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Magneto-optical properties of GaAsSb/GaAs quantum wells

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We have measured the diamagnetic shift of a heavy-hole exciton in a single 60 Å wide $GaAs_{0.7}Sb_{0.3}$/GaAs quantum well as a function of magnetic field up to 32 T at 1.3 K using photoluminescence spectroscopy. The sample was grown on (001)-oriented GaAs substrate using solid-source molecular beam epitaxy. We have calculated the variation of the diamagnetic shift as a function of magnetic field using a variational approach and a free exciton model. We assumed a weak type-I conduction-band lineup in our calculations. We found that the values thus obtained are more than twice as large as the observed values. A similar calculation assuming a complete localization of the heavy hole leads to the values of the diamagnetic shift which agree very well with the experimental data. Our study suggests that the excitons are strongly localized in $GaAs_{0.7}Sb_{0.3}$/GaAs quantum well structures at low temperatures, and that this heterostructure has a weak type-I conduction-band lineup.
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Study of the structural, electronic, and optical properties of semiconductor alloys has attracted enormous attention during the past three decades. This interest has been motivated by their extensive applications in a variety of microwave and optoelectronic devices and by a strong desire to understand their fundamental properties. With the availability of mature epitaxial crystal growth technologies, such as molecular beam epitaxy (MBE) and metal organic chemical vapor deposition, and their various variants, it is now possible to grow high-quality layers and heterostructures of these alloys with controlled compositions and sharp interfaces.

Recently, the GaAsSb alloy system grown on GaAs substrates has attracted considerable attention due to its potential applications in optoelectronic devices operating in the 1.3 μm region.[1,2] Attempts have been made to incorporate nitrogen in this system to further reduce the band gap for applications in the 1.5 μm region.[3,4] Therefore, a precise knowledge of its band parameters and a proper understanding of its optical properties are needed to fully exploit its potential.

A number of groups have studied the optical properties of GaAsSb/GaAs quantum well structures in the absence of a magnetic field.[5–10] In this letter, we present a study of the variation of the diamagnetic shift (δ) of an excitonic transition in a GaAsSb/GaAs quantum well as a function of the magnetic field at 1.3 K. The Sb composition in our sample is nominally 30% and the magnetic field is varied from 0 to 32 T. We find that the variation of δ, as a function of the magnetic field we measure, is much smaller than that calculated using the formalism of Greene and Bajaj[11] assuming a free exciton model. To explain our data on the magnetic field dependence of the variation of δ, we assume that the hole is completely localized; the hole mass is infinite. A similar assumption about the behavior of the hole was made in a completely disordered InGaP-grown lattice matched on GaAs to explain the observed variation of δ with magnetic field in this material.[12]

The sample studied in this work was grown on a Si-doped (100)-oriented GaAs substrate by MBE. It contained a single 60 Å wide GaAsSb quantum well with nominally 30% Sb concentration. The MBE growth was performed using elemental As and Sb solid cracking sources. The structure consisted of a 3000 Å thick GaAs layer, followed by a 60 Å wide quantum well with a 3000 Å thick GaAs barrier layer grown on it. The GaAs barrier layers were grown at 590 °C, while the growth temperature of the quantum well was 460 °C. Growth rates were 1.0 and 1.6 μm/h for the barriers and the active layer, respectively. The Sb composition in the quantum wells was estimated from the Sb and As flux ratio. The sample was not subjected to any annealing treatments.

The photoluminescence (PL) 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 excitation source. The laser beam was injected into the optical fiber by means of an optical beam splitter and the PL signal was detected by a 0.27 m, f14 optical monochromator, and a IEEE 488-based data acquisition system. Typical laser power densities used in our measurements were of the order of 1 W/cm^2. A North Coast EO-817 germanium photodetector, together with a 30 Hz optical chopper and a phase sensitive lock-in system, were used to record the infrared spectrum.

