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Citation: Appl. Phys. Lett. 93, 242104 (2008); doi: 10.1063/1.3050531
View online: http://dx.doi.org/10.1063/1.3050531
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Interface roughness in short-period InGaAs/InP superlattices

Yu. A. Pusep, G. C. Gozzo, and R. R. LaPierre

Instituto de Física de São Carlos, Universidade de São Paulo, 13560-970 São Carlos, São Paulo, Brazil
Centre for Emerging Device Technologies, McMaster University, Hamilton, Ontario L8S 4L7, Canada

(Received 28 October 2008; accepted 27 November 2008; published online 16 December 2008)

Electron mobility was studied in lattice-matched short-period InGaAs/InP superlattices as a function of the width of the wells. The decreasing mobility with decreasing well width was shown to occur due to the interface roughness. The roughnesses of InGaAs/InP and GaAs/AlGaAs interfaces were compared. Much smoother InGaAs/InP interfaces resulted in higher electron mobility limited by interface roughness. © 2008 American Institute of Physics. [DOI: 10.1063/1.3050531]

The problem of roughness is one of the central problems of semiconductor heterointerfaces. The interface roughness fundamentally limits the properties of optoelectronic devices based on narrow quantum wells (single quantum wells and superlattices). The theory of the interface roughness scattering was developed in Refs. 1 and 2. It was established that maximum mobility may be obtained in two limits: $k_F \Lambda \ll 1$ and $k_F \Lambda \gg 1$, where $k_F$ and $\Lambda$ are the Fermi wave number and the lateral size of interface roughness, respectively. The influence of the interface roughness on electron transport properties was extensively studied in GaAs/AlGaAs heterostructures in Refs. 3–7, where a validity of the theory was confirmed. According to these data, the roughness of the GaAs/AlGaAs is characterized by the 0.6–5.0 Å height and 6–10 nm length. Very short lateral size of the GaAs/AlGaAs interface yielded the condition $k_F \Lambda \approx 1$ in the range of the actual electron densities used in electronic devices ($10^{11}$–$10^{12}$ cm$^{-2}$) resulting in low mobilities. It is worth mentioning that as was indicated in Ref. 5, the actual structure of heterointerfaces may be more complicated than the one modeled by steps and terraces considered in Refs. 1 and 2. For instance, the inclusion of possible charge defects at the GaAs/AlGaAs heterointerface may affect the mobility of the electrons in the wells with thickness larger than 7 nm. Also, it was demonstrated that the use of alternate beam [molecular beam epitaxy (MBE)] and/or the superlattice (SL) buffer layers results in an increase in the lateral interface size up to 20–30 nm, remarkably improving the electron mobility. A search for a heterostructure with even longer lateral interface size is highly desirable. Somewhat longer interface roughness (about 30 nm) was recently reported in InGaAs/InP heterostructures grown by metalorganic vapor phase epitaxy; this heterosystem is also important as a semiconductor material with application in the field of spintronics and quantum information processing. A manipulation of the electronic properties (including $g$-factor engineering) important in device applications is possible in SLs—structures consisting of periodic sequences of the layers made of two different semiconductor materials. In such structures the dynamic electron properties and $g$-factor can be tuned in the direction perpendicular to the layers by a variation in their thicknesses or compositions. In this work the interface roughness was studied in lattice-matched short-period InGaAs/InP SLs grown by MBE. We demonstrated the electron mobility limited by the interface roughness, which is one order of magnitude higher than in similar GaAs/AlGaAs heterostructures.

In order to examine the interfaces, a total number of 30 periods of the lattice-matched (In$_{0.5}$Ga$_{0.5}$As)$_m$(InP)$_n$ SLs with $m=(6–25)$ ML, where $m$ is the thickness of the layers expressed in monolayers (1 ML=2.9 Å), were grown on semi-insulating (001) InP substrates by MBE. The barriers of the SLs were doped by Si in order to form a gas of degenerate electrons with the density of $(2–3) \times 10^{17}$ cm$^{-3}$. The periodicity of the SLs was proved by x-ray diffraction, which yielded the height of the interface roughness of approximately 2 ML.

