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DENSITIES AND MOBILITIES OF COEXISTING ELECTRONS AND HOLES IN GaSb/InAs/GaSb QUANTUM WELLS

H. MUNEKATA, E.E. MENDEZ, Y. IYE and L. ESAKI

IBM Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598, USA

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Quantum wells of GaSb/InAs/GaSb have been prepared by molecular beam epitaxy (MBE) with emphasis on the correlation of the growth parameters with their electronic properties as characterized by magnetotransport measurements. An electron mobility of 3.5×10^5 cm^2/V s has been obtained for the first time in the presence of holes. The holes disappear at a critical InAs thickness around 60 Å resulting from a semimetal–semiconductor transition.

The InAs–GaSb system is known to exhibit unusual magnetotransport properties arising from coexisting two-dimensional electrons and holes which result from the peculiar band offsets at the interface between the two materials [1–4]. In spite of these extensive studies, the preparation and characterization of high-quality samples involving high mobilities were not achieved.

In the present study, we have made efforts to correlate the growth conditions for such quantum well structures with the densities and mobilities for both electrons and holes derived from two-carrier analysis on low-temperature galvanomagnetic measurements.

The samples were prepared by molecular beam epitaxy, and consisted of an undoped n-type InAs layer sandwiched between undoped p-type GaSb layers. First, an 8000 Å GaAs buffer layer was grown at 580°C on a semi-insulating GaAs(100) substrate mounted on a rotating holder. Then, the first GaSb layer was grown as thick as 8000 Å, after the substrate temperature was readjusted to 450°C. This was followed by an InAs well layer ranging from 50 to 250 Å thick, and finally a 200 Å or 1000 Å GaSb overlayer was grown on the top. Epitaxial film growth was interrupted in transition from the GaSb layer to the InAs layer and vice versa in order to switch the molecular beams of both the group III and the volatile group V elements. The thickness of the InAs well layer was deduced from a known growth rate of 1.2 Å/s, obtained from bulk InAs grown on GaSb/GaAs(100) substrates. The unintentionally introduced carrier concentrations in both base materials were at least two orders of magnitude lower than the densities of two-dimensional carriers due to the charge transfer.

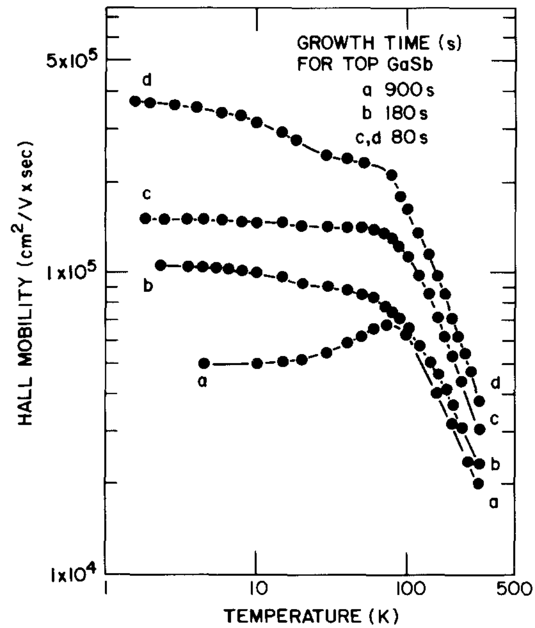

Fig. 1. Temperature dependence of effective electron mobility for the samples grown under different growth time for a GaSb overlayer. The growth interruption time for each sample was fixed at 30 s.

It has been found that two growth parameters play important roles in determining the quality of the samples; (i) the interruption time in transition from GaSb to InAs and vice versa, and (ii) the growth time of the GaSb overlayer. For the former growth parameter, we found that continuous growth of the layers without interruption was not the best procedure to achieve high mobilities: electron mobilities for such samples were always lower than those prepared with an interruption time of 30 s. This is probably due to the formation of a transition layer at InAs/GaSb interface induced by residual group V elements in the case of the continuous growth. The surface smoothing during the growth interruption might also contribute to the mobility enhancement.

Fig. 1 shows the influence of the latter growth parameter on the temperature dependence of effective electron mobility determined from conventional Hall measurements assuming one-carrier conduction. We found that the shorter growth time improves the quality of the samples, leading to an electron mobility as high as 3.5×10^5 cm^2/V s, with an electron density of 1.0×10^{12} cm^{-2}. This is the highest mobility ever achieved for InAs layers. Such behavior can be explained in terms of impurity diffusion through the InAs/GaSb interfaces, which determines the amount and spatial distribution of the scatter-

