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Interface-roughness-controlled exciton mobilities in $GaAs/Al_{0.37}Ga_{0.63}As$ quantum wells

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The influence of the interface morphology on exciton transport is studied by space- and time-resolved spectroscopy of $GaAs/Al_{0.37}Ga_{0.63}As$ quantum wells grown continuously and with growth interruption. The growth-interrupted quantum wells exhibit smaller lifetimes than continuously grown structures due to nonradiative contributions to recombination. The exciton mobility, in contrast, is significantly higher in the growth-interrupted samples, reflecting a reduction of interface-roughness scattering.

Abrupt interfaces in semiconductor heterostructures can be obtained by modern epitaxy processes such as molecular-beam epitaxy (MBE), chemical beam epitaxy (CBE), or metalorganic vapor-phase epitaxy (MOVPE). The quality of the interfaces is essential for many heterostructure devices based on carrier transport parallel to the interface. Information about the interface cannot be obtained by conventional surface investigation methods. However, low-temperature photoluminescence (PL),[1-6] photoluminescence excitation (PLE) spectroscopy,[2,5,6] cathodoluminesence imaging,[7-9] reflection high-energy electron diffraction,[10] or chemical imaging studies[11] did provide useful information on the interface topology. These studies indicate that heterostructure interfaces are pseudosmooth (very small residual roughness) within lateral regions, which vary in size between some nanometers (small terraces) and some micrometers (extended islands). The characteristic step height of the interface roughness is usually interpreted to vary in units of one monatomic layer (ML), e.g., 0.283 nm for GaAs/$Al_xGa_{1-x}As$ interfaces.

The quality of the interfaces depends on growth parameters such as temperature, flux,[12] and mainly the growth-interruption time at the interfaces.[2,12] Some authors[2-5] used PL, PLE, and the lateral extension of free excitons[13] to estimate the size of the islands. Despite the importance of the interface quality for device applications, the influence of growth interruption on transport properties has been studied rarely up to now. Deveaud *et al.*[4] and Kohl *et al.*[5] used time-resolved spectroscopy to study exciton transfer between monolayer islands for $T=15$ and 5 K, respectively. To the best of our knowledge, no comparison of the experimental transport properties of interrupted-growth (IG) and continuous-growth (CG) grown structures has been carried out up to now.

We have investigated the exciton transport in quantum-well (QW) structures grown with and without growth-interrupted interfaces as a function of temperature and well width L_z. In order to determine transport properties we used a time-of-flight method providing diffusivities and mobilities. Our study indicates that interface-roughness scattering is largely suppressed in layers grown with appropriate growth interruption. For the time-of-flight experiments the samples were covered by masks consisting of light transmittive holes (radius >0.5 μm) in an opaque Ni-Cr layer. Excitons are created resonantly in the QW's within the hole area by short ($\lesssim 10$ ps) weak laser pulses (initial exciton densities below 10^{16} cm^{-3}). The exciton concentration under the hole is probed by the time-resolved radiative emission. If the excitons diffuse under the mask they do not contribute to the detectable recombination. Time-resolved experiments using mask diameters of the order of the diffusion length allow us to deduce the transport properties with high accuracy. Details of our method have been published previously.[14]

For our experiment we used samples grown by MBE on GaAs substrates which contain GaAs QW's of nominal widths $L_z=10$, 5, 2.5, and 1.5 nm separated by $Al_{0.37}Ga_{0.63}As$ barriers of 30 nm thickness. For more details on the precise sample structure and PL spectra see Ref. 2. One sample was grown with 2-min growth interruption at each interface, whereas a second one was grown continuously.

