Effect of compensation of electron and hole scattering potentials on the optical band edge of heavily doped GaAs/$Al_xGa_{1-x}As$ superlattices

Yu. A. Pusep,[1] F. E. G. Guimarães,[1] M. B. Ribeiro,[1] H. Arakaki,[1] C. A. de Souza,[1] S. Malzer,[2] and G. H. Döhler[2]
[1]*Instituto de Fisica de São Carlos, Universidade de São Paulo, 13560-970 São Carlos, SP, Brazil*
[2]*Institut für Technische Physik I, Universität Erlangen, D-91058 Erlangen, Germany*
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The optical broadenings studied by the photoluminescence in the intentionally disordered GaAs/AlGaAs superlattices were compared with the broadenings of the individual electron states measured by the Shubnikov-de Haas oscillations. It was shown that the combined effect of the electron and hole energy blurrings is to decrease the optical broadening with respect to the individual state broadenings resulting in very sharp optical edges even in highly disordered superlattices. It was also found that the impurities almost equally influence the electron and hole scattering potentials, contrary to what happens due to the structural superlattice disorder.

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The possibility to study disorder effects in semiconductor superlattices, where the disorder can be produced either by randomly varying layer thicknesses or by random layer compositions, was mentioned already in the first proposal of superstructured materials.[1] The great advantage of such random materials is a controlled nature of the disorder which allows us to distinguish the impact of the randomness on their properties.

The optical measurements, which are determined by the joint density of states, present a powerful method to study the disorder effects. The disorder affects the joint density of states through the modification of the energy and broadening of the electron conduction and valence band states. The renormalization of the electron energy and the broadening of the absorption edge in the presence of disorder were discussed in detail in Ref. 3. The first application of the photoluminescence (PL) to explore the localization of carriers in the intentionally disordered superlattices was performed in Ref. 2 where, however, no connections to the joint density of states and to the optical band edge were performed. In this communication we demonstrate that in disordered semiconductors the shape of the optical band edge drastically depends on the character of the optical transitions. According to Ref. 3, the indirect optical transitions form the broadened band edge, while, as we will show the direct transitions may lead to a sharp band edge, even in the presence of strong disorder.

The interaction of the carriers with imperfections causes the blurring of their energy:[4]

$$\frac{\hbar}{\tau_{e(h)}} = 2\pi u_{e(h)}^2 N_i \gamma, \tag{1}$$

where $\tau_{e(h)}$ is the electron (hole) single-particle relaxation time, $u_{e(h)}$ is the electron (hole) scattering potential, N_i is the concentration of imperfections and γ is the density of states on the Fermi surface. This blurring results in a broadening of the Landau levels which can be obtained by the magnetotransport measured in the range of the Shubnikov-de Haas oscillations.[5] Depending on the doping (n- or p-type) the broadenings of the electron states of the conduction or valence bands can be obtained.

On the other hand, both the electron states of the valence and conduction bands contribute to the optical interband transitions. Therefore, the electron and hole blurrings (1) give rise to the broadening of the PL edge. In such a case, the intensity near the PL edge can be calculated according to[6]

$$I(\omega) = I_0\left[\frac{1}{2} + \frac{1}{\pi}\arctan(2\tau\delta\Omega)\right], \tag{2}$$

where I_0 is the PL intensity at the edge in the ideal (disorder-free) case, $\delta\Omega = \hbar\omega - 2E_F$, with E_F being the Fermi energy and τ the characteristic relaxation time which determines the absorption edge broadening. This relaxation time is defined by the formula

$$\frac{\hbar}{\tau} = 2\pi(u_e - u_h)^2 N_i \gamma. \tag{3}$$

This means that the broadening of the optical edge cannot be expressed in terms of the mean free times τ_e and τ_h. The formulas (2) and (3) were obtained in the limit $\hbar/\tau \ll E_F$ for the interaction of electrons with the short-range impurity potentials. These assumptions are also valid in our samples with a short-range structural disorder potential.

