Magnetoluminescence properties of GaAsSbN/GaAs quantum well structures

R. T. Senger[a)] and K. K. Bajaj
Department of Physics, Emory University, Atlanta, Georgia 30322

E. D. Jones, N. A. Modine, K. E. Waldrip, F. Jalali, J. F. Klem, and G. M. Peake
Sandia National Laboratories, Albuquerque, New Mexico 87185

X. Wei and S. W. Tozer
NHMFL, Florida State University, Tallahassee, Florida 32310

(Received 27 August 2003; accepted 7 November 2003)

We report a measurement of the variation of the diamagnetic shift of a heavy-hole exciton in a single coherently strained $GaAs_{0.685}Sb_{0.3}N_{0.015}$/GaAs quantum well as a function of magnetic field up to 32 T at 1.3 K using photoluminescence spectroscopy. The excitons are known to be localized in this alloy system. This localization is simulated by assuming that the hole is completely immobilized, i.e., its mass is infinite. Using this model we have calculated the variation of the diamagnetic shift with magnetic field in this quantum well structure following a variational approach. We find that the observed variation of the diamagnetic shift with magnetic field agrees quite well with that calculated when the mass of the conduction electron in the well is assumed to be 0.09 m_0, about 50% larger than in $GaAs_{0.7}Sb_{0.3}$, an increase similar to that found in GaAsN for the same nitrogen composition.
 [DOI: 10.1063/1.1637439]

Ever since the early work of Weyers *et al.*[1] and Kondow *et al.*[2] there has been an extensive effort devoted to the study of the structural, electronic, and optical properties of III–V compounds and their alloys containing small percentage of nitrogen (N). The observation of a drastic reduction (about 180 meV) in the energy band gap of GaAs, for instance, with a small concentration of N (~1%) has stimulated an enormous interest in optoelectronic devices grown on GaAs operating in the 1.3 μm region. Introduction of nitrogen in GaAs also leads to smaller values of the lattice parameter. Thus, the addition of a dilute amount of N offers a unique feature of reducing simultaneously both the band gap and the lattice parameter of a given III–V semiconductor or an alloy.

To reduce the value of the band gap of GaAs-based materials further, InGaNAs quaternary was proposed by Kondow *et al.*[3] Since then laser diodes based on this material operating in the 1.3 μm region have been demonstrated[4–6] and applications to solar cells,[7] and heterojunction bipolar transistors have been investigated.[8]

Recently, Ungaro *et al.*[9] have shown that the incorporation of a small amount of nitrogen (~1%) in GaAsSb ternary alloy reduces its band gap by almost 180 meV; about the same as in InGaAs. It is known that in a GaAsSb/GaAs quantum well structure, for a given value of Sb composition, the value of the band gap is smaller than in InGaAs/GaAs quantum well for the same In composition as long as the widths of the quantum wells in each case are smaller than the critical thickness.[10] Thus, for a given value of nitrogen composition, one can obtain lower values of the band gap in GaAsSbN/GaAs quantum wells than in InGaAsN/GaAs quantum wells.

In this letter we present a study of the behavior of the diamagnetic shift (δ) of an excitonic transition in a coherently strained GaAsSbN/GaAs quantum well as a function of magnetic field using photoluminescence spectroscopy at 1.3 K. The compositions of Sb and N in our sample are estimated to be about 30% and 1.5%, respectively. The magnetic field was applied parallel to the direction of growth, and was varied from zero to 32 T. The value of δ increases as a function of magnetic field as expected. We find that the variation of δ as a function of magnetic field we measure is much smaller than what would be expected for a free exciton. To explain our data on the variation of δ with magnetic field, we propose, as was done in the case of InGaP alloy[11] and GaAsSb/GaAs quantum wells,[12] that the exciton is strongly localized at a defect or a potential fluctuation or both. To simulate this localization we assume, as before, that the hole is completely localized, namely, the hole mass is treated as infinite.

