# Optical studies of strained type II $GaAs_{0.7}Sb_{0.3}$/GaAs multiple quantum wells

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We report a detailed investigation on the optical transitions of strained type II $GaAs_{0.7}Sb_{0.3}$/GaAs (100) multiple quantum wells. For the theoretical calculations, both of the elastic deformational potential of intrinsic compressive biaxial strain, and quantum confinement effects are included. The asymmetric photoluminescence spectra reveal the features of excited state transition and quantum confinement Stark effect at high and low temperatures, respectively. The asymmetry features have also been investigated and confirmed by low-temperature photoluminescence experiments under different excitation power. From polarized photoluminescence excitation and photoconductivity spectra, both of the type I and type II optical transitions can also be clearly identified. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1576497]

## I. INTRODUCTION

Recently, the type II GaAsSb/GaAs quantum well structures have been shown to be potentially useful materials for optoelectronic devices, such as the fabrication of sources and detectors in long wavelength for optical-fiber communications, photodiodes, photocathodes, light-emitting diodes, edge-emitting lasers, and vertical-cavity surface-emitting lasers.[1–4] Its type II band structure also provides an excellent opportunity to improve the performance of heterojunction bipolar transistors. Besides its technological potential, it serves as a model system for investigating the atomic ordering and compositional modulation expected in III–V–V alloys. In spite of its importance, the optical properties of this system have not been clearly understood due to the difficulties in growing high quality samples as well as the detection of type II luminescence.[5,6] In this article, we present a detailed investigation on the optical transitions in type II GaAsSb/GaAs multiple quantum wells (MQWs) by photoluminescence (PL), photoluminescence excitation (PLE), and photoconductivity (PC) spectroscopies. A theoretical analysis of the band structure, including the effects of intrinsic compressive biaxial strain and quantum confinement were carried out for the studied materials. A comparison between the theoretical and experimental results will be presented.

## II. SAMPLE AND EXPERIMENTS

The samples used in the present study were grown with a VG V-80MKII solid-source molecular beam epitaxy on an undoped semi-insulating GaAs (100) substrate. The Sb source was supplied using an EPI model 175 standard crackers K cell, and the As source was supplied from a 150 $cm^3$ K cell. The cracker zone temperature was 1050 °C, while the bulk zone temperature was about 430 °C, and the growth temperature of the buffer layer and MQWs were 600 and 500 °C, respectively. The structure of MQWs contains a 500-Å-thick GaAs buffer layer, five periods of $GaAs_{0.7}Sb_{0.3}$ 50 Å/GaAs 300 Å quantum well, a 45 s As flux exposure was applied to each interface of the $GaAs_{0.7}Sb_{0.3}$ well, and a 1000 Å GaAs cap layer. The antimony composition in the $GaAs_{0.7}Sb_{0.3}$ layer was determined using double crystal x-ray diffraction measurement.

For the experimental system, the PL spectra were recorded by a Spectra Pro 300i monochromator and detected by an InGaAs detector. An Ar-ion laser working at 514.5 nm was used as the excitation source. For the PC measurement, the ohmic contacts were formed on the surface of the sample by indium drops, and annealing the sample at 250 °C for 10 min. A halogen lamp dispersed by a monochromator was used as the photoexcitation light source, and the conductivity was measured by a Keithley 236 source measure unit with a constant current. For the PLE measurement, a halogen lamp and a monochromator generated the excitation light with appropriate filter and polarizer, which was incident normal to the growth direction, and the analyzing spectrometer was set at the PL emission peak about 1.06 eV.