Figure 1 displays the temperature dependence of exciton lifetimes determined from fits to the decay of the QW emission using no mask for CG and IG QW's of 5 nm (top) and 10 nm (bottom) well width. The dotted curve in the inset shows a typical decay profile of an IG sample. For all studied well width and temperatures the lifetime in IG QW's is found to be shorter than in CG samples. This decrease of the exciton lifetimes after growth interruption is most likely due to the incorporation of additional impurities.[2,3] The maximum values of the CG QW's exceed 4 ns, indicating very low defect concentration in the layers. In Fig. 1, for $T>170$ K, the lifetimes decrease again with growing temperatures which may be due to increasing nonradiative recombination probabilities. This decrease is

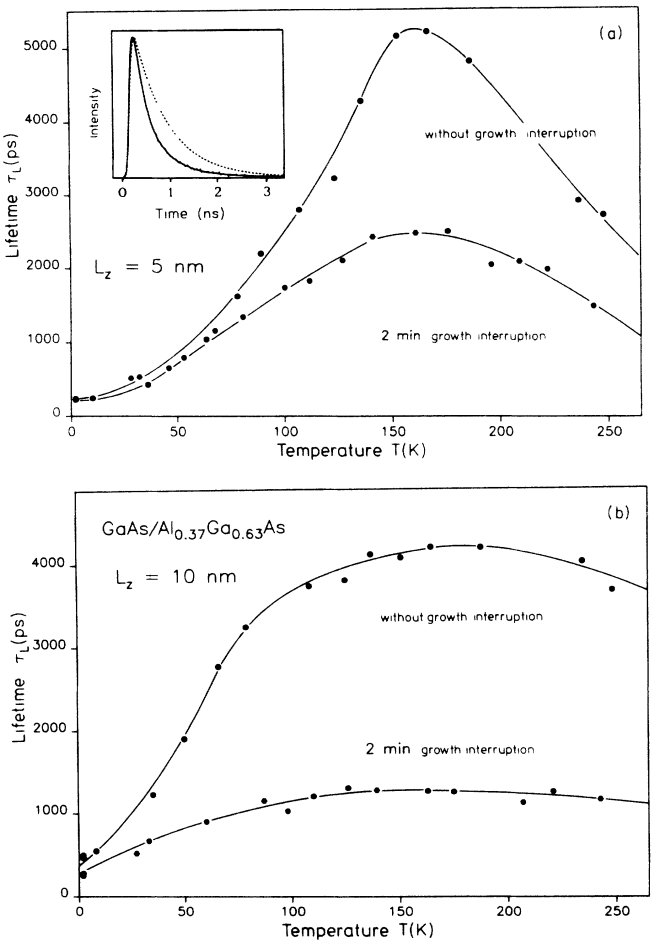

FIG. 1. Lifetimes of continuously and interrupted grown QW's as a function of temperature for well widths of 5 nm (top) and 10 nm (bottom). For all temperatures the continuously grown QW's show larger lifetimes than the growth interrupted QW's. The inset displays a comparison of the emission of a QW of $L_z = 5$ nm for $T = 49$ K as a function of time measured without a mask (dotted trace) and using transparent holes of 2 μm radius (solid line).