It is seen that the relaxation time τ in Eq. (3) depends on the difference of the electron and hole scattering potentials and, therefore, may be smaller than the individual broadenings. Moreover, the formula (3) means that in the case $u_e = u_h$ the optical edge is sharp even in the presence of the scattering by imperfections. This is because with the same scattering of electrons and holes and the same initial energy spectra, the electron and hole wave functions and energy eigenvalues modified by imperfections are exactly the same. In this case, as it is shown in Fig. 1, the optical transitions occur only between the like states and there are no transitions between the different states which are orthogonal. The energy deficits ΔE are identical for all the transitions which form the optical edge. This results in a sharp optical edge. Such an effect may cause the absorption or PL edge much

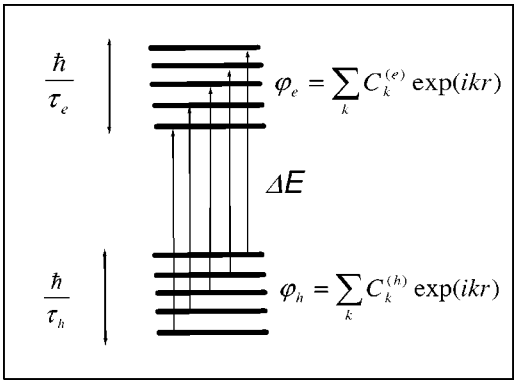

FIG. 1. Scheme of the optical transitions between the valence band states φ_h and the conduction band states φ_e which in the presence of disorder are represented by superpositions of states with different quasimomenta distributed in the energy intervals $\hbar/\tau_h$ and $\hbar/\tau_e$, respectively.

sharper than the expected from the transport measurements of the broadenings of the single electron states.

In this work we study the influence of the intentional disorder on the broadening of the PL edge of the doped GaAs/AlGaAs superlattices. In order to distinguish the effect of the individual states on the PL edge we compare the broadenings of the PL edges with the broadenings of the individual electron states obtained by the Shubnikov-de Haas oscillations, both measured in the superlattices with different disorder strengths.

The samples studied here were the $(GaAs)_m(Al_{0.3}Ga_{0.7}As)_6$ superlattices (where the thickness of the layers is expressed in monolayers, ML) grown by molecular beam epitaxy on (001) GaAs substrates. In order to form the degenerate electron system all the samples were doped with Si. The samples with the nominal doping concentrations 7.0×10^{17} cm^{-3}, 1.2×10^{18} cm^{-3}, and 1.7×10^{18} cm^{-3} were studied. The disorder was introduced by a random variation of the well thicknesses (m) around the nominal value 17 ML. The disorder strength was characterized by the disorder parameter $\delta=\Delta/W$, where Δ is the full width at half maximum of a Gaussian distribution of the electron energies calculated in the isolated quantum wells and $W\approx55$ meV is the miniband width of the nominal superlattice in the absence of disorder. Details of the sample growth and characterization can be found in Ref. 7. In all the samples the low temperature ($T=1.7$ K) mobilities were found in the interval $1200-2000$ cm^2/V s resulting in the parameter $k_Fl=7.5-14.2$, which corresponds to the metallic electron system. The PL measurements were performed at 4.2 K using a He-Cd laser line at 442 nm for excitation. The PL signal was detected in the lock-in mode by a GaAs photomultiplier mounted on a 0.5 m monochromator. Parallel magneto-transport measurements were carried out on the Hall bar samples using standard four probe low-frequency (5 Hz) lock-in technique in a pumped liquid He cryostat in the magnetic field directed parallel and perpendicular to the layers at the temperature 1.7 K.