In Fig. 1, we display the PL spectra of a 60 Å wide GaAsSb/GaAs single quantum well at the lower and upper

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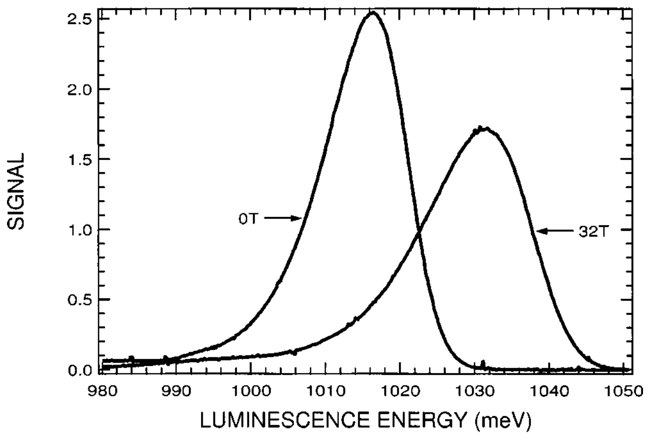

FIG. 1. PL spectra of a 60 Å wide $GaAs_{0.7}Sb_{0.3}/GaAs$ quantum well at 1.3 K, for magnetic field values of zero and 32 T.

limits of the range of applied magnetic field, namely at $B=0$, and $B=32$ T. The position of the heavy-hole excitonic transition at zero magnetic field is at 1.0165 eV which is considerably lower than the value of the band gap of GaAs at 1.3 K (1.5196 eV). This transition broadens and shifts to higher energies with increasing values of the magnetic field. At 32 T, the transition energy is measured to be 1.0315 eV.

In order to calculate the diamagnetic shifts, we follow a variational formalism similar to that of Greene and Bajaj.[11] Applying the magnetic field in a direction perpendicular to the plane of the structure and using the symmetric gauge, the Hamiltonian of the system regarding the 1*s* state is given by,[11]

$$H=\sum_{i=e,h}\left(-\frac{\hbar^2}{2m_i}\frac{\partial^2}{\partial z_i^2}+V_i^{\mathrm{conf}}(z_i)\right)-\frac{\hbar^2}{2\mu}\frac{1}{\rho}\frac{\partial}{\partial\rho}\rho\frac{\partial}{\partial\rho}$$
$$-\frac{e^2}{\varepsilon_0\sqrt{\rho^2+(z_e-z_h)^2}}+\frac{1}{8}\mu\omega_c^2\rho^2, \tag{1}$$

where $\omega_c=(eB)/(\mu c)$, such that the energy of the first Landau level of the exciton is given by $\hbar\omega_c/2$. Here m_e is the effective mass of the conduction electron, m_h is the heavy-hole mass along the z direction, and μ is the reduced mass in the transverse plane. Both μ and m_h can be expressed in terms of Luttinger band parameters γ_1 and γ_2:[11] $\mu=(1/m_e+(\gamma_1+\gamma_2)/m_0)^{-1}$, $m_h=(\gamma_1-2\gamma_2)^{-1}m_0$, where m_0 is the free electron mass. The particle position vectors are denoted by $\mathbf{r}_i=(\boldsymbol{\rho}_i,z_i)$, and $\boldsymbol{\rho}=\boldsymbol{\rho}_e-\boldsymbol{\rho}_h$ is the relative coordinate.

Consistent with the above Hamiltonian, we use a three-parameter trial wave function of the form

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

where $f_i(i=e,h)$ are the envelope functions of the electron and the hole in the quantum well, and λ, a, and b are the variational parameters which provide the flexibility of ψ to conform to all the natural limits of the system. A variational upper bound to the ground-state energy of the system as a function of the magnetic field is calculated as, $E_0(B)=\min_{\lambda,a,b}\langle\psi|H|\psi\rangle$. Then, the diamagnetic shift is defined as, $\delta=E_0(B)-E_0(B=0)$.

In Fig. 2, we display the variation of the diamagnetic shift (δ) as a function of magnetic field in a 60 Å thick coherently strained GaAsSb/GaAs quantum well as we calculated. The values of the various physical parameters used in our calculations are obtained by linear interpolation between those of GaAs and GaSb given in Table I. The dashed curve is obtained using a free exciton model, and the experimental data is represented by solid squares. As seen in Fig. 2, the calculated value of δ, for instance at 10 T, is more than a factor of 2 larger than the measured value. At higher values of the magnetic field, the difference between the calculated and the measured values is even larger. It should be pointed out that in our calculations, we have used 1.014 eV for the band gap of the coherently strained $GaAs_{0.7}Sb_{0.3}$ well in GaAs. Prins *et al.*[6] have used high-pressure PL measurements to investigate the conduction- and the valence-band offsets between coherently strained and unstrained GaAs and suggest that the conduction-band states have a weak type-I lineup. A recent study by Johnson *et al.*[10] also suggests an almost flat (weak type-I) GaAsSb/GaAs conduction-band alignment for Sb concentrations of up to 37%. Therefore, for the conduction-band offset, we have used a value of 10 meV. A weak type-II band lineup has also been suggested by some groups.[7,8] We find that our results for the free exciton model are relatively insensitive to a weak type-I or a weak type-II band lineup.