## III. THEORETICAL CALCULATION

In order to identify the observed spectral features, we have numerically solved a one-dimensional Schrödinger equation for a finite square quantum well based on the envelope-function approximation and phenomenological deformational potential theory. First, the ratio of the discontinuity in the unstrained valence band edge $Q_v^0$ is about 0.85 ($GaAs_{0.7}Sb_{0.3}$/GaAs), which exhibits a type I band alignment, and the unstrained bulk band gap of the GaAsSb layer is 1.05 eV at 20 K.[6] When the GaAsSb layers were grown on a (100) GaAs substrate, they experienced a tetragonal distortion due to the built-in biaxial compressive strain. The off-

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TABLE I. Parameters of band gap energy, strain related constants, and effective mass (strain independence) for the $GaAs_{1-x}Sb_x$/GaAs material system.

| Parameter | Symbol (unit) | GaAs | GaSb | Reference |
|---|---|---|---|---|
| Lattice constant | $a$ (Å) | 5.6533 | 6.09593 | 6 |
| Energy band gap (0 K) | $Eg$ (eV) | 1.519 | 0.812 | 9 |
| Elastic stiffness constant | $C_{11}$ (1011 dyn/cm$^2$) | 11.879 | 8.842 | 6 |
| Elastic stiffness constant | $C_{12}$ (1011 dyn/cm$^2$) | 5.376 | 4.026 | 6 |
| Hydrystatic deformation potential: | | | | |
| for conduction band | $a_c$ (eV) | −7.17 | −6.85 | 6 |
| for valence band | $a_v$ (eV) | 1.16 | 0.79 | 6 |
| Shear deformation potential: | | | | |
| for valence band | $b$ (eV) | −1.7 | −2.0 | 6 |
| Electron effective mass | $m_e/m_0$ | 0.067 | 0.045 | 6 |
| Heavy-hole effective mass | $m_{hh}/m_0$ | 0.5 | 0.4 | 6 |
| Light-hole effective mass | $m_{lh}/m_0$ | 0.082 | 0.05 | 10 11 |

diagonal strain-tensor elements vanish, and the three major diagonal elements, $\varepsilon_{ii}$ $(i=x,y,z)$, can be expressed as $\varepsilon_{xx}=\varepsilon_{yy}\equiv(a_b-a_w)/a_w\equiv\varepsilon_0$; $\varepsilon_{zz}\equiv(-2C_{12}/C_{11})\varepsilon_0$, where $a_b$ and $a_w$ are respective lattice constants of GaAs and GaAsSb; $C_{11}$ and $C_{12}$ are the elastic stiffness constants. For the (100) growth direction, the biaxial compressive strain can be equalized by a hydrostatic (compressive) pressure and a uniaxial stress along the growth direction, which enlarges the band gap and splits the valence-band degeneracy at the center of Brillouin zone, respectively. Therefore, the band edge shift of conduction band (CB), heavy-hole (*hh*), and light-hole (*lh*) valence band (VB) in the sample are described by

$$\delta E_C=2a_c\left[\frac{C_{11}-C_{12}}{C_{11}}\right]\varepsilon_0;$$

$$\delta E_{lh}^{hh}=\left[2a_V\left(\frac{C_{11}-C_{12}}{C_{11}}\right)\pm b\left(\frac{C_{aa}+C2_{12}}{C_{11}}\right)\right]\varepsilon_0, \quad (1)$$

where $a_c$ and $a_v$ are respective hydrostatic deformation potentials of the CB and VB, and $b$ is shear deformation potential.[6–8] The signs + and − are for the *hh* and *lh* band edge, respectively. After the band edge shifts induced by compressive strain are taken into account, the MQWs structure transfers from type I to type II band alignment. The parameters used in our calculation are listed in Table I.[9–11] Finally, we include the quantum confinement effect of a finite square quantum well, and we display our calculated results in Table II.

## IV. RESULTS AND DISCUSSION

In Fig. 1, we show the temperature dependence of the PL spectra for the studied $GaAs_{0.7}Sb_{0.3}$/GaAs MQWs. The peak is attributed to the type II transition arising from the GaAs conduction band to the GaAsSb valence band. At low temperature, we can see an evident asymmetry attached to the lower energy side of the peak. This low energy shoulder can be attributed to the quantum confinement Stark effect (QCSE).[12–14] The existence of the internal field is probably due to the charged surface states, because the strain induced piezoelectric field is absent along (100) direction for a zinc blende structure.[7,8] With increasing temperature, the peak shifts towards lower energy and becomes broad. When the temperature is higher than around 160 K, the asymmetry gradually transfers toward the higher energy side. We can see this behavior more pronounced at room temperature. After the Gaussian fitting, these two peaks can be associated with the type II $e1$-$hh1$ and $e2$-$hh2$ transitions according to our calculated results as shown in Table II.