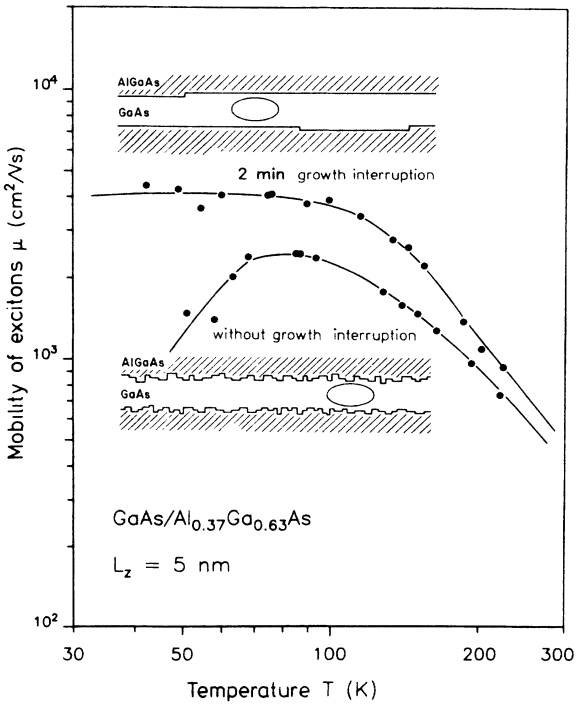

FIG. 2. Mobilities of excitons as a function of time for interrupted grown (upper curve) and continuously grown QW's (lower curve) evaluated from experimental transport profiles. The inset shows a schematic illustration of two interface models which describe both types of QW's. Terrace length smaller than the extension of excitons (ellipse) are attributed to continuously grown QW's. In contrast, extended monolayer flat islands are found in growth interrupted QW's.

found to be stronger for smaller well width, and this trend also continues for $L_z = 2.5$ and 1.5 nm.

For the transport measurements the samples are covered by masks and the radiative emission passing the transmittive holes is recorded as a function of time.[14] Due to lateral exciton transport under the covered parts of the masks the time decay of the emission sensitively includes transport information: The inset of Fig. 1 shows the emission of a IG QW with $L_z = 5$ nm as a function of time recorded with (solid line) and without mask (dotted line) at $T = 49$ K. We observe a much faster decay in appropriately masked structures due to exciton diffusion under the mask. Using the continuity equation including a diffusion and a recombination term as presented in detail in Ref. 14, we have determined the excitonic diffusivity in all CG QW's and in IG QW's of large well width (> 5 nm).

Using the Einstein relation, the exciton diffusivities are converted[14] into exciton mobilities. Figure 2 depicts the experimental values for the mobility of excitons in an IG QW of $L_z = 5$ nm in comparison with data of the corresponding CG QW as a function of temperature. In the entire temperature range studied here the exciton mobilities of the IG QW exceed the mobilities of the CG QW. The difference in the mobilities between samples with the two types of interface is very significant at low temperatures and rather small for $T > 150$ K. This indicates that for low temperatures the interface-roughness scattering limits the exciton mobilities in structures of high interface roughness (CG) in agreement with the results in Ref. 14. In contrast, the exciton mobilities of IG QW's are nearly constant in the temperature range below 100 K. This indicates the dominant influence of barrier alloy scattering[14] in IG samples, because this scattering process is not temperature dependent.

The insets in Fig. 2 schematically illustrate the influence of growth interruption on PL spectra and the exciton motion. In CG QW's interface roughness with typical terrace lengths smaller than the exciton extension (given by the ellipse) lead to a significantly enhanced scattering rate compared to extended islands in IG samples. (PL spectra of CG structures show a single line broadened by interface roughness,[15] since the exciton averages over many terraces. In contrast, controlled growth interruption can lead to smoothing of the interfaces and permits to vary the lateral size of pseudo-monolayer-flat regions significantly.[2,10,12] These QW is-

lands reveal their individual energy-level scheme given by the overlap of two interface islands on the opposite interfaces of the GaAs layer. The sharp multiple lines observed in IG QW samples[2] were attributed to free-exciton emission from extended pseudo-monolayer-flat QW islands differing in thickness by a single ML.)

For the evaluation of transport profiles of thin IG QW ($L_z < 5$ nm) the simple continuity equation cannot be used. In addition to the diffusive transport within the islands the transfer between the islands by energy relaxation and thermal reactivation has to be considered. We assumed a rectangular shape of the islands as the simplest possibility for a full coverage of the interface. The size of the islands and their contribution to the area of the interface are parameters, which can be determined by the simultaneous evaluation of temperature-dependent experiments using the separated emission lines due to the recombination of excitons on islands with different monolayer flat islands. For a given L_z the results of time-integrated and time-resolved studies on unmasked structures as well as time-resolved studies of masked samples are simultaneously fitted. The parameters are determined by selecting out the best simultaneous fits for all measurements of a given L_z. Details of our model, including diffusion processes in contrast to Refs. 4 and 5, can be found in Ref. 16 and will be given in a more extended forthcoming publication.

