Ambipolar Carrier Diffusion in $In_{0.53}Ga_{0.47}As$ Single Quantum Wells

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The microluminescence surface scan technique (MSST) has been used to investigate photocarrier diffusion in undoped $In_{.53}Ga_{0.47}As$ - InP single quantum well (QW), in the temperature (T) range from 15 K to 295 K. Narrowing of the photoluminescence (PL) spatial profile is observed as the temperature is lowered, indicating reduction of the photocarrier diffusion length upon cooling. It was found that the width of the PL spatial profile follows a linear function of temperature, but a change in slope by a factor of 2.6 is observed at about 200 K, indicating a change of the dominant carrier scattering mechanism. In the temperature range of 15 K to 200 K, the ambipolar photocarrier diffusion mechanism seems to be correlated to impurity states thermally activated.

I Introduction

Investigations of photocarrier transport properties in two-dimensional heterostructures have a great deal of interest, since they play a central role in the design and operation of photovoltaic devices. Experimental techniques which incorporate spatial resolution capabilities have been recently developed, being used to investigate the physical processes of light emission and photocarrier dynamics in semiconductor quantum wells (QW). Cathodoluminescence (CL) [1] and optical beam induced current (OBIC) [2] have been extensively used to measure the carrier diffusion length. An early study of photocarrier transport used a spatially scanned pump-probe technique for imaging the in-plane motion [3]. The microluminescence surface scan technique (MSST) has been recently applied to study the photocarrier transport mechanism in bulk semiconductors [4]. In the MSST, a tightly focused laser beam is used to excite the sample surface, and the lateral spread of electron-hole pair is observed by scanning the microluminescence image at the focal plane of the system. Such a measurement allows the determination of the effective diffusion length of the photoexcited carriers, which in turn provides indirect information about parameters as important as the photocarrier lifetime and the photocarrier mobility. In this work, we use the MSST setup to investigate the transport properties of photocarriers in an undoped single QW of InGaAs lattice-matched to InP, in the temperature range of 15 K to 295 K.

II Experiment

The lattice-matched InGaAs-InP single QW (LV 614) used in this study was grown by Vapor Levitation Epitaxy (VLE) [5]. The nominally undoped sample consists of a 0.6 μm InP buffer layer epitaxially grown on top of an InP substrate, followed by a 110 Å thick InGaAs layer, and covered with a 600 Å InP cap-layer. The sample was mounted in a temperature-controlled optical cryostat, and optically excited using an Ar^+-ion laser tuned at 514 nm, which provides energy excitation above the InP band gap. The laser beam was focused down to a spot of 4 μm in diameter, thus allowing lateral photoluminescence (PL) measurements with very good resolution. The radial PL intensity distribution is chopped, synchronously amplified and measured using a Nitrogen-cooled Germanium detector, as described elsewhere [6]. Photoexcitation creates electron-

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hole pairs, all across the structure, which are quickly captured by the InGaAs single QW. Following photoexcitation, lateral carrier diffusion and spontaneous radiative recombination take place, the later is the main source of the PL intensity (I_{PL}). The optical excitation intensity was set at a level strong enough to produce carrier density in the range of 1-5 x 10^{17}cm^{-3}, where carrier recombination is dominated by the bimolecular mechanism. Thus, the recombination rate is given by Bnp, where B is the bimolecular recombination coefficient, n and p are respectively the electron and hole densities. The PL intensity is given by $I_{PL} = Bnp$. Finally, two main assumptions have been made here. First, the photogenerated carrier density is assumed to be higher than any residual dopant density, and second, the charge neutrality is assumed, so that the photoinduced hole density is equal to the photoinduced electron density.

III Results and Discussions

Fig. 1 shows typical spatial PL distributions, at different temperatures. The observed PL distribution is usually described within the diffusion theory. Since photocarriers are mainly confined in the InGaAs layer, carrier transport can be well described by the two-dimensional diffusion equation, in the steady state regime. The diffusion equation that describes the electron density, in polar coordinates reads:

$$D\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial n}{\partial r}\right] = G(r) - \frac{n}{\tau} - Bnp \ , \qquad (1)$$