Sample used in this study was grown on Si-doped (001)-oriented GaAs substrate by molecular beam epitaxy (MBE). It contained a single 60 Å wide GaAsSbN quantum well with nominal Sb composition of about 30%. The MBE growth was performed using elemental As and Sb sources fitted with crackers. An RF plasma source using high purity nitrogen gas provided the reactive nitrogen species. The concentration of N was controlled through the use of a shutter and by varying the growth rate of the film. In the case of GaAsSbN layers, the temperature of the substrate must remain within a fairly narrow range in order to maintain proper control of the concentrations of the constituents of group V elements and the quality of the quantum wells. Our structure consisted of a 3000 Å wide GaAs barrier layer grown on GaAs substrate followed by a 60 Å wide quantum well on which was grown another 3000-Å-thick GaAs layer. The GaAs layers were

[a)]Present address: TÜBİTAK-UEKAE, P.K.74, 41470 Gebze, Kocaeli, Turkey; electronic mail: senger@physics.emory.edu

grown at 590 °C while the growth temperature of the quantum well was 460 °C. The growth rates used were 1.0 and 1.6 μm/h for the barriers and the active layer, respectively. The sample was subjected to *ex situ* rapid thermal annealing at 825 °C for 10 s under a GaAs cover wafer in an enclosed graphite susceptor backfilled with nitrogen. It is known[13] that the photoluminescence (PL) characteristics of GaAsSbN are considerably modified by rapid thermal annealing. It leads to improvements in the intensity, reduction in the PL linewidth and a blueshift of the PL peak. These effects are attributed to the drastic reduction in nonradiative channels due to the annealing of crystalline imperfections such as point defects and arsenic antisites. However, no structural changes were observed after annealing.[13] The nitrogen content in our samples is estimated to be about 1.5% as determined by the nitrogen flux and the growth conditions. An accurate determination using electron recoil detection technique is in progress. For the sake of a comparative study, one quantum well sample with the same structure as described above but without nitrogen, i.e., only GaAsSb, with nominally the same Sb concentration was also grown.

The PL spectroscopic measurements were carried out at 1.3 K. The sample was attached to the end of a 100 μm core diameter optical fiber and was immersed in liquid He. An argon-ion laser operating at 514.5 nm was used as an irradiating source. The laser beam was injected into the optical fiber by means of an optical beamsplitter and the returning PL signal was directed to a 0.27 m focal length, $f/4$ optical monochromator and an IEEE 488-based data acquisition system. Typical values of the power densities used on our samples were of the order of 1 W/cm^2. A North Coast EO-817 germanium photodetector together with 30 Hz optical chopper and a phase sensitive lock-in system were used to record the infrared spectrum.

In Fig. 1(a) we display a typical PL spectrum of an unannealed 60 Å wide single GaAsSb/GaAs quantum well with 30% Sb concentration at 1.3 K. The energy of the emission peak at 1.0165 eV is considerably less than the value of the band gap of GaAs (1.5196 meV) and has a full width at maximum (σ) of 13.5 meV.

In Fig. 1(b) we display the PL spectra of a 60 Å wide single GaAsSbN/GaAs quantum well at two different values of the magnetic field, namely, zero and 32 T. The excitonic transition is located at 0.8210 eV and has a value of σ of about 28 meV, at zero field. The Sb concentration in this well is estimated to be about 30%. An addition of a small percentage ($\sim$1.5%) of nitrogen reduces the value of the excitonic transition energy in the $GaAs_{0.7}Sb_{0.3}$ quantum well of the same thickness by 196 meV, a result similar to that found by Ungaro *et al.*[9] The excitonic transition at 0.8210 eV shifts to higher energies and broadens as a function of the magnetic field, as expected.

We have calculated the variation of the diamagnetic shift of this excitonic transition as a function of magnetic field in this quantum well structure using a variational formalism similar to that of Greene and Bajaj.[14] We have used the expression for the Hamiltonian given in the earlier reference and have adopted the following form of a three-parameter variational wave function for our calculations:

