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Experimental evidence of asymmetric carrier transport in InGaAs quantum wells and wires grown on tilted InP substrates

A. F. G. Monte, S. W. da Silva, J. M. R. Cruz, and P. C. Morais[a)]
Universidade de Brasília, Instituto de Física, Núcleo de Física Aplicada, 70919-970, Brasília-DF, Brazil

A. S. Chaves
Universidade Federal de Minas Gerais, Instituto de Ciências Exatas, Departamento de Física, 30161-970, Belo Horizonte-MG, Brazil

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The influence of the interface morphology upon the electron–hole transport in intrinsic $In_{0.53}Ga_{0.47}As/InP$ quantum structures was investigated by scanning the photoluminescence intensity profile on the sample surface. The results suggest that the carrier diffusion is very sensitive both to the roughness of the interfaces and the presence of finite-width terraces. It was found that the carrier density profile shows asymmetric diffusion normal to the terraces whereas it shows symmetric expansion along the terraces. Simulations of the asymmetry in the carrier density profile using a non-Fickian diffusion equation described by the Lévy statistics show a excellent agreement with the experimental data. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1507619]

The investigation of carrier transport in low dimensional semiconductor structures has been motivated by a number of theoretical studies.[1] The transport properties of electrons and holes have been successfully studied using microphotoluminescence techniques.[2] In particular, spatially resolved photoluminescence (PL) of quantum wires (QWRs) has been observed through microscopic PL measurement.[2] Following excitation by a tightly focused laser beam, the spatial distribution of the PL intensity on the sample surface can be measured by pinhole scanning the magnified luminescence image.[3] Such an approach permits the study of the effective diffusion length characterized by the lateral spread of carriers in the structure.

Recently, it has been reported that the diffusion of carriers in semiconductor InGaAs/InP quantum wells (QWs) can be asymmetric, as long as the substrate on top of which the QW is growth is slightly tilted with respect to the growth direction.[4] It has been shown that carrier diffusion in QW layers with the normal oriented along the [001] direction is clearly distinct from diffusion in QWs grown on 2° tilted (toward the [111] direction) substrates, both QWs with a width of 110 Å. In the first case, carrier diffusion is axially symmetric; whereas in the second case, it is asymmetric, showing a tail along the [110] direction. The effect of substrate misorientation upon carrier transport has been studied in AlGaAs/GaAs (Ref. 5) and InGaAs/GaAs.[6] In this letter, we extend our previous results,[4] showing the asymmetric diffusion in four InGaAs/InP samples, three containing QWRs and one containing a very narrow QW. More specifically, we report studies on the diffusion of photoexcited carriers in InGaAs QWRs with thicknesses varying from 3 to 6 Å, whereas the lateral dimension varies from about 40 to 160 Å, and in an InGaAs QW with an average thickness of 12 Å (4 monolayers). The PL image taken from the InGaAs QWs and QWRs, grown on tilted InP substrates,[4] has shown asymmetric carrier diffusion, in contrast to the symmetric carrier expansion in InGaAs QW structures grown on nontilted InP substrates.[7]

Samples used both in this and a previous study[4] were grown by vapor levitation epitaxy.[8] Sn-doped InP substrates, oriented 2° off the (100) toward the (111), were used to grow the InGaAs/InP quantum structures. The growth rates were about 2 and 0.5 Å/s for the InP and InGaAs layers, respectively. Using extremely short InGaAs growth times (0.5, 1, and 2 s), it was possible to grow uniform QWRs having a few monolayers of height and sufficiently narrow lateral width. These quantum structures are extremely thin, thus allowing the recombination luminescence of excitons bound to them to be substantially modified in comparison to the PL from the bulk.[9] Longer InGaAs growth times (for instance 10 s) allows the growth of very thin QWs instead of QWRs. The InP substrate as well as the epitaxial InP surface, upon which the InGaAs grows, are not perfectly planar and have steps of monolayer height ($a_0 = 2.93$ Å). Hence, the QW boundaries are sets of terraces that supposedly present fractal morphology, and the QWRs supposedly also compose a fractal set. The morphology of the QWs is schematically represented in Fig. 1(a). As suggested in Ref. 10, the diffusion in such fractal systems is non-Fickian, and if the system does not have space inversion symmetry, the diffusion can be asymmetric. This is what happens for carrier motion along the [110] direction. For motion along the $[1\bar{1}0]$ direction, we expect a symmetric non-Fickian diffusion. These predictions, confirmed in Ref. 4 for a broader QW, are here confirmed for a narrow QW and different kinds of QWRs.