where D is the effective carrier diffusion coefficient, and τ is the effective carrier lifetime. *G(r)* is the photocarrier generation term provided by a Gaussian-shaped laser spot, depending only upon the optical excitation intensity. As long as both the linear and quadratic terms are kept in the right-hand side of Eq. (1), numerical simulation shows that a Gaussian function represents a good solution for *n(r)*. The carrier diffusion length (L) is then obtained from the simulated curve, and goes parallel with the full width at half maximum (FWHM) of the spatial PL profile. The temperature dependence of the spatial PL expansion (FWHM) is shown in Fig. 2. Our data show an increase in the width (FWHM) of the spatial PL profile as the temperature increases from 15 K to 295 K. We found the FWHM going with the temperature according to a linear function αT, with $\alpha = 0.07$ in the temperature range of 15 K to 200 K, and $\alpha = 0.18$ in the temperature range of 200 K to 295 K. The change in the slope of the curve, at about 200 K, is probably associated to the thermal activation of a defect center, as discussed below. A narrower spatial PL distribution, as experimentally observed at low-temperatures, and, consequently, a smaller carrier diffusion length, could be attributed to confinement of the carriers close to the center of the laser spot due to gap renormalization [7]. However, different mechanisms can account for the scattering rate and, therefore, for the carrier diffusion length, including phonon scattering, interface roughness, and impurities [8]. Note that any expansion eventually becomes exponential at large distances, and carrier recombination is dominated by non-radiative interface recombination. Close to the laser spot, however, Coulomb interaction between carriers does not allow spatial charge separation, and carrier density reduction is dominated by ambipolar carrier recombination (Bnp). The most likely mechanism associated to the expansion of the photoexcited carriers, at low-temperatures, is the interface roughness scattering. As the temperature increases, the radiative recombination rate decreases, while the non-radiative recombination increases. At low-temperatures, the electron-hole pair recombination rate is higher, as observed by the increase of the radiative recombination coefficient [9], and the diffusion process of the electron-hole pair is accordingly reduced [10]. Indeed, the decrease of the effective ambipolar diffusion, with decreasing temperature, is then expected due to both the increase of the radiative recombination, and the trapping of carriers by thermal activated impurity centers. Fig. 3 shows the total number of recombination carriers as a function of temperature, given by the total area under the PL spatial distribution. Particularly interesting is the abrupt decay of the density of the carriers that recombine radiatively around 150 K. This would be explained by assuming the thermal activation of a defect center with an activation energy of about 12 meV. Thus, trapping of carriers in such a thermal induced impurity center would explain the change in slope by a factor of about 2.6. Fig. 4 shows that the spatial PL distribution (FWHM) increases with the optical excitation intensity, and saturates at higher laser power. The saturation behavior, we found here, is physically conceivable since, at high excitation intensities, the scattering centers become saturated due to the high photocarrier density.

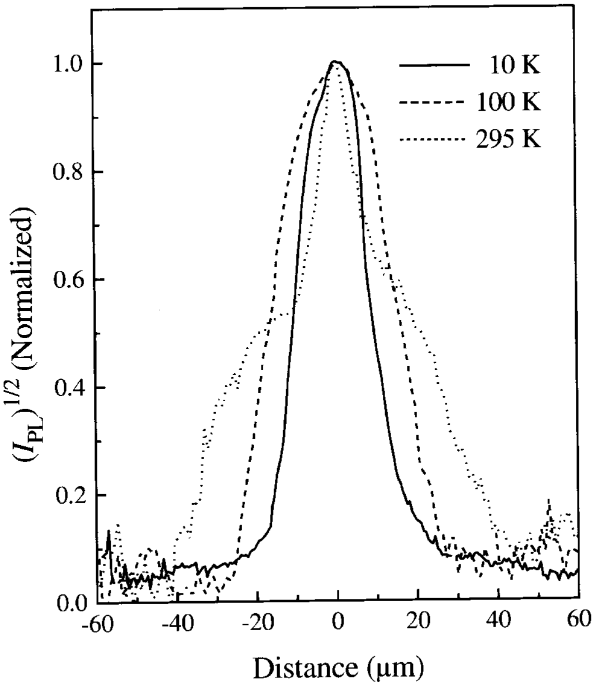

Figure 1. Square root of the PL intensity (I_{PL}) of the 110 Å thick $In_{0.53}Ga_{0.47}As$ SQW for three temperatures. These data clearly show the spatial expansion of the photoexcited carriers since $n \propto (I_{PL})^{1/2}$. The laser spot diameter on the sample surface was about 4 μm (FWHM).