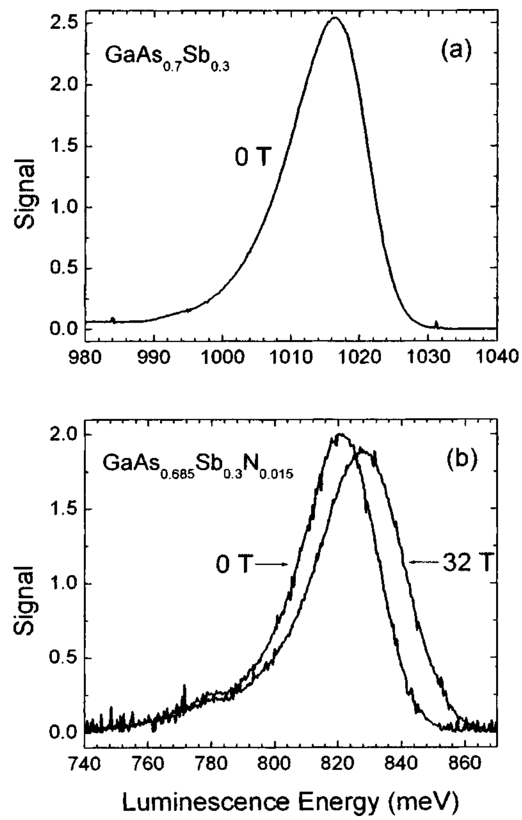

FIG. 1. Photoluminescence spectrum: (a) a 60 Å wide $GaAs_{0.7}Sb_{0.3}$/GaAs quantum well (reference sample) at zero magnetic field, (b) a 60 Å wide $GaAs_{0.685}Sb_{0.3}N_{0.015}$/GaAs quantum well for magnetic field values of zero and 32 T. Measurements are made at 1.3 K.

$$\psi(\mathbf{r}_e,\mathbf{r}_h)=f_e(z_e)f_h(z_h)\times\exp[-\lambda\sqrt{(\boldsymbol{\rho}_e-\boldsymbol{\rho}_h)^2+a^2(z_e-z_h)^2}]\times\exp[-b^2(\boldsymbol{\rho}_e-\boldsymbol{\rho}_h)^2],$$

where f_i $(i=e,h)$ are the well known envelope functions of the electron and the hole in the quantum well, $\mathbf{r}_i=(\boldsymbol{\rho}_i,z_i)$ are the electron and hole position coordinates, and λ, a, b are the variational parameters. The values of the various physical parameters[15] we use in our calculations are obtained by linear interpolation between those of GaAs and GaSb, where the conduction band masses are 0.067 and 0.042 m_0, and the dielectric constants are 12.5 and 15.7, respectively. We assume that the addition of a small amount ($\sim$1.5%) of nitrogen does not change the values of these parameters except for the values of the mass of the conduction electron and the conduction band offset.[10] Recently we have measured the variation of the diamagnetic shift of an excitonic transition as a function of magnetic field in $GaAs_{0.7}Sb_{0.3}$/GaAs quantum wells at 1.3 K using PL spectroscopy.[12] We find the best agreement between the calculated and the measured values when the heavy-hole is assumed to be completely localized; namely its mass is assumed to be infinite, thus suggesting a strong exciton localization. In the present calculation we have also assumed a strong exciton localization in GaAsSbN/GaAs quantum wells (namely the hole mass taken as infinite), and have treated the conduction band mass as an adjustable parameter. We have used 0.273 and 0.472 eV for the conduction and the valence band offsets, respectively. We have assumed that the addition of a small amount of nitrogen

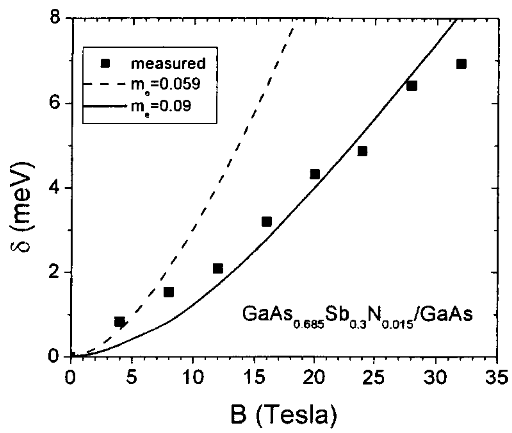

FIG. 2. Variation of the diamagnetic shift of the heavy-hole excitonic transition in a 60 Å wide $GaAs_{0.685}Sb_{0.3}N_{0.015}$/GaAs quantum well as a function of the magnetic field. Symbols represent the experimental data. The curves are calculated using the localized exciton model with infinite heavy-hole mass. The conduction band masses are taken as 0.059 and 0.09 m_0 for the dashed and solid curves, respectively.

affects only the conduction band and changes it from either weakly type-II or weakly type-I to moderately type-I.[10]