The samples were pumped with an Ar^+-ion laser tuned at 514.5 nm. The laser beam was focused down to a spot of 5 μm in diameter. Photoexcitation creates electron–hole pairs, which are captured by the lower band gap InGaAs layer. The source of PL is the electron–hole transition of the InGaAs layer. The magnified image of the PL intensity profile was focused on a 25 μm wide pinhole attached to step motors, obtaining spatial resolution of 2 μm. By generating

[a)]Author to whom correspondence should be addressed; electronic mail: pcmor@unb.br

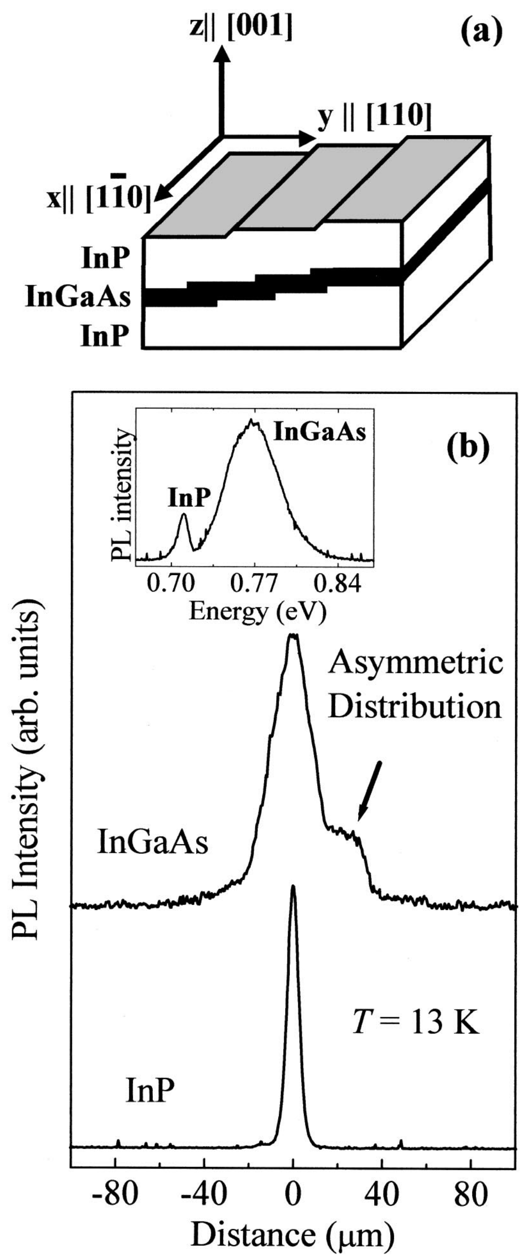

FIG. 1. (a) Schematic representation of the sample morphology showing the profile of the $In_{0.53}Ga_{0.47}As$ stepped layers. (b) Carrier profile in the $In_{0.53}Ga_{0.47}As$ layer compared with the diffusion in the InP barrier. The inset is the PL spectrum taken from the 2 s sample.

carriers in the spot region and measuring the total luminescence intensity as a function of the distance from the spot, it was possible to obtain the ambipolar diffusion length (L). Since we measure the radiative electron–hole pair recombination, the luminescence intensity (I) will be proportional to the local carrier concentration (n).

Figure 1(b) shows the spatial profile of the PL emission intensity taken from the InGaAs structure (QWR) with a growth time of 2s. The spatial PL scanning was taken parallel to the [110] direction. Figure 1(b) also shows (see inset) the low-temperature PL spectrum of the sample, revealing the optical features associated to both the InGaAs layer and the InP matrix. The diffused carrier distribution in the InGaAs layer is relatively broad and asymmetric, showing a shoulder on its right-hand side. In contrast, the carrier distribution in the InP matrix is symmetric and relatively narrow.

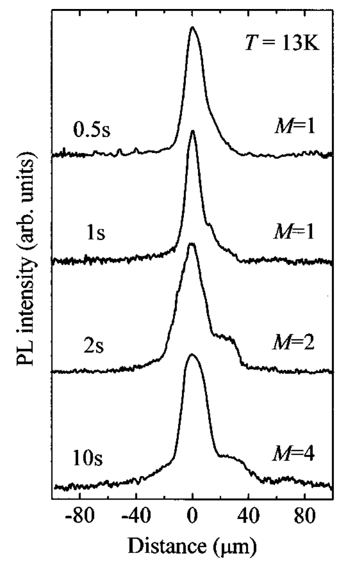

FIG. 2. Carrier density profiles taken from different quantum structures, as quoted by the growth times.

One of the reasons for this behavior is that carriers diffusing in the InP matrix do not have time to feel the interface roughness since they are captured by the QWRs on a very short time scale. On the other hand, carriers in the InGaAs QWR diffuse in the layer plane and feel the presence (band offset potential) of terraces built due to the tilting of the substrate.

Figure 2, also taken from a PL scanning parallel to the [110] direction, shows the variation observed in the spatial carrier distribution, for InGaAs/InP samples grown at different InGaAs growth times. The carrier distribution observed from the 10 s sample is highly asymmetric with a shoulder on the right-hand side of the main feature. The asymmetry in the diffused carriers profile reduces as the sample growth time decreases from 10 to 0.5 s. These findings show that the carrier distribution profile depends directly on the morphology of the InGaAs layer. For instance, it seems clear that in a very narrow QWR system, which is the case of the 0.5 s sample (see Fig. 2), carrier diffusion is limited by kinks and bends occurring in the wires, which create potential fluctuations that impede the transport. Also, given the small wire lateral separation, carrier hopping, or tunneling between adjacent wires may occur as well. The long diffusion length observed is believed to be a manifestation of the high mobility transport in the InGaAs layer[7] as well as on its long carrier lifetime. On the other hand, the change of the diffusion length with wire width is considered to depend on the competition between one-dimensional and two dimensional characters associated with interface fluctuation.[11] These effects explain why the observed carrier diffusion, perpendicular or parallel to the wires, are much larger than the excitation spot.