It should be mentioned that the influence of disorder on the collective excitations (plasmons) was studied by Raman

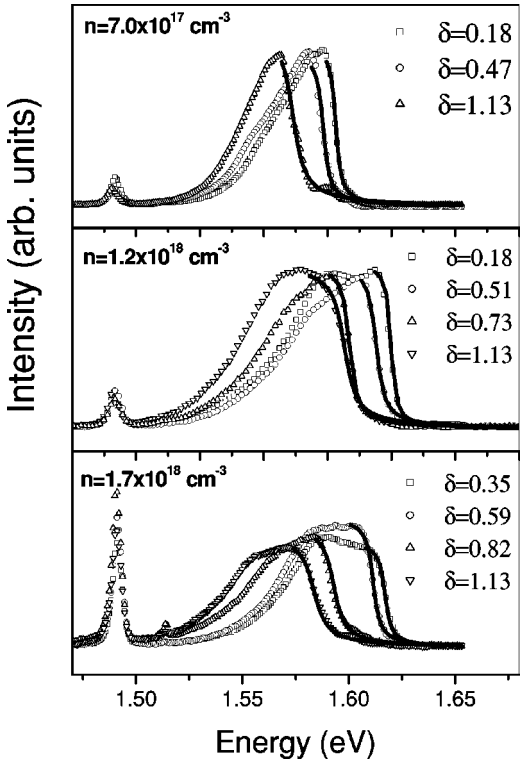

FIG. 2. Photoluminescence spectra measured at $T=4.2$ K in the $(GaAs)_m(Al_{0.3}Ga_{0.7}As)_6$ superlattices with different disorder strengths doped with $N=7.0\times10^{17}$ cm^{-3} (a), $N=1.2\times10^{18}$ cm^{-3} (b) and 1.7×10^{18} cm^{-3} (c). The full lines are the PL intensities calculated near the Moss-Burstein edges according to Eq. (2).

scattering in similar intentionally disordered superlattices in Ref. 7. Some of the samples used in this work were already characterized by the magneto-transport measurements in Refs. 8 and 9 where the anisotropic character of the intentional disorder was demonstrated and the weak-localization correction to the conductivity was explored. In all these cases clear consequences of the intentional structural disorder consistent with the theoretical predictions were found in the responses of electrons either to the field of radiation or to the electric field. Moreover, these data demonstrated that the disorder produced by random variation of the thicknesses of the layers provides well quantitatively controlled disorder strength.

Some of the PL spectra of the differently doped disordered superlattices are shown in Fig. 2. They show that the disorder leads to a significant red shift and broadening of the PL edge. The peaks at the energy 1.49 eV are due to the GaAs substrate. As it was shown in Ref. 3, in the presence of disorder, due to the redistribution of the electron density, the Fermi energy decreases by a value approximately equal to the amplitude of the fluctuations of the random potential. In the degenerate semiconductors the high frequency position of the PL edge is associated with the Fermi energy. Therefore, the red shift of the PL edge is related to a deviation of the Fermi energy from its value in a perfect crystal and, consequently, to the amplitude of the superlattice random potential which may be roughly estimated as a value of $\Delta=W\delta$. The observed PL red shift ($\Delta\nu$) is depicted in Fig. 3 as

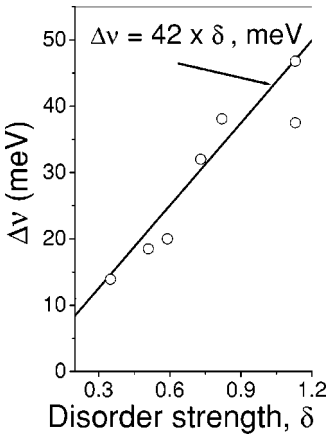

FIG. 3. Disorder induced red shifts of the PL edges measured in the closely doped random superlattices with $N=1.2\times10^{18}$ cm^{-3} and 1.7×10^{18} cm^{-3}. The full line represents the expected disorder induced shift of the Fermi energy.

