introduction of GaNAs layers. According to the calculation result, the ground state of hole wave function has only a negligible change, while the energy level of the ground state of electrons decreases noticeably due to the reduction of barriers height. Therefore, the reduction of barrier height at conduction band in the GaNAs layers causes a significant redshift of the PL peak energy. Moreover, together with increasing of emission

wavelength, the luminescence intensity from strain-compensated structure sample B was slightly degraded, but it was still quite comparable to that of sample A. And the FWHM values of the PL peak are 35.3 and 30.8 meV for DS and SS samples, respectively. This confirms that the crystal quality of both samples is comparable.

The temperature dependence of the PL spectra of sample B is measured under different excitation intensity. When the excitation intensity is low, a weak S-shape temperature dependence of PL peak can be seen between 10 and 80 K due to the carrier localization by the potential fluctuation [11,12]. However, the PL spectra of sample B are dominated by the peak originated from near-band-edge transitions when the excitation intensity is high enough ( $I_{\text{ex}} = 1.5 \text{ W/cm}^2$ ) and no other PL peak was observed, as can be seen from Fig. 2(a). In Fig. 2(b), the PL peak energy values of samples

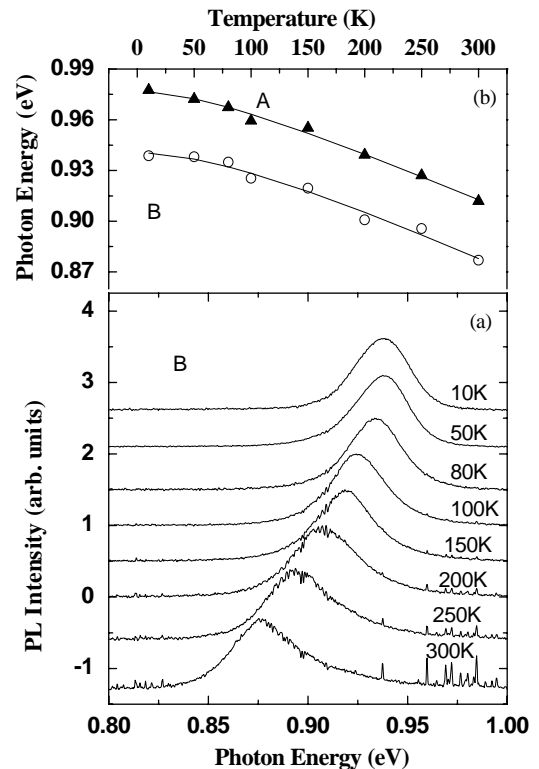


Fig. 2. (a) Temperature dependence PL spectra of  $\text{Ga}_{0.64}\text{In}_{0.36}\text{N}_{0.016}\text{As}_{0.984}/\text{GaAs}$  QW with GaNAs layers. (b) Peak energy of the PL spectra vs. temperature for samples A and B.

A and B are plotted as a function of temperature. The temperature dependence of PL peak can be well fitted using Varshni equation. In both samples, the difference of peak energies between 10 and 300 K is nearly 62 meV, and the difference of PL peak energy of two samples remains nearly constant in the whole temperature region. According to Varshni equation [13]

$$E_g(T) = E_g(0) - \alpha T^2 / (\beta + T), \quad (1)$$

where  $T$  is the absolute temperature,  $E_g(0)$  is the band gap at  $T = 0$ , and  $\alpha$  and  $\beta$  are constants. The fitting of the experimental data indicates that  $\alpha$  and  $\beta$  values for A are  $3 \times 10^{-4}$  eV/K and 123 K and for B are  $3.3 \times 10^{-4}$  eV/K and 175 K, showing that the temperature coefficient of  $E_g$  of sample B is comparable to that of sample A. In addition, the values of FWHM of sample B are a little larger

than that of sample A. Such a difference may be related with a larger amount of absolute strain at the interface between the GaNAs strain-compensated layer and the GaInNAs well layer [8].

In order to make clear whether inserting GaNAs layers between the GaInNAs well and GaAs barrier has other effects on the GaInNAs well except for the observed redshift, the peak energy as a function of excitation intensity is measured and shown in Fig. 3. It is found that the peak energy exhibits a blueshift with increasing excitation intensity at 10 K, and the value is 17 and 18 meV for samples A and B, respectively, as shown in inset (a) of Fig. 3. The values of blueshift of both samples are nearly the same for a change in excitation intensity of four decades of magnitude. Because the blueshift behavior is considered to be related with the carrier localization, it can be

