Nature of persistent photoconductivity in GaAs_{0.7}Sb_{0.3}/GaAs multiple quantum wells

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The optoelectronic properties of undoped type-II GaAs_{0.7}Sb_{0.3}/GaAs (100) multiple quantum wells have been investigated by photoluminescence (PL), and photoconductivity measurements. Quite interestingly, persistent photoconductivity (PPC) has been discovered in this material. The decay kinetics of the PPC effect can be well described by the stretched-exponential function $I_{\text{PPC}}(t) = I_{\text{PPC}}(0)\exp[-(t/\tau)^\beta]$, ($0 < \beta < 1$), which is similar to the behavior observed in many disorder systems. Through the study of the PPC effect under various conditions, and combining with the characteristics of the PL spectra, we identify that the origin of the PPC effect arises from the spatial separation of photoexcited electrons and holes. Here, the photoexcited electrons fall into the GaAs layer, and holes are trapped by local potential minima due to alloy fluctuations in the GaAsSb layer. This process prevents the recombination of electrons and holes, and thus the PPC occurs. In order to return to the initial states, photoexcited electrons have to overcome the energy barrier caused by the conduction band offset. © 2004 American Institute of Physics. [DOI: 10.1063/1.1787613]

The type-II GaAsSb/GaAs quantum well (QW) structures have attracted much attention because of its potential applications in optoelectronic devices, such as vertical-cavity surface-emitting lasers, photodiodes, and light-emitting diodes in long wavelength optical-fiber communications.¹⁻⁴ Besides its technological potential, the unique nature of its type-II band alignment is also very attractive for scientific interest. For example, it can serve as a model system for investigating the atomic ordering and compositional modulation expected in III-V-V alloys. It also exhibits a giant optical anisotropy due to the asymmetry of interface chemical bands.⁵ In spite of several attempts published previously,⁵⁻¹⁵ the optical properties of this material 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, we present an investigation on the transitions in type-II GaAs_{0.7}Sb_{0.3}/GaAs multiple quantum wells (MQWs) by photoluminescence (PL), and photoconductivity (PC). Quite interestingly, persistent photoconductivity (PPC) has been discovered in this material system. Through a detailed study of the PPC effect under different conditions, and combining with the result obtained from the PL spectra, the mechanism responsible for the observed PPC has been proposed.

The GaAs_{0.7}Sb_{0.3}/GaAs MQWs were grown on undoped semi-insulating GaAs (100) substrates by a VG V-80MKII solid-source molecular beam epitaxy. The Sb source was supplied using an EPI model 175 standard crackers K-cell, and the As source was supplied from a 150 c.c. 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 sample consists of a 500 Å undoped GaAs buffer layer, a series of five periods of 50-Å-thick GaAsSb wells

and 300-Å-thick GaAs barriers capped by a 1000-Å-thick GaAs. The antimony composition in the GaAs_{0.7}Sb_{0.3} layer was determined using double crystal x-ray diffraction measurement.

For the PC measurement, the ohmic contacts were formed on the sample surface by indium drops, and annealing the sample at 250 °C for 10 min. The sample was placed inside a closed-cycle He refrigerator, a halogen lamp dispersed by a monochromator was used as the photoexcitation light source with appropriate filters. A Keithley 236 source measure unit was used to measure the conductivity. In order to ensure that each set of data has the same initial condition, the system is always allowed to warm to 300 K in dark and relax to equilibrium after each measurement, and then cooled down to the desired temperature. For the PL measurement, the signal was 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.

Figure 1 shows a typical low temperature PL spectrum, which arises from the type-II band edge transition. The detailed investigation of the PL spectra has been published previously.⁵⁻¹⁵ According to our results,^{5,6} the origin of the PL signal was established through the type-II band alignment as well as the unusual large blueshift with pumping intensity. This fairly strong luminescence intensity results from the accumulation of electrons and holes near the interface, which reduces the distance of the spatially separated electrons and holes. It also implies the good quality of our studied samples. It is worth noting that the PL quenching is a thermally activated process with an activation energy of 66.6 meV as shown previously.^{5,6} This value is in good agreement with the conduction band offset between the GaAs and GaAsSb layer.

In the photoconductivity measurement, we have discovered a very interesting phenomenon in GaAsSb/GaAs MQWs. A typical low temperature ($T=35$ K) photoresponse excited by a monochromatic radiation with the photon en-

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FIG. 1. Photoluminescence spectra recorded at low temperature (20 K).

ergy of 1.1 eV is shown in Fig. 2(a). It clearly indicates that the light-enhanced conductivity persists for a very long period of time after termination of the light source. In order to understand the mechanism of the observed PPC effect, we have investigated the PPC effect under several different conditions. Figure 2(b) shows the excitation photon energy dependence of the PPC behavior taken at 50 K. For comparison, each curve is normalized to unit at the time when illumination is switched off. It is found that the similar retention behavior can still be observed when the monochromatic light source is set from 1.1 eV (the type-II transition energy) to 1.6 eV (greater than the GaAs barrier band gap), but when the photon energy is lower than 1.1 eV, the PC response decays rapidly and the PPC effect becomes unclear. This result indicates that the photoexcited carriers involved in the PPC effect are related to the valence-band to conduction-band transition, including both type-I (in GaAs and GaAsSb layers) and type-II transitions.