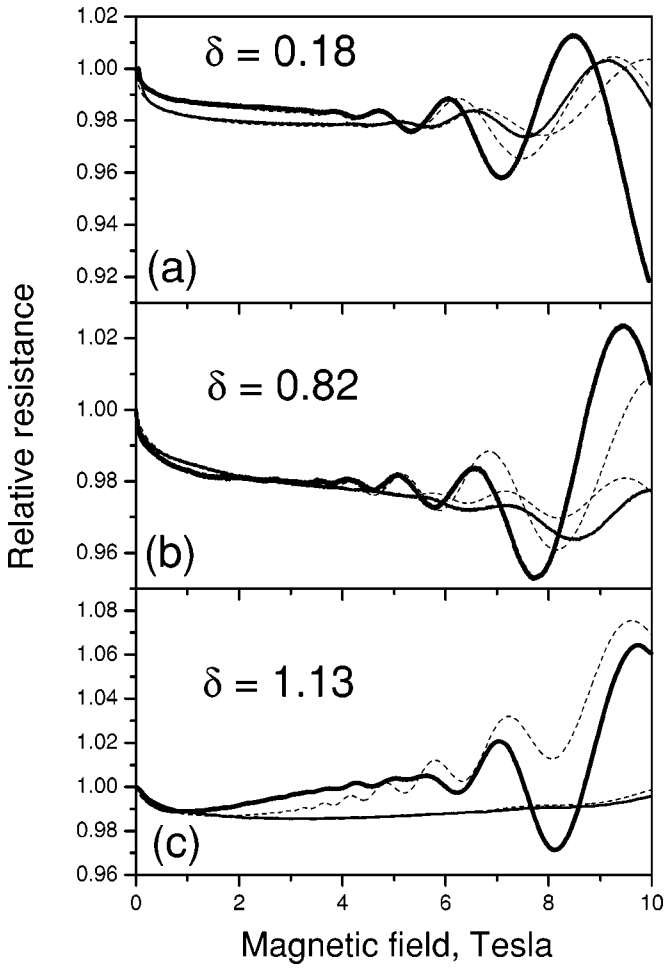

FIG. 4. Relative magnetoresistances measured at $T=1.7$ K in the disordered $(GaAs)_m(Al_{0.3}Ga_{0.7}As)_6$ superlattices with $N=7.0\times10^{17}$ cm^{-3} with different orientations of the magnetic field, parallel (thick lines) and perpendicular (thin lines) to the growth direction z. Dashed lines are the calculated magnetoresistances.

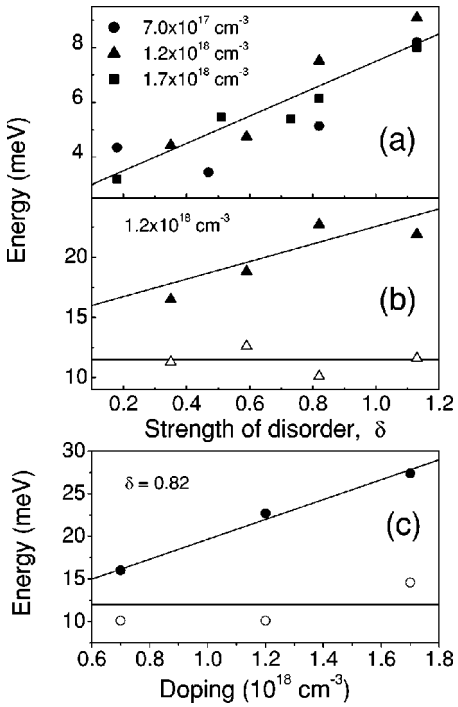

FIG. 5. Characteristic broadenings of the PL edge $\hbar/\tau$ (a) and the electron broadenings $\hbar/\tau_e$ (b), (c) obtained in the differently doped disordered superlattices $(GaAs)_m(Al_{0.3}Ga_{0.7}As)_6$. The open and full circles in panels (b), (c) correspond to the parallel and vertical electron energy broadenings, respectively. The lines are guides for eyes.

a function of the disorder strength. It is well described by the dependence $\Delta\nu=42\delta$, meV, where the linear coefficient was indeed found very close to the value of the nominal miniband width ($W=55$ meV). Thus, our data demonstrate good agreement with the theory.[3]

The magnetoresistance traces measured with different orientations of the magnetic field are shown for selected superlattices in Fig. 4. They reveal well developed Shubnikov-de Haas oscillations. The amplitudes of these oscillations were found smaller for the magnetic fields directed along the layers than for the fields perpendicular to the layers. This shows a strong anisotropy of the electron energy broadening, which correspondingly was found larger along the disorder direction (vertical broadening) than parallel to the layers (parallel broadening).