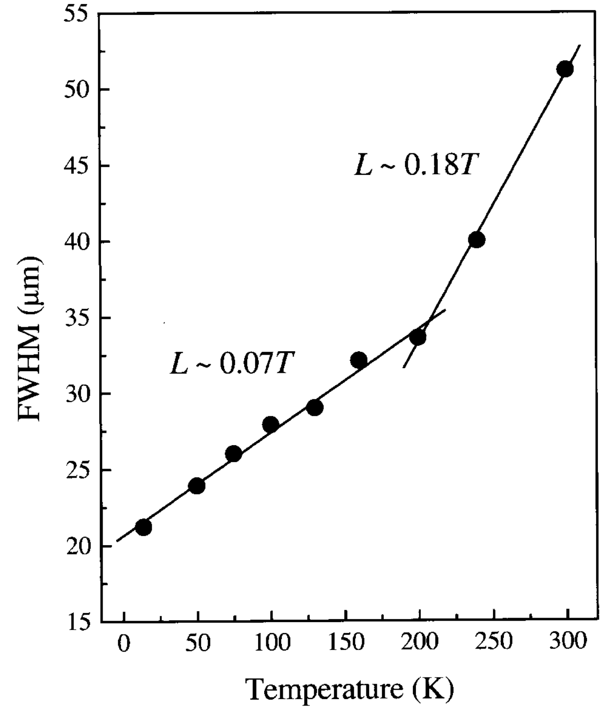

Figure 2. Spatial PL distribution (FWHM) as a function of temperature. The solid line is a fit to the experimental data based on a linear temperature dependence. A change in slope would indicate a change of the dominant carrier scattering mechanism.

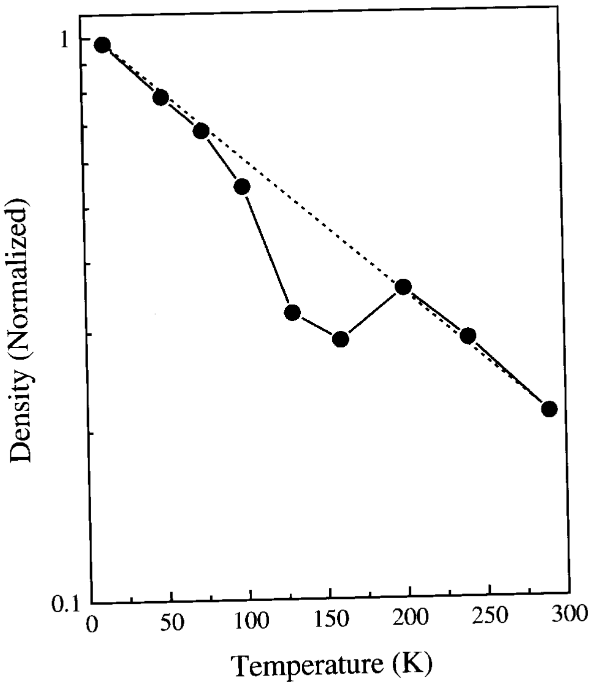

Figure 3. Total carrier density that recombine radiatively as function of temperature. We observe an abrupt change on the carrier density at about 150 K, which may be associated to thermal activation of an impurity related recombination channel. The solid and dashed lines are only guides to the eyes.

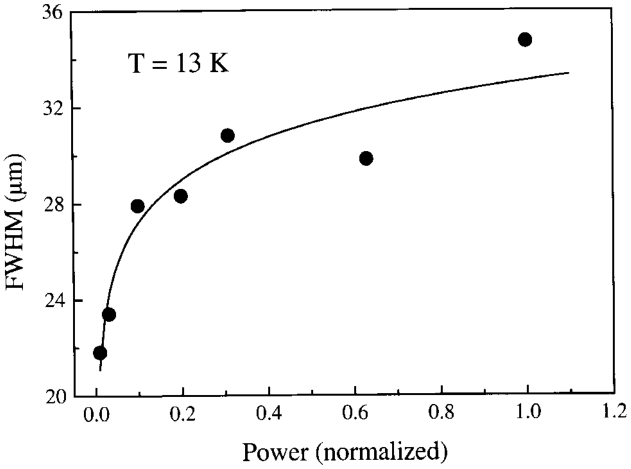

Figure 4 Spatial PL distribution (FWHM) at 13 K as a function of the excitation intensity. The solid line is only to guide the eyes.

IV Conclusions

In summary, the microluminescence surface scan technique (MSST) has been used to investigate carrier diffusion in a single QW of InGaAs lattice-matched to InP, as a function of both temperature and optical excitation. We found that ambipolar carrier recombination dominates the carrier diffusion process close to the laser spot, and the carrier diffusion length increases linearly with the temperature. A change in slope by a factor of 2.6 is observed at about 200 K, indicating a likely change of the dominant carrier scattering mechanism, and appears to be correlated with the thermal activation of a defect center. At low-temperatures, the carrier diffusion length saturates with increasing optical excitation intensity, indicating the presence of a defect-limited carrier diffusion.

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