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Optical studies of molecular beam epitaxy grown GaAsSbN/GaAs single quantum well structures

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In this work, the authors present a systematic study on the variation of the structural and the optical properties of GaAsSbN/GaAs single quantum wells (SQWs) as a function of nitrogen concentration. These SQW layers were grown by the solid source molecular beam epitaxial technique. A maximum reduction of 328 meV in the photoluminescence (PL) peak energy of GaAsSbN was observed with respect to the reference GaAsSb QW. 8 K and RT PL peak energies of 0.774 eV (FWHM of ~25 meV) and 0.729 eV (FWHM of ~67 meV) (FWHM denotes full width at half maximum) corresponding to the emission wavelengths of 1.6 and 1.7 μm, respectively, have been achieved for a GaAsSbN SQW of N ~ 1.4%. The pronounced *S*-curve behavior of the PL spectra at low temperatures is a signature of exciton localization, which is found to decrease from 16 to 9 meV with increasing N concentration of 0.9%–2.5%. The diamagnetic shift of 13 meV observed in the magnetophotoluminescence spectra of the nitride sample with N ~ 1.4% is smaller in comparison to the value of 28 meV in the non-nitride sample, indicative of an enhancement in the electron effective mass in the nitride QWs. Electron effective mass of $0.065m_o$ has been estimated for a SQW with N ~ 1.4% using the band anticrossing model. © *2007 American Vacuum Society.* [DOI: 10.1116/1.2720860]

I. INTRODUCTION

InGaAsN/GaAs, GaAsSbN/GaAs, and InGaAs(Sb)N/GaAs dilute nitride alloy systems lattice matched to GaAs are of potential interest in optical communications in the 1.55 μm emission wavelength region. InGaAsN/GaAs has been the most extensively studied system; however, the operating wavelength of 1.55 μm necessitates N and In concentrations exceeding 2% and 35%, respectively, leading to considerable degradation of the structural and optical properties.[1–4] More recently InGaAsN(Sb)/GaAs system has been demonstrated to be successful in this wavelength range[2,3,5] but five components make the system more complex. The work on GaAsSbN/GaAs system has been somewhat limited.[6–11] Our earlier work on the GaAsSbN quantum wells[6] (QWs) shows that good quality structures with emission at 1.55 μm can be reached for a N concentration of ~1.4%.

In this work, we present a detailed and systematic study of the effect of N incorporation on the structural, low temperature photoluminescence characteristics and the calculated conduction band electron effective mass values. The temperature dependence of PL characteristics in the low temperature regime is dominated by localized excitons caused by the potential fluctuations introduced by N incorporation. The exciton localization was found to become weaker with increasing N concentration. The magnetophotoluminescence data indicate enhanced conduction band (CB) electron effective mass in nitride QWs in comparison to the non-nitride QWs. The computation of the enhanced effective mass value using band anticrossing (BAC) model is also presented.

II. EXPERIMENTAL DETAILS

The GaAsSbN/GaAs single QW (SQW) structures were grown using the solid source molecular beam epitaxial technique with N plasma source. The GaAsSbN QW layers were sandwiched between GaAs layers followed by GaAlAs to improve carrier confinement in the QWs. The growth temperatures of the QWs and GaAlAs barriers were 470 and 580 °C, respectively, and these samples were exposed to Sb and As flux prior to QW growth. All the samples were subjected to *in situ* annealing in As ambient at 650 °C to improve the luminescence.[6] High resolution x-ray diffraction (HRXRD) was performed with a Bede Scientific Metrix-F automated diffractometer, equipped with a microsource x-ray generator. The motorized detector slit was set to 0.5 mm wide, giving a 2θ angular resolution of 150 arc sec. The compositions of Sb and N were determined using simulation of the HRXRD spectra and secondary ion mass spectroscopy data. The Sb composition in all the samples was in the range