The characteristic broadenings of the PL edges $\hbar/\tau$ were determined in the superlattices with different disorder strengths by the fit of the PL spectra, calculated by Eq. (2), to the experimental spectra measured in the range of the Moss-Burstein edge (see Fig. 2, where the continuous lines are the spectra calculated near the edge). The values $\hbar/\tau$ obtained by this way are depicted in Fig. 5(a). In spite of the relatively strong randomization, the PL edges were found surprisingly sharp when compared to the transport data [Fig. 5(b)].

The electron energy broadenings ($\hbar/\tau_e$) associated with the broadenings of the Landau levels were obtained by the fits of the magnetoresistances calculated according to Ref. 10 to the experimental magneto-transport data. The dependences of the vertical and parallel electron broadenings $\hbar/\tau_e$

on the disorder strengths obtained by the magneto-transport measurements in the differently doped superlattices are shown in Fig. 5(b) for the SL's with the doping 1.2×10^{18} cm^{-3}. The similar data obtained in other SL's are presented in Ref. 8. The vertical electron energy broadening and the optical broadening display similar behaviors—the noteworthy enhancement with the increasing disorder. While, as expected, the parallel electron energy broadenings were not affected by the vertical superlattice disorder. As it was mentioned above, the broadenings of the individual electron states were found considerably higher than the characteristic broadenings of the PL edges. This discrepancy is explained by the effect of the partial compensation of the electron scattering potential by the hole scattering potential, which is demonstrated by Eq. (3). This is evidence that the scattering potential of the holes is fairly comparable to that of the electrons.

Furthermore, as it is shown in Fig. 5(c), the vertical individual electron broadenings were found to increase with the increasing doping level, which represents a noticeable contribution of the impurity scattering. At the same time, the characteristic broadenings of the PL edge did not exhibit such an influence of the doping—the optical broadenings were found to depend only on the disorder strength and not on the doping level. This may happen because a random variation of the superlattice potential, which takes place in the presence of the intentional disorder, produces more difference between the scattering potentials u_e and u_h than do the impurities.

The anisotropy of the individual electron broadening increasing with the raising doping concentration is shown in Fig. 5(c). Obviously, this effect is due to the modulation of the doping concentration along the growth direction which consequently, generates the corresponding modulation of the impurity scattering potential. Such a modulation may take place because during the growth the flux of Si was kept constant while the growth rates of the GaAs and AlGaAs layers were different, 0.5 ML/s and 0.7 ML/s, respectively. Thus, a higher doping concentration is expected in the GaAs wells than in the AlGaAs barriers and the resulting difference between the impurity scattering potentials should increase with the increasing doping level.

Conclusion: The broadenings of the PL edges and of the Landau levels were studied and compared in the *n*-doped, intentionally disordered GaAs/AlGaAs superlattices. The first one is associated with the combined effect of the electron and hole energy blurrings, while the second one is due to the blurrings of the electron energy states of the conduction band. The broadenings of the PL edges were found to be considerably smaller than those of the electron states. It was shown that this is explained by the fact that the optical edge broadening is determined by the difference between the electron and hole scattering potentials. Therefore, in the case of their proximity, the resultant characteristic optical broadening may be much smaller than the individual electron (hole) energy broadening. Both, the intentional superlattice disorder and impurities enhance the individual electron and hole scattering potentials. However, according to our data, in contrast to the scattering due to the superlattice disorder, the impurity scattering almost does not influence the difference between them. This suggests similar electron and hole impurity scattering potentials.

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