The mobility measurements were performed on samples patterned into Hall bars with an active area of $2 \times 5$ mm$^2$. The Ohmic contacts were fabricated by depositing indium. The transport measurements parallel to the surface of the samples were carried out at $T=4.2$ K using a standard low-frequency (1 Hz) lock-in technique in a liquid He cryostat.

In the following we demonstrate that the interface roughness dominates the electron mobility in the SLs considered in this study. The theory, which describes the interface roughness in terms of the height ($\Delta$) and the lateral length ($\Lambda$) of the interface roughness, predicts the variation in the mobility as a function of the well width ($L_w$) proportional to the power law $L_w^{\gamma}$. According to the theory, the mobility is a two-valued function of the lateral length of the interface roughness, which behaves differently in two limits $k_F \Lambda \ll 1$ and $k_F \Lambda \gg 1$, decreasing and increasing with the variation in the Fermi energy, respectively. At $k_F \Lambda = 1$ the mobility reveals a minimum. As it was mentioned above, the short length roughness of the GaAs/AlGaAs interface results in this minimum mobility. Thus, the dependence of the mobility on the electron density may be used to distinguish between the actual theoretical limits and then appropriately use the corresponding formula. The similar analysis was performed in Ref. 4. The inset in Fig. 1(a) shows the electron mobilities measured in differently doped InGaAs/InP SLs with the well widths weakly varying in the interval of 6–10 ML. We attribute the increasing mobilities with the electron concentration to the effect of the Fermi energy variation. Conse-
FIG. 1. Dependence of the electron mobility (a) and the parameter $k_F l$ (b) on the width of the InGaAs wells measured in the InGaAs/InP SLs (closed circles) and in the GaAs/AlGaAs SLs (open circles). Diamonds, triangles, squares, and stars in panel (a) are the data from Refs. 4, 3, 6, and 8, respectively. The solid line is the power law $L_{w}^{6}$ dependence describing the data obtained in homogeneously doped InGaAs/InP SLs. The hatched area indicates the region of the power law dependences describing the data obtained in GaAs/AlGaAs heterostructures. The inset shows the electron mobilities measured in the differently doped InGaAs/InP SLs.

sequently, we conclude that in the InGaAs/InP SLs studied here, $k_F \Lambda > 1$.

The electron mobilities measured in InGaAs/InP SLs with different periods and electron concentrations of $(2–3) \times 10^{17} \text{cm}^{-3}$ are depicted in Fig. 1(a). As seen, the experimental data are reasonably described by the power law $L_{w}^{6}$ (solid line), which implies an interface roughness scattering dominating at the well width smaller than 20 ML. In such case the decreasing mobility with the decreasing well thickness may be described by the theory, allowing for the determination of the interface profile (the height and the lateral size of the interface roughness). According to this theory, in the limit $k_F \Lambda \gg 1$, the mobility limited by the interface scattering is given by

$$
\mu_{IF} \propto \frac{L_{w}^{6} \Lambda^{3}}{\Delta^2} g(\Lambda),
$$

where $g$ is a smooth function of $\Lambda$ and the electron concentration. The effective masses necessary for the calculation of $g(\Lambda)$ were taken from Ref. 13, while the Fermi energies were determined by the Shubnikov–de Haas oscillations ($E_F \approx 10 \text{meV}$). The dependence of the mobility on the well width calculated in this way is shown in Fig. 1(a) and it well describes the experimental data. Using the interface roughness height determined by x-ray diffraction, we calculated the length of the interface roughness in the InGaAs/InP heterostructures as $\Lambda = 63 \text{nm}$, which indeed was found much longer than that in the GaAs/AlGaAs heterostructures. These results were compared with the mobilities measured in the short-period GaAs/AlGaAs SLs, in the GaAs/AlGaAs multiquantum wells, and in the single GaAs/AlAs quantum wells. All these data are shown in Fig. 1(a), where the hatched area corresponds to the region of the power law $L_{w}^{6}$ dependences describing the data obtained in different GaAs/AlGaAs heterostructures. Reasonably narrow distribution of the experimental data obtained in different samples indicates a universal character of the interface roughness of the GaAs/AlGaAs interface. The deviation of the mobilities from the power law $L_{w}^{6}$ measured in the homogeneously doped SLs and multiquantum wells [open circles and squares in Fig. 1(a)], observed at well thicknesses larger than 20 ML, is due to the ionized impurity scattering dominating in wide well heterostructures, while much higher mobilities limited by the interface roughness were achieved in the selectively doped single quantum wells [triangles, stars, and diamonds in Fig. 1(a)].