The relationship between growth time and lateral wire width is the most important factor to understand the asymmetry observed on the carrier diffusion profile. According to Worlock *et al.*,[12] the lateral wire width in these samples are around 40, 80, and 160 Å for 0.5, 1, and 2 s growth times, respectively. The number of monolayers height (M) increases with the growth time, as indicated in Fig. 2. Wire coupling is ignored for the 0.5 s sample, which presents only one mono-

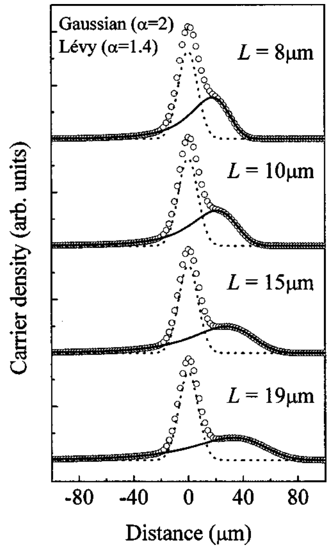

FIG. 3. Carrier density profiles simulations according to Eqs. (1) and (2), at different diffusion lengths (L).

layer in thickness and about 40 Å of lateral width. In the 1 s sample, which is one monolayer high but presents a wider terrace, the asymmetry is slightly observed. For the 2 s sample, which is two monolayers high, the wires are coupled together and the carrier diffusion asymmetry is quite strong. In the 10 s sample, the wires are completely merged in a QW structure and the morphology of the terraces resembles the profile shown in Fig. 1(a).

In order to understand the diffusion of photogenerated carriers in the tilted InGaAs/InP quantum structures, the diffusion was modelled using two distinct regimes. One regime is the normal diffusion, which follows the diffusion equation given by the Fick's law.[13] The other regime is the anomalous diffusion described by the Lévy's statistics.[10] It has been shown that the solution of the diffusion equation in a nonfractal medium can be described by a Gaussian distribution, whereas the solution in an asymmetrical fractal medium is described by an asymmetric Lévy distribution.[4] As yet, we could not understand why those two regimes of diffusion coexist in the system, as already shown in Ref. 4.

In Fig. 3, the solution of the diffusion equation is given taking into account both the Gaussian and the Lévy distribution of carriers. The following equations are used to describe the carrier density profile:[10]

$$n(x)=N\int_{-\infty}^{\infty}\frac{dk}{2\pi}p(k,\overline{t})e^{ikx} \tag{1}$$

and

$$p(k,t)=\exp\left[\left|k^{\alpha}\right|\frac{D_l+D_r}{2}\cos\left(\alpha\frac{\pi}{2}\right)t\right] \times\exp\left[|k^{\alpha}|\frac{D_l-D_r}{2}\sin\left(\alpha\frac{\pi}{2}\right)t\right], \tag{2}$$

where $n(x)$ corresponds to the local carrier density, N is the total number of photogenerated carriers, and $\overline{t}$ is some average diffusing lifetime. $\alpha(1<\alpha<2)$ is a parameter related to the degree of asymmetry or fractality of the system. D_l and D_r are the diffusivities to the left- and the right-hand side, respectively. Left- and right-hand side diffusivities can be distinct if the medium does not present space inversion symmetry.

The dotted lines in Fig. 3 correspond to the Gaussian distribution $(\alpha=2)$, whereas the solid lines correspond to the Lévy distribution for $\alpha=1.4$. The combined solution (circles in Fig. 3), obtained by adding both Gaussian and Lévy distributions can be compared to the experimental data. It is observed that by varying the diffusion length parameter, $L=(D_t^-)^{1/2}$, in the Lévy distribution, one gets a sequence for the carrier distribution similar to the experimental data (see Fig. 2). As is well known, the distribution corresponding to $\alpha=2$ is Gaussian, and always symmetric, independent of the eventual difference between the diffusivities D_l and D_r. The asymmetry observed in the carrier density is strong evidence that carriers obey the fractional derivative diffusion equation.[10] The increase of the diffusion length with the increase of the number of monolayers explains why the asymmetry is more pronounced in a QW than in a QWR structure.

In summary, diffusion of photoexcited carriers in InGaAs quantum structures embedded in InP has been investigated using spatially resolved PL measurements. It is revealed that the carrier diffusion normal to the wires has an asymmetric component superimposed to a symmetric one. However, the carrier expansion along the wire direction shows a symmetric profile. This indicates that carrier mobility in InGaAs/InP tilted structures is very sensitive to the interface roughness and terrace widths. Combination of asymmetric and symmetric diffusion along different directions could be a key aspect in the design of mesoscopic devices.

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