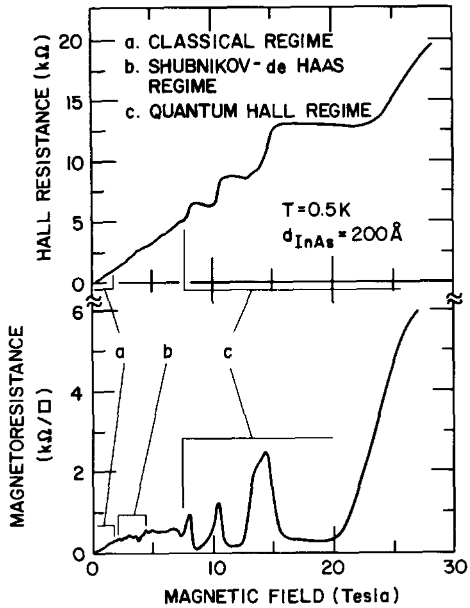

Fig. 2. Typical curves of magnetoresistance and Hall resistance at 0.5 K for the sample with 200 Å InAs well layer.

ing centers in the InAs well. Exact origin of impurities is not clear at present.

The high-quality samples thus made were characterized by magnetoresistance ρ_{xx} and Hall resistance ρ_{xy} at various magnetic fields to determine the densities and the mobilities of both electrons and holes. Fig. 2 shows typical ρ_{xx} and ρ_{xy} curves up to 29 T for a sample with a 200 Å InAs well thickness. At high magnetic fields, indicated as "regime c" in fig. 2, well-defined Hall plateaus together with extra anomalous structures [3] are clearly observed with compensated filling factors given by $i = i_e - i_h$ [5]. Therefore, the effective carrier density of $N_{eff} = N - P$ is estimated using the formula, $N_{eff}(\mathrm{cm}^{-2}) = 2.42 \times 10^{10} B(\mathrm{tesla}) i$. In the intermediate magnetic field "regime b" in fig. 2, the period of Shubnikov–de Haas oscillations gives the density of electrons N. By subtracting N_{eff} from N, one can obtain P, the density of holes. Furthermore, in the low field "regime a" in fig. 2, large temperature-independent positive magnetoresistance was observed together with non-linear Hall resistance, characteristic of two-carrier conduction. By theoretical curve fitting using N and P obtained from higher fields, one consistently obtains the remaining two parameters, thus, the mobilities of electrons μ_n and holes μ_p; for example, $N = 1.2 \times 10^{12}$ cm^{-2}, $P = 3.5 \times 10^{11}$ cm^{-2}, $\mu_n = 1.0 \times 10^5$ cm^2/V s, and $\mu_p = 1.5 \times 10^4$ cm^2/V s at 0.5 K for the sample in fig. 2.

As the InAs layer thickness is reduced, the ground quantized level for

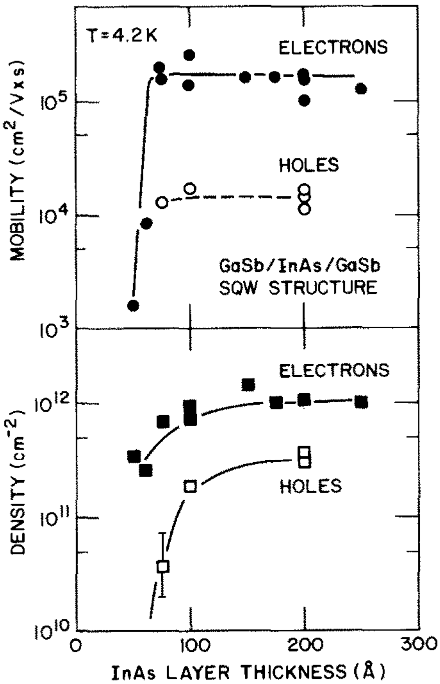

Fig. 3. Densities and mobilities of both electrons and holes as a function of InAs well width.

electrons confined in this layer shifts toward higher energy, impeding the process of electron transfer. This leads to a monotonic reduction of both electron and hole densities with InAs layer thickness, as shown in fig. 3. The imbalance in carrier densities implies the existence of positively charged centers in the vicinity of InAs/GaSb interface due to extrinsic origin, such as lattice mismatch as large as 0.6%. At the thickness of 60 Å, no holes have been observed because the Fermi level in the InAs potential well crosses over to the valence band edge of GaSb, corresponding to the semimetal–semiconductor transition. Note that this value is directly obtained from disappearance of the positive magnetoresistance, which is more accurate than that determined previously from the change in electron density alone [1]. A drastic drop has been simultaneously observed in electron mobility around this thickness, as also shown in fig. 3. This can be qualitatively explained if we consider that the scattering due to the imperfection of InAs/GaSb interface starts to dominate for such thin-well samples, although the change in carrier screening should take into account. It is to be noted, however, that $\mu_n = 2.0 \times 10^5$ cm^2/V s has already been achieved for an InAs well, only slightly above this critical thickness, such as 75 Å.

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