The similar behavior also appears in the excitation power dependence of the PL spectra as shown in Fig. 2. When the excitation power increases, the QCSE gradually disappears, while the transition of higher energy states becomes more pronounced. Therefore, changing excitation power provides an alternative method to control optical transitions. This behavior can be understood as follows. The built-in electric field due to surface charges can tilt the band

TABLE II. Calculated results of transition energies for $GaAs_{1-x}Sb_x$/GaAs MQWs at 20 K.

| | Calculated | |
|---|---|---|
| Symbol (unit) | by the effective mass without the influence of strain | by the enhanced effective mass due to strain |
| Type I transition: (electrons and holes are stored in GaAsSb well layer) | | |
| *c-hh1* (eV) | 1.200 | 1.197 |
| *c-hh2* (eV) | 1.270 | 1.258 |
| *c-lh1* (eV) | 1.410 | 1.380 |
| Type II transition: (electrons and holes are, respectively, stored in GaAs and GaAsSb layers) | | |
| *e1-hh1* (eV) | 1.070 | 1.067 |
| *e2-hh2* (eV) | 1.132 | 1.119 |

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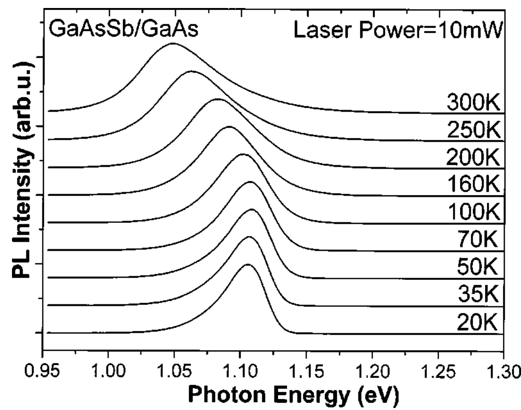


FIG. 1. Temperature dependence of photoluminescence spectra measured at excitation power of 10 mW. At high and low temperature, the spectra exhibit an asymmetry on the high and low energy side, respectively.

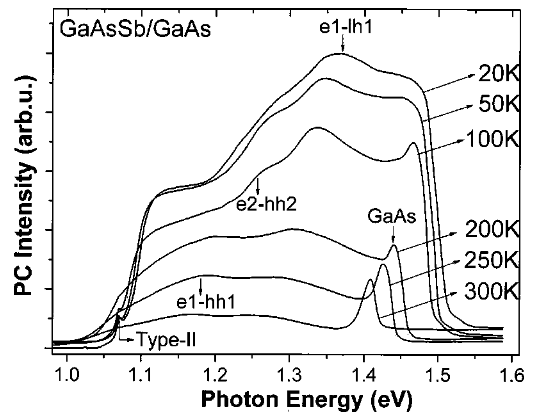


FIG. 3. Temperature dependence of photoconductivity spectra. Arrows indicate the peak energy positions at 20 K, which were attributed to type I ($e1$-$hh1$, $e2$-$hh2$, and $e1$-$lh1$) transitions in GaAsSb wells, type II transitions between GaAs and GaAsSb layers, and GaAs absorption transition.

edge and result in a redshift of the emission energy and the observation of the QCSE. With increasing excitation power, the peak shifts toward higher energy, and becomes symmetric and broad due to the screening of the internal electric field by the photoexcited carriers. If the excitation power is increased further, the excited states will have a higher occupation probability, and the asymmetry turns towards high-energy side.