To further explore the origin of the PPC phenomenon, the PPC decay curves at different temperatures with a fixed excitation photon energy (1.1 eV) have been studied. We found that the decay rate of the PPC increases gradually with

FIG. 2. (a) Typical build up and decay behavior of persistent photoconductivity in GaAsSb/GaAs multiple quantum wells at 35 K. (b) Excitation photon energy dependence of the persistent photoconductivity taken at 50 K.

FIG. 3. Temperature dependence of the persistent photoconductivity taken at 1.1 eV. The inset plot of $\ln\{\ln[I_{\text{PPC}}(0)/I_{\text{PPC}}(t)]\}$ vs $\ln(t)$ at various temperatures.

increasing temperature. The decay kinetics in photocurrent after turning off the illumination can be described by the stretched exponential function

$$I_{\text{PPC}}(t) = I_{\text{PPC}}(0) \exp[-(t/\tau)^\beta] \quad (0 < \beta < 1). \quad (1)$$

Here $I_{\text{PPC}}(0)$ is the PPC buildup level at the moment of light excitation being removed, τ is the relaxation time constant, and β is the decay exponent. This is demonstrated in the inset to Fig. 3 by a representative plot of $\ln\{\ln[I_{\text{PPC}}(0)/I_{\text{PPC}}(t)]\}$ vs $\ln(t)$ at different temperatures. The stretched exponential relaxation has been commonly observed in many disordered systems.^{16–19} This result implies that the energy barrier responsible for the PPC effect has the nature of random local potential fluctuations similar to that in disordered materials.

From a least-squares fit to the curves, we can determine the exponential parameters τ and β at different temperatures. As shown in Fig. 4(a), the value of β is rather insensitive to the change of temperature. For the relaxation time τ , at low temperature region ($T \leq 50$ K), τ weakly depends on temperature. In the high temperature region ($T \geq 50$ K), the PPC decay exhibits a thermally activated process as shown in Fig. 4(b). The decay time constant τ can be expressed as τ

FIG. 4. (a) Temperature dependence of decay exponential factor β , and (b) semilogarithmic plot of the decay time constant τ as a function of $1/T$.

FIG. 5. The schematic diagram of the band structure of GaAsSb/GaAs quantum wells. It illustrates the origin of the occurrence of persistent photoconductivity.

$=\tau_0 \exp(E_{\text{rec}}/kT)$, where E_{rec} is the capture barrier high, and k is the Boltzmann constant. From the high temperature region, we obtain that the capture barrier E_{rec} is 63.3 meV, which is about the same as the activation energy of the PL quenching. This value is equal to the height of the conduction band offset between the GaAs well layer and the GaAsSb layer.^{5,13,14} It implies that the PL quenching and the PPC relaxation have the same mechanism, which can be attributed to the thermal excitation of conduction electrons from the GaAs to GaAsSb layer. This explanation is also consistent with the result shown in Fig. 3, where the remaining photoconductivity decreases with increasing temperature.

Based on the above-mentioned experimental results, we propose that the origin of the PPC behavior arises from the effect of spatially separated electrons and holes. After photoexcitation, electrons fall into the conduction band of the GaAs layer, and holes are in the GaAsSb layer as shown in Fig. 5. Due to the existence of intrinsic potential fluctuations such as random nature of alloy disorder, some holes are trapped by local potential minima in the GaAsSb layer. It prevents the recombination of electrons and holes, and leaves photoexcited electrons as free carriers, thus the PPC occurs. In order to recombine with holes, electrons have to overcome the energy barrier, which is the energy difference between the conduction band of the GaAs and GaAsSb layers. This explains why the activation energies for the PPC and PL quenching have the similar value. Because of the random nature of alloy disorder, the capture barrier reflects the characteristic of potential fluctuations. Thus, similar to many disorder systems, the decay kinetics shows a stretched exponen-

tial behavior rather than a simple exponential function. We thus can see that our purposed mechanism can be used to explain all the results obtained from PC and PPC spectra.

In conclusion, we have reported the observation of the PPC effect in GaAs_{0.7}Sb_{0.3}/GaAs MQWs. Through the studies of the PPC and PL under different conditions, we suggest that the PPC behavior is related to the type-II nature of the band alignment of GaAsSb/GaAs heterostructures. It is caused by the spatially separated electrons and holes, where electrons fall into the GaAs layer and holes are trapped by local potential minima due to alloy fluctuations in the GaAsSb layer. It prevents the recombination of electrons and holes, and thus the PPC occurs. In order to return to the original states, electrons have to overcome the energy barrier caused by the conduction band offset.

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