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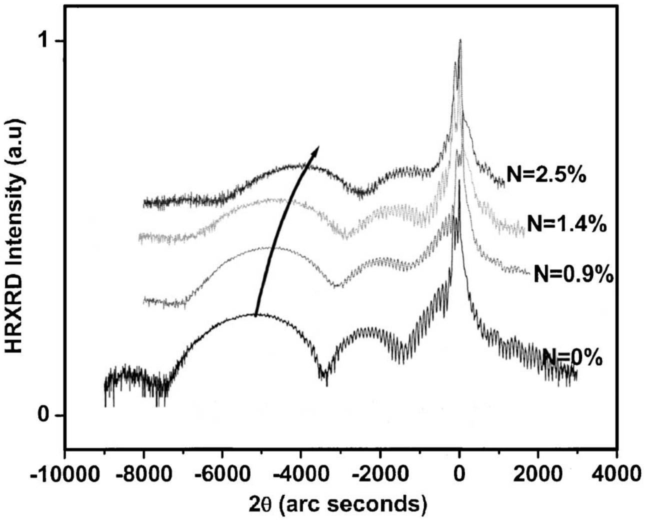

FIG. 1. (004) HRXRD θ-2θ scan spectra for GaAsSbN SQWs with increasing N incorporation.

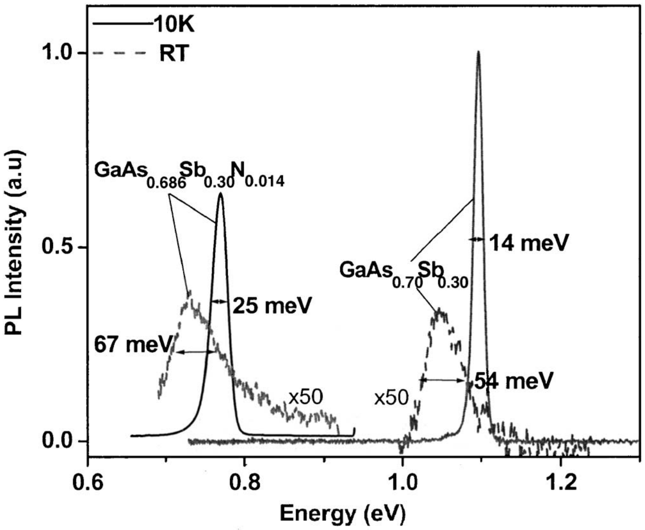

FIG. 2. 10 K and RT PL spectra of GaAsSb and *in situ* annealed GaAsSbN (N ~ 1.4%) SQWs.

of 28%–30%. The details of the PL measurements are given in Ref. 6. Low temperature (4 K) magnetophotoluminescence measurements were carried out with the magnetic field varying from 0 to 32 T and were directed normal to the sample. The details of these are given in Ref. 7.

III. RESULTS

Figure 1 illustrates the HRXRD spectra of GaAsSbN SQW with GaAlAs barriers grown for various N concentrations. With the introduction of small amount of N (0.9%–2.5%) the quaternary GaAsSbN layer peak shifts to the right of the compressively strained reference GaAsSb QW peak grown under similar conditions. Pendullosung fringes are observed in all the samples. N composition in the SQWs increases almost linearly but only a marginal increase in the Sb composition with increasing N flux is observed.

Figure 2 displays the low temperature (10 K) and room temperature PL spectra of the GaAsSbN SQW structure for N ~ 1.4% grown at 470 °C, along with those of the reference GaAsSb SQW for comparison. The 10 K PL spectral position of the quaternary SQW shifted to lower energy by ~328 meV exhibited a somewhat higher PL linewidth of 25 meV and a lower intensity as compared to the non-nitride QW. The PL peak wavelengths corresponding to a 10 K emission of 1.6 μm (FWHM of ~25 meV) and a RT emission of 1.7 μm (FWHM of ~67 meV) (FWHM denotes full width at half maximum) have been achieved. The PL peak energy decreases rapidly up to N ~ 1.4% but thereafter the reduction in PL peak energy seizes, as shown in Fig. 3.

Figure 4 shows the temperature dependence of the PL spectra of the SQWs for N concentrations of 0%, 0.9%, 1.4%, and 2.5%. The low temperature PL peak energy exhibits redshift and blueshift with increasing temperature up to ~100 K and thereafter decreases monotonically with temperature. This characteristic *S*-curve behavior becomes less pronounced with the increasing N concentration (Fig. 4).