Figure 3 shows PC spectra taken at different temperatures. The PC spectra contain clear features of optical transitions due to different quantized electron and hole states. On the basis of the temperature dependence of the spectra, we can deduce five different transitions, which include both type I and type II transitions. Comparing the experimental transition energies with our theoretical calculation as shown in Table II, it is clear that the measured energies of the type II and type I transitions are in good agreement with the theoretical calculation by the strain dependence of effective masses. It is known that a strain can smooth down the hole-band curvatures, and the near band edge effective masses should be respectively increased.[6,14] It has also been shown that the strain-induced enhancement of the effective mass on the *lh* is much greater than *hh*. Therefore, it is reasonable to expect that the effective mass of holes in GaAsSb/GaAs MQWs does change under the influence of strain. For the type I transitions observed here, in order to fit the experimental data we use a relatively large effective mass for holes in GaAsSb layers, i.e., $m_{lh} \cong 0.145\ m_0$ and $m_{hh} \cong 0.564\ m_0$, while $m_{lh} \cong 0.0724\ m_0$ and $m_{hh} \cong 0.47\ m_0$ for the unstrained bulk material.

To further confirm our identification for both of the *hh* and *lh* transitions, we have performed the polarization-dependent PLE by edge-excitation mode at 20 K as shown in Fig. 4. In an ideal quantum well, the strength of the $e1$-$hh1$ and $e1$-$lh1$ transitions are strongly dependent on the polarization of the excitation radiation. The relative strengths of *hh* and *lh* transitions were predicted to be 3/4 and 1/4 for excitation polarized perpendicular to growth direction (TE mode), and 0 and 1 for excitation polarized along the growth direction (TM mode), respectively.[15] Indeed, in Fig. 4, we can easily distinguish the *hh* and *lh* transitions, as deduced from the fact that the relative intensity between the lower energy ($c$-$hh1$) and higher energy ($c$-$lh1$) peak in TE mode is higher than that in TM mode.[16–18] It therefore provides a direct evidence to confirm our assignment for the *hh* and *lh* transitions.

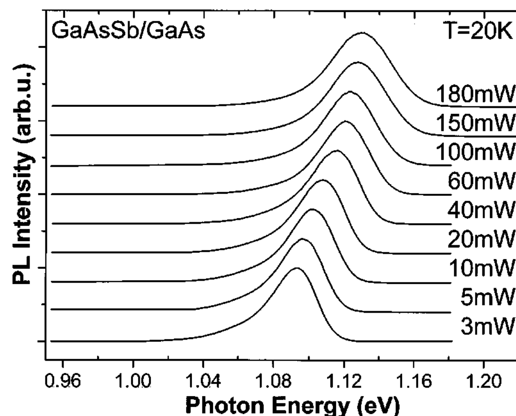


FIG. 2. Dependence of photoluminescence spectra on the excitation power measured at 20 K.

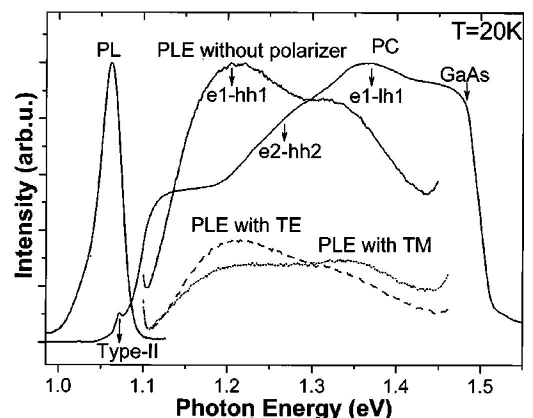


FIG. 4. Photoluminescence, photoconductivity, and photoluminescence excitation spectra obtained at 20 K. The excitation energy for photoluminescence experiment is set at 1.52 eV, and the photoluminescence excitation spectra are obtained by detecting the emission signal at 1.06 eV.

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## V. SUMMARY

In summary, a detailed investigation of the optical transitions of type II GaAsSb/GaAs MQWs has been performed using PL, PC, and PLE spectra. It has been demonstrated that both of the QCSE and excited states can contribute to the PL signal depending on excitation power and temperature. In addition, the rich transitions contained in the PC spectra have also been identified. The identification of the heavy hole and light hole transitions were further confirmed by the edge emission in TE and TM modes. By comparing the theoretical calculation and experiment data, it was found that the valence band effective masses in GaAsSb can be significantly enhanced due to the strain effect.

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