Giant polarized photoluminescence and photoconductivity in type-II GaAs/GaAsSb multiple quantum wells induced by interface chemical bonds

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Anisotropic property of type-II GaAs/GaAsSb heterostructures was studied by photoluminescence (PL) and photoconductivity (PC). It was found that the PL and PC spectra exhibit a strong in-plane polarization with respect to $\langle 011 \rangle$ axis with polarization degrees up to 40%. We showed that the polarization does not depend on the excitation intensity as well as temperature, which excludes any extrinsic mechanisms related to the in-plane anisotropy. The observed polarized optical properties of GaAsSb/GaAs multiple quantum wells was attributed to the intrinsic property of the orientation of chemical bonds at heterointerfaces. © 2002 American Institute of Physics.

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The GaAsSb/GaAs heterostructure system has been revived with the development of advanced technology recently. Particularly, its type-II band alignment provides an excellent opportunity to improve the performance of both heterojunction bipolar transistors and optoelectronic devices.^{1,2} Recently, devices using this system have been successfully developed, such as the fabrication of sources and detectors in long wavelength for fiber-optics communications, photodiodes, photocathodes, light-emitting diodes, and double-heterostructure lasers.^{1,2} 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. In this letter, a peculiar optical anisotropy of GaAsSb/GaAs multiple quantum wells (MQWs) has been discovered. Based on the studies of the dependents of excitation intensity and temperature, we suggest that our observed anisotropy is an inherent property of the type-II band alignment in GaAsSb/GaAs MQWs.

Several papers on the study of in-plane optical anisotropy of heterostructures at interfaces such as InAs/GaSb and InGaAs/InP have recently been published.^{3–5} The optical anisotropy was attributed to a lower symmetry of an isolated interface between two semiconductors compared with the interior volume. Because a heterostructure needs to deposit two different materials together, it can break the chemical bond symmetry and create new anisotropy properties. Semiconductor heterostructures, in an ABC/AB-type combination, have nonequivalent normal and inverted interfaces, which can cause in-plane anisotropy not found in a quantum structure with an equivalent interface. Specifically, for a quantum heterostructure with a type-II band alignment, the indirect transition due to spatially separated electrons and holes is restricted in a very narrow region containing the interface,

and the emitted radiation will exhibit the anisotropic characteristics of the interface chemical bonds.^{6–8} In this letter, we report the interface-induced in-plane anisotropy in GaAsSb/GaAs MQWs. The degree of polarization in the photoluminescence (PL) spectra as large as 40% has been observed. Through the study of the temperature and pumping-intensity dependences of the polarized PL spectra, we demonstrate that the observed polarization is an intrinsic property of the GaAsSb/GaAs heterostructure. In addition, we discover that the photoconductivity (PC) spectra are also very sensitive to the polarization of the incident radiation. Unlike the PL spectra, the polarization of the PC spectra can be induced by interface defects, and it covers a wide range of wavelengths. We, therefore, point out that the polarized PC measurement is a very powerful technique to detect the effects of anisotropic defects at heterointerfaces.

The type-II GaAs_{0.7}Sb_{0.3}/GaAs MQWs were grown on semi-insulating GaAs(100) substrates using a VG V-80MKII molecular-beam epitaxy. Besides the Ga beam and As₄ beams, the Sb source was supplied using an EPI model 175 standard cracker *K* cell. The cracker zone temperature was 1050 °C, while the bulk zone temperature was about 430 °C. The As source was supplied from a 150 cc *K* cell. The structure of MQWs contains a 500 nm GaAs buffer layer, five periods of GaAs_{0.7}Sb_{0.3} 50 Å/GaAs 300 Å quantum well, and a 1000 Å GaAs cap layer. The growth temperature of the buffer layer and MQWs were 600 °C and 500 °C, respectively. The composition of antimony in the GaAs_{0.7}Sb_{0.3} layer was determined from double-crystal x-ray diffraction measurement. Details of the growth condition can be found elsewhere.^{9–12} For the PL measurement, the spectra were dispersed by a Spectra Pro 300i monochromator, and detected by an InGaAs detector. An Ar-ion laser with wavelength 488 nm was used as the excitation source. For the PC measurement, ohmic contacts were formed by depositing indium drops to the four corners of the samples, and annealing the sample at 250 °C for 10 min. A tungsten lamp dispersed by triple-grating monochromator was used as the light source. A constant current was supplied to the sample by a Keithley

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FIG. 1. Schematic diagram of the band alignment and bond sequence of GaAsSb/GaAs MQWs.

236 source measure unit. The conductivity signal was detected as a change in the voltage drop across the sample using a lock-in amplifier. A detailed description of the experimental setup has been given elsewhere.^{13,14}

Figure 1 shows the energy-band alignment for GaAsSb/GaAs MQWs schematically. In contrast to type-I semiconductor structures, in type-II structures, the energy minima for electrons and holes lie in different layers. Spatially separated electrons and holes are easily realized in such a system, in which electrons are confined in the GaAs layer and holes are localized in the GaAsSb layer. For the spatially indirect transition, it is caused by the wave function overlap between electron and hole across interface. Because some Sb atoms may replace the As atoms in zinc-blende structure, the interfaces in this quaternary GaAsSb/GaAs heterostructure consist of Sb—Ga and As—Ga bonds or As—Ga and Ga—Sb bonds. It is obvious that the lower and the upper interfaces of the quantum well are not equivalent with respect to the bond directions. Their contributions to the anisotropy cannot compensate each other.^{15,16} Therefore, the in-plane anisotropy inherently exists in the GaAsSb/GaAs MQWs studied here.