The comparison between the data obtained in the InGaAs/InP and similar GaAs/AlGaAs heterostructures demonstrates that the mobilities limited by the interface roughness are at least one order of value higher in the former heterosystem than in the latter one. The analysis of the experimental data presented above shows that this occurs due to the much longer interface roughness found in the InGaAs/InP heterostructure, which agrees with the data obtained in Refs. 9 and 10. This conclusion was proved by the investigation of the localization properties in both heterosystems. First of all, the parameters $k_F l$ (where $l$ is the free path length) calculated in InGaAs/InP and GaAs/AlGaAs SLs are shown in Fig. 1(b). The value of this parameter determines the effect of the electron localization: when $k_F l \gg 1$ the electron system reveals metallic properties, while at $k_F l \ll 1$ the electrons are localized. The clear metal-to-insulator transition was observed in the GaAs/AlGaAs SLs with the decreasing well thickness, while no insulating state was found in similar InGaAs/InP SLs.

Moreover, the localization effects may be probed by the temperature dependence of the resistance: the exponential decrease in the resistance with increasing temperature indicates the localization effects, while no significant influence of the temperature points to the metallic phase. The temperature dependences of the resistances measured in the InGaAs/InP and GaAs/AlGaAs SLs and shown in Figs. 2(a) and 2(b) exhibit the effect of the electron localization in the GaAs/AlGaAs SL with 10 ML well width, while no localization effects were distinguished in the InGaAs/InP SL even with 7 ML well width. The full line in Fig. 2(b) is the resistance calculated according to Mott’s law for variable-range hopping:

$$
\rho(T) = \rho_0 \exp \left[\left(\frac{T_0}{T}\right)^{1/4}\right],
$$

where $T_0$ is the characteristic temperature. The best fits to the data obtained in the GaAs/AlGaAs SL with a well width of 10 ML was obtained with $T_0 = 7.8 \text{K}$. 

The absence of the localization effects in the InGaAs/InP SLs is consistent with their long length of the
interface roughness. The roughness of the InGaAs/InP interface with the lateral length longer than the electron wavelength $k_F \Lambda$ does not localize electrons, while the roughness of the GaAs/AlGaAs interface, which is of the same lateral size as the electron wavelength $k_F \Lambda$, effectively localizes electrons.

In conclusion, much higher electron mobilities were found in lattice-matched short-period InGaAs/InP SLs than those in similar GaAs/AlGaAs SLs. The dependences of the low-temperature mobilities on the well widths indicated that the interface roughness scattering controls scattering process in both types of the SLs with the quantum well thicknesses smaller than 20 ML. Additionally, the interface roughness was studied in InGaAs/InP SLs by high-resolution x-ray diffraction. We demonstrated that the roughness of the MBE grown InGaAs/InP interface is characterized by an average height of 2 ML and an average length of 63 nm (217 ML), which exceeds the lateral roughness length so far achieved by the metalorganic vapor phase epitaxy. This interface roughness length was found to be considerably longer than the lateral length of the interface roughness characterizing the GaAs/AlGaAs heterointerface (6–25 nm). The examination of the localization effects in both GaAs/AlGaAs and GaAs/AlGaAs heterosystems supports this conclusion.

The financial support from Brazilian agencies FAPESP, CNPq, and the Natural Sciences and Engineering Research Council of Canada is gratefully acknowledged.