The temperature dependence of PL peak energy of the SQWs was fitted using the well-known Varshni empirical relation,[8]

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{\beta + T}, \tag{1}$$

where T is the absolute temperature, $E_g(0)$ is the band gap at 0 K, and α and β are the fitting parameters. The values of these parameters for all the samples are tabulated in Table I. This table also lists the values of the parameters $T_{\rm trans}$, $E_{\rm loc}^{\rm max}$, and $T_{\rm deloc}$ which are defined as the onset of the transition temperature regime where localized excitons begin transition to higher energy localized states, the maximum localization energy measured as the largest energetic difference between the experimental PL peak energy and value of the energy obtained using Varshni relation, and the temperature at which

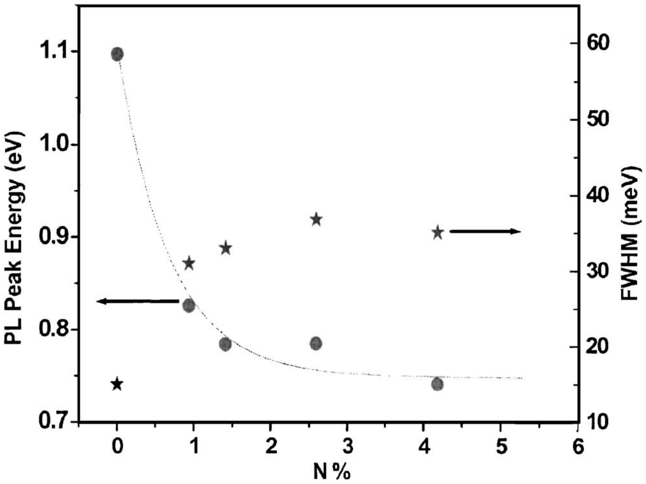

FIG. 3. 10 K PL peak energy shifts and FWHM variations for different N concentrations. The solid line represents the trend line of variation of the PL peak energy with N concentration.

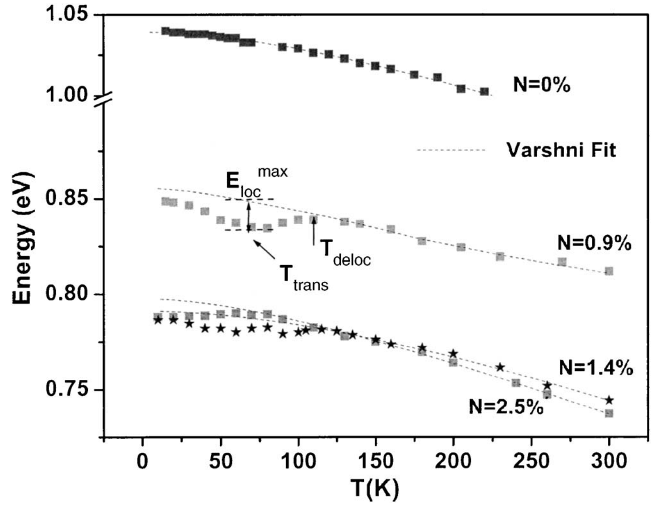

FIG. 4. Temperature dependence of QWs for different N concentrations illustrating the *S*-curve behavior of the PL peak position and the Varshni fitting [Eq. (1)].

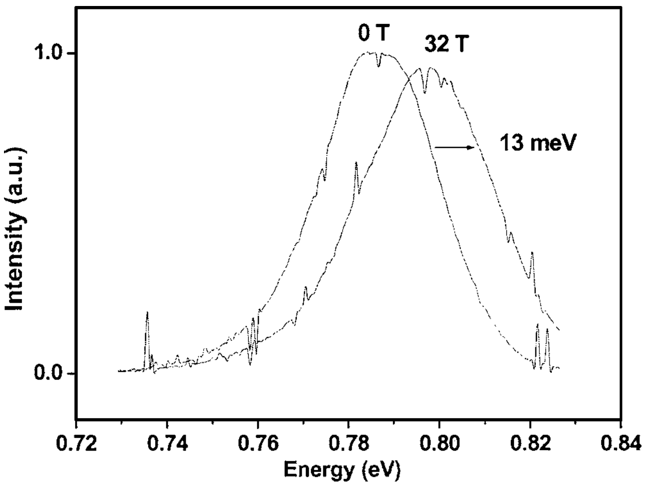

FIG. 5. Magento-PL spectra of GaAsSbN (N ~ 1.4%) SQW at 4 K at 0 and 32 T.

delocalization of the carriers is complete, respectively. The values of these parameters are found to decrease with increase in N concentration.