Anisotropy property of the PL spectra of the emitted radiation along (011) and (0 $\bar{1}$ 1) direction is shown in Fig. 2. The peak at 1.05 eV corresponds to the spatially indirect transition as marked by type-II transition in Fig. 1. As we can see, the PL intensity is very sensitive to the polarization. Figure 3 shows the PL intensity versus the angle of the analyzer. Solid dots are experimental data, and the curve is fit to $\cos^2 \theta$. The polarization degree defined as

$$P_I = (I_{001} - I_{0\bar{1}1}) / (I_{011} + I_{0\bar{1}1}), \quad (1)$$

can be as large as 40%. This value is too large to be explained by strain or electric-field effects.¹⁷ In order to clarify

FIG. 2. Polarized PL spectra of GaAsSb/GaAs MQWs under 74 mW excitation. The inset shows the excitation geometry for the PL measurement.

that the observed polarized PL spectra are induced by the anisotropic nature of the interface chemical bonds, we have performed the pumping power and temperature dependences of the polarization. It is found that the degree of polarization is not sensitive to the change of pumping power in the range of 45 to 168 mW. The degree of polarization is also very stable with respect to the change of temperature from 20 to 300 K. These results can be used to rule out any extrinsic mechanisms related to the in-plane anisotropy. For example, the built-in electric fields caused by unintentional doping will be screened under light irradiation. We can also exclude a significant role of localized states and nonradiative channels in the formation of the in-plane anisotropy, since they will be gradually saturated by the pumping source. We, thus, conclude that the polarization of the spatially indirect PL in GaAsSb/GaAs is an inherent nature of the interface chemical bonds. Polarized PL measurements, therefore, provide a simple tool to probe interface anisotropy in quaternary heterostructures. We believe that this result is very important for the application of GaAsSb/GaAs in optical devices.

The PC spectra for the incident radiation at different polarization angles are shown in Fig. 4. We can also see that the PC spectra display a strong polarization dependence. Since the energy that corresponds to the spatially indirect transition in the GaAsSb/GaAs MQWs is about 1 eV, we,

FIG. 3. PL intensity vs analyzer angle for GaAsSb/GaAs MQWs. The solid curve is a $\cos^2 \theta$ fit.

FIG. 4. Polarized PC spectra of GaAsSb/GaAs MQWs. The angle θ was measured with respect to $(01\bar{1})$ orientation.

therefore, choose the photoresponse signal at around 1 eV to analyze the polarization behavior. Using the same definition of the polarization degrees defined for the PL spectra, we obtain that the value of P can also be as high as 40%. In addition, we can see that the polarization dependence of the PC spectra covers a wide range of wavelengths as shown in Fig. 4. Figure 5 shows the polarization dependence of the PC response at around 1 eV. The data can also be described by the $\cos^2 \theta$ rule. The maximum and minimum signal correspond to the polarization along (011) and $(0\bar{1}1)$, respectively, which is similar to the behavior of the PL spectra. It indicates that the anisotropic PC response arises from the interface chemical bonds. However, the wide range response of the PC spectra as shown in Fig. 4 does not solely come from the type-I or type-II band-to-band transitions as marked in Fig. 1. The transition of the continuous energy states can

FIG. 5. Polarized PC signal around 1 eV vs analyzer angle for GaAsSb/GaAs MQWs. The solid curve is a $\cos^2 \theta$ fit.

be attributed to interface imperfections. For example, there may exist wrong bonds at interfaces (e.g., Sb—Ga and As—Ga bonds or As—Ga and As—Ga in GaAsSb/GaAs heterostructures), which are different from the bonds in constituent layers. These wrong bonds can be considered as a kind of localized distortion, i.e., a certain “defectlike” impurity, with respect to the host structure. Thus, polarized PC spectra provide a very good opportunity to search the effects of microscopic interface defects in semiconductor heterostructures. It is worth noting that the PL and PC polarization curves are shifted by 90° . The exact origin is still unclear. However, it may be due to the fact that the PL signal arises from the electron–hole recombination and the PC response is dominated by the remaining electrons and holes in the extended states. Thus, when the PL intensity is larger, the PC signal will become smaller.

In conclusion, a strong polarization dependence has been observed in type-II GaAsSb/GaAs MQWs by PL and PC measurements, and the polarization degrees can be as large as 40%. This finding should be very important for the application of GaAsSb/GaAs MQWs in optoelectronic devices. We have showed that the effects of anisotropy arise from the inherent nature of the interface chemical bonds in a type-II heterostructure. In addition, we have pointed out that polarized PC measurement is a very sensitive tool to probe the effects of interface imperfections.

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