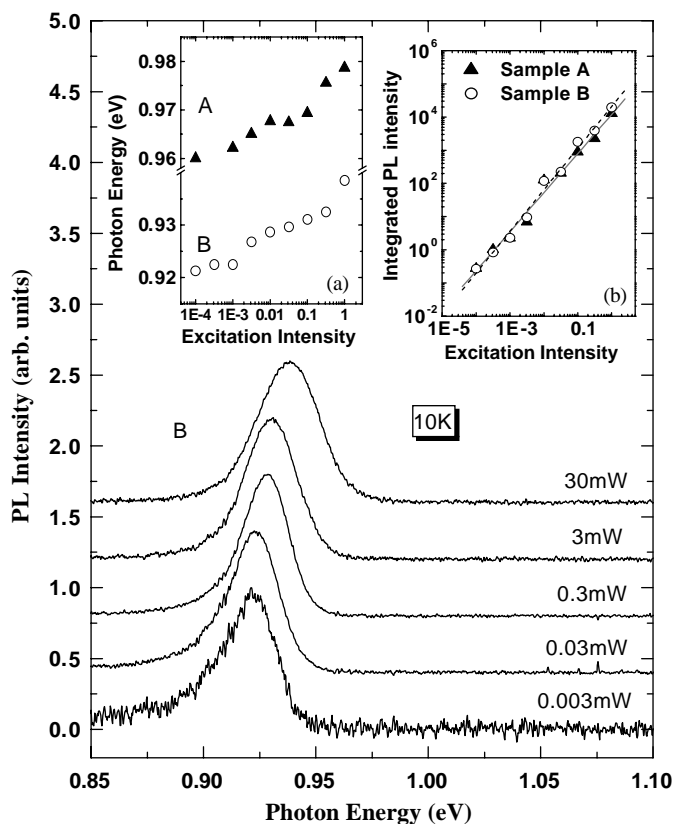


Fig. 3. PL spectra at different excitation intensity at 10 K of sample B; inset (a) peak energy of sample A (closed triangles) and sample B (open circles) plotted as a function of excitation intensity at 10 K. And integrated PL intensity of sample A (closed triangles) and sample B (open circles) plotted as a function of excitation intensity at 10 K in inset (b).

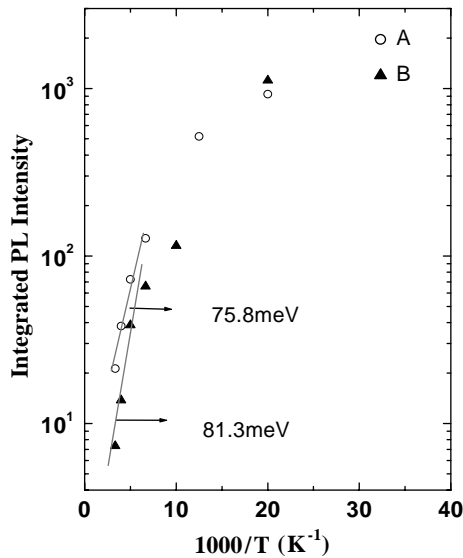


Fig. 4. Integrated PL Intensity plotted as a function of reciprocal temperature for GaInNAs QW (A) without GaNAs layers; and (B) with GaNAs layers.

concluded that no additional localized states are induced by the insertion of the GaNAs layers. The PL intensity of GaInNAs QW in both samples exhibits a linear dependence on the excitation intensity with a slope of nearly 1, as shown in inset (b) of Fig. 3, which is the typical feature of excitonic transition-induced luminescence process.

The temperature dependence of the PL integrated intensity is shown in Fig. 4 for samples A and B. The data could be fitted to the Arrhenius relationship [14]:

$$I_{\text{PL}} = I_0/[1 + A \exp(T/T_0)]. \quad (2)$$

We found that the activation energy, which is derived by the linear part of the plot, for carrier thermal quenching is quite similar, i.e. 75.8 and 81.3 meV, respectively, and the reduction of the PL integrated intensity between 10 and 300 K is also comparable between SS and DS samples. It shows once again that the inserting GaNAs layers have little effect on the carrier localization and non-radiative recombination.

#### 4. Conclusion

The PL spectra of quaternary GaInNAs/GaAs QW with strain-compensated GaNAs layers were carefully studied. In comparison with the reference GaInNAs/GaAs QW, the emission wavelength is extended towards longer wavelength about 1.41  $\mu\text{m}$  without degrading the crystal quality after the insertion of the GaNAs layers. The results of theoretical calculation shows that the ground state of electron wave function in the DS structures is still mainly distributed in the GaInNAs well layer region. The reduction of the barrier height can effectively reduce the emission energy of QW. The temperature- and excitation intensity-dependent PL spectra showed that no remarkable deterioration of optical properties were induced by inserting the GaNAs layers. Even after the thermal annealing, a blueshift may be introduced [15–20], the high-quality GaInNAs/GaAs QWs with strain-compensated GaNAs layers emitting at 1.3 or 1.55  $\mu\text{m}$  can be achieved by using optimized growth conditions.

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