Figure 5 depicts a magneto-PL spectrum of GaAsSbN SQW for N ~ 1.4%. A blueshift of 13 meV (28 meV shift in GaAsSb QW) and broadening of the spectra are observed in the presence of magnetic field (32 T) as expected.[7,12,13] The variation of diamagnetic shift, δ defined as $E_g(B)-E_g(B=0)$, as a function of the applied magnetic field (B) for N ~ 1.4% is shown in Fig. 6. The δ observed in GaAsSb SQW vary linearly with B while the variation in GaAsSbN SQW is sublinear and is significantly less than that observed in GaAsSb reference QW. The effective mass of the nitride QW has been estimated using the BAC model[14] as follows. The standard equation obtained from the definition of density of states to calculate the effective mass is

$$m_{\mathrm{eff}} = m^{*}\left\{1 + \left[\frac{V_{NM}}{E_N - E_M(k)}\right]^2\right\}, \tag{2}$$

where the resonant energy level E_N, introduced by N is assumed to be around 1.65 eV above the valence band edge as in InGaAsN and GaAsN systems,[14,15] and $E_M(k)$ is the interacting CB energy level of the host semiconductor GaAsSb. In the above equation, the value of V_{NM} is computed using the low temperature PL peak energy in the energy dispersion relation (see Refs. 14 and 15).

Using $m^{*}=0.050m_0$, for the electron effective mass in the host GaAsSb at low energies and low values of the wave vector k, m_{eff} for the GaAsSbN SQW is computed to be ~$0.065m_o$ for the N concentration of ~1.4%.

IV. DISCUSSION

The presence of Pendullosung fringes in the x-ray rocking curves attest to the excellent quality of the grown layers and abrupt interfaces (Fig. 1). The ternary GaAsSb QWs are compressively strained and with increasing N concentration, the strain in the QW layer becomes more tensile. Sb incorporation is found to be relatively independent of N composition in our QWs.

The PL peak energy decreases at a faster rate for N concentrations up to 1.4%, as shown in Fig. 3. A reduction of ~328 meV in energy has been observed in the GaAsSbN SQW for N ~ 1.4% and Sb ~ 30% with reference to GaAsSb SQW, which is much larger than the reported values[7,9–11] in this material system.

S-curve behavior observed at low temperatures in the temperature dependence of the PL peak energy position of the GaAsSbN SQWs, as shown in Fig. 4, is commonly attributed to the localized behavior of excitons due to the potential fluctuations arising from the compositional variation and/or N related defects. The observed trend in the localization energy and transition and delocalization temperatures with N concentration can be explained qualitatively as follows. The

TABLE I. Varshni's parameters for the temperature dependence of the PL peak energy for different N concentrations.

N%	$E_{10\ \mathrm{K}}$	α (meV/K)	β (K)	$E_{\mathrm{loc}}^{\mathrm{max}}$ (meV)	T_{trans} (K)	T_{deloc} (K)
0	1.039	0.36	245	⋯	⋯	⋯
0.9	0.823	0.37	273	16	75	100
1.4	0.786	0.36	325	8	60	90
2.5	0.788	0.33	204	9	10	80

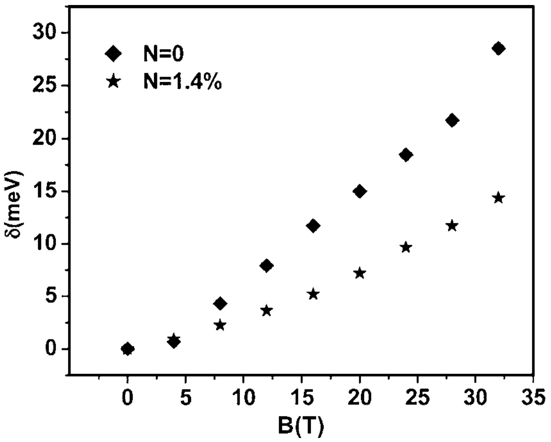

FIG. 6. Variation of the diamagnetic shift as a function of the magnetic field for the ternary and the quaternary SQWs.

nitride QW at low N concentration of 0.9% exhibits the highest localization energy of about 16 meV. The excitons require elevated temperatures as high as ~80–100 K to detrap from the potential wells. As the N concentration increases, these deeper potentials appear to become shallower as evidenced by the less pronounced *S* curve. This unexpected trend could be attributed to any or combination of the following effects. These are decreased alloy fluctuations, increased confinement of carriers screening these potential modulations,[16] and effective annihilation of N related defect centers.