In Fig. 2 we display the variation of the diamagnetic shift of the excitonic transition as a function of magnetic field in our quantum well structure calculated using the model described earlier (solid line). The experimental data are represented by solid squares. We find that the use of 0.09 m_0 as the value of the mass of the conduction electron leads to the calculated values that agree quite well with the experimental data. This is almost an enhancement of about 50% in the mass of the conduction electron in $GaAs_{0.7}Sb_{0.3}$ (0.059 m_0). This is a determination of the enhancement of the mass of the conduction electron in $GaAs_{0.685}Sb_{0.3}N_{0.015}$ alloy system. This enhancement in the mass of the conduction band electron is similar to that obtained in GaAs after the incorporation of similar concentration of nitrogen.[16] It should be pointed out that a strong localization of excitons has also been observed in InGaAsN/GaAs quantum wells.[17]

In summary, we have measured the variation of the diamagnetic shift of the heavy-hole exciton transition in a coherently strained single $GaAs_{0.685}Sb_{0.3}N_{0.015}$/GaAs quantum well structure as a function of the applied magnetic field up to 32 T at 1.3 K using photoluminescence spectroscopy. The value of the peak energy of this transition shifts from 0.8210 to 0.8279 eV when the magnetic field is varied from zero to 32 T. The observed variation of the diamagnetic shift with magnetic field is compared with the results of a variational calculation, which assumes that the hole is completely localized. We find the observed variation of the diamagnetic shift with magnetic field agrees very well with that calculated when the mass of the conduction electron is assumed to be 0.09 m_0. This is a determination of the mass of the conduction electron in $GaAs_{0.685}Sb_{0.3}N_{0.015}$ alloy system. Thus, introduction of a small concentration of nitrogen (~1.5%) into $GaAs_{0.7}Sb_{0.3}$ leads to an enhancement of the value of the mass of the conduction electron by more than 50%.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract No. DE-AC04-94AL85000. High field measurements were performed at the National High Magnetic Field Laboratory, which is supported by NSF Cooperative Agreement No. DMR-9016241 and by the State of Florida.

[1] M. Weyers, M. Sato, and H. Ando, Jpn. J. Appl. Phys., Part 2 **31**, L853 (1992).
[2] M. Kondow, K. Uomi, K. Hosomi, and T. Mozume, Jpn. J. Appl. Phys., Part 2 **33**, L1056 (1994).
[3] M. Kondow, K. Uomi, A. Niwa, T. Kitatani, S. Watahiki, and Y. Yazawa, Jpn. J. Appl. Phys., Part 1 **35**, 1273 (1996).
[4] M. Reinhardt, M. Fischer, M. Kamp, and A. Forchel, Electron. Lett. **36**, 1025 (2000).
[5] D. A. Livshits, A. Y. Egorov, and H. Riechert, Electron. Lett. **36**, 1381 (2000).
[6] J. S. Harris, Jr., Semicond. Sci. Technol. **17**, 880 (2002).
[7] S. R. Kurtz, J. F. Clem, A. A. Allerman, R. M. Sieg, C. H. Seager, and E. D. Jones, Appl. Phys. Lett. **80**, 1379 (2002).
[8] P. M. Asbeck, R. J. Welty, C. W. Tu, H. P. Xin, and R. E. Welser, Semicond. Sci. Technol. **17**, 898 (2002).
[9] G. Ungaro, G. Le Roux, R. Teissier, and J. C. Harmand, Electron. Lett. **35**, 1246 (1999).
[10] J. C. Harmand, A. Caliman, E. V. K. Rao, L. Largeau, J. Ramos, R. Teissier, L. Traverse, G. Ungaro, B. Theys, and I. F. L. Dias, Semicond. Sci. Technol. **17**, 778 (2002).
[11] J. Zeman, G. Martinez, K. K. Bajaj, I. Krivorotov, and K. Uchida, Appl. Phys. Lett. **77**, 4335 (2000).
[12] R. T. Senger, K. K. Bajaj, E. D. Jones, N. A. Modine, K. E. Waldrip, F. Jalali, J. F. Klem, G. M. Peake, X. Wei, and S. W. Tozer, Appl. Phys. Lett. **83**, 2614 (2003).
[13] J. C. Harmand, G. Ungaro, J. Ramos, E. V. K. Rao, G. Saint-Girons, R. Teissier, G. Le Roux, L. Largeau, and G. Patriarche, J. Cryst. Growth **227**, 553 (2001).
[14] R. L. Greene and K. K. Bajaj, Phys. Rev. B **31**, 6498 (1985).
[15] I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, J. Appl. Phys. **89**, 5815 (2001).
[16] C. Skierbiszewski, Semicond. Sci. Technol. **17**, 803 (2002).
[17] M. A. Pinault and E. Tournié, Solid-State Electron. **47**, 477 (2003).