Figure 3 depicts the influence of growth interruption on the excitonic mobilities at $T=55$ K as a function of well width. For both IG and CG samples the mobility increases strongly as the well width is increased. For the CG QW's this trend reflects predominantly the decrease of the interface roughness scattering rate.[14] Simultaneously the influence of barrier alloy scattering[14] decreases. As shown in Fig. 3 we generally observe larger mobilities in IG QW's than in corresponding CG QW's. This indicates a partial suppression of interface-roughness scattering in appropriately grown IG layers. [The evaluation of the experimental data for large IG QW's ($L_z=5$ and 10 nm) yields in the simple diffusion model or the transfer model nearly the same mobility values. However, for smaller well widths ($L_z=2.5$ and 1.5 nm) we obtain significant deviations between the results of the two models. In these cases only the transfer model may be used.]

The difference between the mobilities of IG and CG QW's is largest for $L_z=5$ nm and decreases for thinner and wider well widths. For a well width of 10 nm, for example, interface-roughness scattering has only a very weak influence on the mobilities, due to the strong well-width dependence of the interface-roughness-limited mobility.[14,17] This trend can be understood as with increasing well width a step of one ML causes a smaller step in the quantization energy and, therefore, creates a decreasing scattering potential with subsequently increasing exciton mobility. In thin QW's ($L_z=1.5$ and 2.5 nm) the small difference of the mobility of IG and CG QW's might be due to significant interface-roughness scattering in both types of thin QW's. This indicates that the IG interface model given in Fig. 2 is not fully appropriate for small IG QW's. Residual interface roughness[11] in IG QW's may induce scattering in small IG QW's.

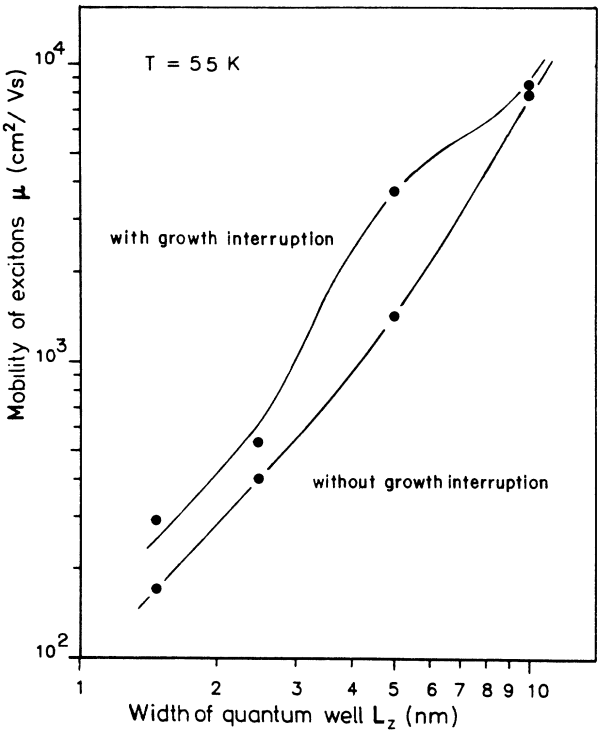

FIG. 3. Exciton mobility as a function of well width for $T=55$ K and different growth conditions ($x_{Al}=0.37$).

In conclusion, we found higher exciton lifetimes in continuously grown QW's probably due to a smaller amount of nonradiative recombination processes compared to interrupted grown QW's. For QW's grown with or without interruption the exciton mobility increases with growing well width, mainly at low temperatures. In particular, the low-temperature mobilities of interrupted grown QW's display significantly higher values than the respective continuously grown samples. This difference appears most clearly for the QW of 5 nm well widths in our structures. Our study indicates that QW layers of suitable well width grown with appropriate growth interruption may be highly suitable for fast low-temperature devices.

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