The PL transition energy in the presence of the magnetic field exhibits a smaller shift in the nitride QWs in comparison to the non-nitride reference sample, implying an enhancement in the electron effective mass value. The electron effective mass calculated using the BAC model for the quaternary QW is $0.065m_o$ lower than those computed by Senger *et al.*[7] ($0.09m_o$) in a GaAsSbN QW for similar N concentration. This is consistent with the larger δ observed for a given magnetic field in both the non-nitride and nitride QWs as our values are almost double than those reported by Senger *et al.*[7] This suggests that the exciton wave function in our samples is weakly localized. It is to be noted that these are preliminary data and further work is being carried out to determine the conduction electron effective mass more accurately.

V. CONCLUSIONS

We have achieved 8 K and RT PL emission at 1.6 μm (FWHM of ~25 meV) and 1.7 μm (FWHM of ~67 meV) in GaAsSbN SQW for N ~ 1.4%. Temperature dependence of the PL spectra exhibited exciton localization at temperatures below ~100 K. PL peak energy reduction of 328 meV from the reference GaAsSb has been observed. The changes in the PL characteristics are significant up to N ~ 1.4% and thereafter saturates. The exciton localization energy and delocalization temperature were found to decrease with increase in N concentration. Electron effective mass is enhanced in nitride QWs in comparison to the non-nitride QWs as expected.

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[1] H. Saito, T. Makimoto, and N. Kobayashi, J. Cryst. Growth **195**, 416 (1998).
[2] Kerstin Volz, Vincent Gambin, Wonill Ha, Mark A. Wistey, Homan Yuen, Seth Bank, and James S. Harris, J. Cryst. Growth **251**, 360 (2003).
[3] L. H. Li, V. Sallet, G. Patriarche, L. Largeau, S. Bouchoule, L. Travers, and J. C. Harmand, Appl. Phys. Lett. **83**, 1298 (2003).
[4] M.-A. Pinault and E. Tournie, Solid-State Electron. **47**, 477 (2003).
[5] James S. Harris, Jr., J. Cryst. Growth **278**, 3 (2005).
[6] L. Wu, S. Iyer, K. Nunna, J. Li, S. Bharatan, W. Collis, and K. Matney, J. Cryst. Growth **279**, 293 (2005).
[7] R. T. Senger *et al.*, Appl. Phys. Lett. **83**, 5425 (2003).
[8] J. Li, S. Iyer, S. Bharatan, L. Wu, K. Nunna, W. Collis, K. Bajaj, and K. Matney, J. Appl. Phys. **98**, 013703 (2005).
[9] J. C. Harmand *et al.*, J. Cryst. Growth **553**, 227 (2001).
[10] G. Ungaro, G. Le Roux, R. Teissier, and J. C. Harmand, Electron. Lett. **35**, 1246 (1999).
[11] J. C. Harmand *et al.*, Semicond. Sci. Technol. **17**, 778 (2002).
[12] J. Zeman, G. Martinez, K. K. Bajaj, I. Krivorotov, and K. Uchida, Appl. Phys. Lett. **77**, 4335 (2000).
[13] R. T. Senger *et al.*, Appl. Phys. Lett. **83**, 2614 (2003).
[14] C. Skierbiszewski *et al.*, Appl. Phys. Lett. **76**, 2409 (2000).
[15] J. Wu, W. Shan, W. Walukiewicz, K. M. Yu, J. W. Ager III, E. E. Haller, H. P. Xin, and C. W. Tu, Phys. Rev. B **64**, 085320 (2001).
[16] H. Dumont, L. Auvray, Y. Montiel, F. Saidi, F. Hassen, and H. Marref, Opt. Mater. (Amsterdam, Neth.) **24**, 303 (2003).