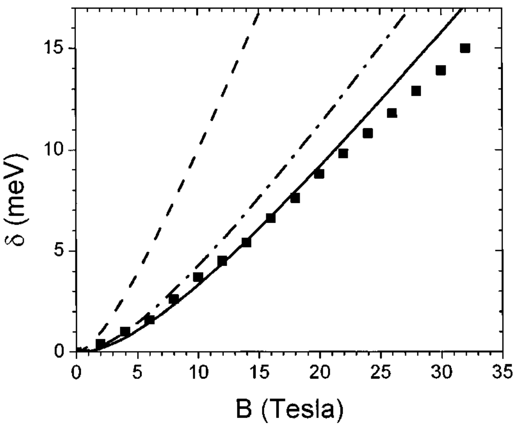

FIG. 2. Variation of the diamagnetic shift of the heavy-hole excitonic transition in a $GaAs_{0.7}Sb_{0.3}/GaAs$ quantum well with a thickness of 60 Å as a function of the magnetic field. Symbols represent experimental data. Dashed curve is calculated using the free exciton model. Dotted–dashed curve is obtained using an infinite mass for the localized heavy hole. In both cases, the conduction-band offset (ΔE_c) is assumed to be 10 meV in a weak type-I band lineup configuration. The solid curve which agrees best with the measurement is obtained by assuming a larger value of 50 meV for ΔE_c, together with infinite hole mass and nonparabolicity corrections for the conduction band.

To explain the unexpected behavior of the diamagnetic

TABLE I. The parameters used in our calculations.[a] The conduction-band mass m_e is given in units of bare electron mass m_0. γ_1 and γ_2 are the Kohn–Luttinger band parameters in terms of which the heavy-hole masses along the z direction and in the plane perpendicular to it are given by $m_h^{(z)}=(\gamma_1-2\gamma_2)^{-1}$ and $m_h^{(\perp)}=(\gamma_1+\gamma_2)^{-1}$, respectively, in units of m_0. ε_0 is the dielectric constant.

Material	m_e	γ_1	γ_2	ε_0
GaAs	0.067	6.98	2.06	12.5
GaSb	0.042	13.4	4.7	15.7

[a] See Ref. 14.

shift with magnetic field in our sample, we propose, for the reasons not completely clear to us at this time, that the hole is completely localized by some defect or by potential fluctuations or both at low temperatures. As mentioned earlier, a similar behavior of the excitonic diamagnetic shift with magnetic field was found in completely disordered InGaP layers grown lattice matched on GaAs.[12] In Fig. 2, we display the variation of δ with magnetic field thus calculated by a dotted–dashed curve. We have also included the effect of the nonparabolicity of the conduction band using an energy-dependent electron effective mass.[13] For the values of the magnetic field larger than 10 T, the calculated diamagnetic shifts are still somewhat larger than the measured values. If we increase the value of the conduction-band offset from 10 meV to 50 meV, however, we find that the values of δ we calculate agree very well with the measured values (solid curve in Fig. 2). The assumption of a small value of the conduction-band offset (50 meV) is consistent with the proposed weak type-I lineup by Prins *et al.*,[6] and by Johnson *et al.*[10] As seen in Fig. 2, at high magnetic fields, the calculated values of the diamagnetic shift are still somewhat larger than the measured values. This may be due to a partial localization of the electron by the alloy potential fluctuations induced by the magnetic field, thus effectively enhancing its mass.

As shown in Fig. 1, the value of the full width at half maximum (σ) of the excitonic transition increases as a function of the magnetic field. The variation, however, is rather small, i.e., about 3.6 meV for 32 T change in the value of the magnetic field. It is clearly not possible to calculate the variation of σ with magnetic field as the relative importance of various scattering mechanisms, such as those due to alloy compositional fluctuations, interface roughness, ionized impurities, alloy clustering, etc., is not known.

In summary, we have measured the variation of the diamagnetic shift of the heavy-hole exciton transition in a coherently strained single GaAsSb/GaAs quantum well as a function of magnetic field upto 32 T at 1.3 K using PL spectroscopy. The value of the peak energy of this transition shifts from 1.0165 to 1.0315 eV when the magnetic field is varied from 0 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 and the quantum well structure has a weak type-I conduction-band lineup, and a very good agreement is found. The physical origin of the hole localization is not understood at this time.

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