Extremely high-mobility two dimensional electron gas: Evaluation of scattering mechanisms

V. Umansky,[a] R. de-Picciotto, and M. Heiblum
Department of Condensed Matter Physics, Braun Center for Submicron Research, Weizmann Institute of Science, Rehovot 76100, Israel

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We report on the characterization of selectively doped GaAs/AlGaAs heterostructures, grown by an extremely clean molecular beam epitaxy system, which exhibit a Hall mobility of a two dimensional electron gas exceeding 10×10^6 cm^2/Vs for a wide range of undoped spacer layer thickness (50–100 nm). A maximum electron mobility of 14.4×10^6 cm^2/Vs was measured at 0.1 K in a structure with a 68 nm spacer thickness and an areal carrier density of 2.4×10^{11} cm^{-2}. This is the highest electron mobility ever reported, leading to a momentum relaxation mean-free path of ~ 120 μm. We present experiments that enable us to distinguish between the main scattering mechanisms. We find that scattering due to background impurities limits electron mobility in our best samples, suggesting that further improvement in structure quality is possible. [S0003-6951(97)01231-X]

Since the first fabrication of a high-mobility two dimensional electron gas (2DEG),[1] embedded in a GaAs/AlGaAs heterostructure, employing the concept of spatial separation between ionized (parent) donor impurities and the resultant 2DEG, has led to a wide range of structures with electron mobility exceeding 1×10^6 cm^2/Vs.[2] Utilizing extremely clean molecular beam epitaxy (MBE) systems led to successive improvements, with recent low temperature mobility values exceeding 1×10^7 cm^2/Vs (Refs. 3–5) [with a record mobility of 11.7×10^6 cm^2/Vs (Ref. 3)].

A number of theoretical works calculated the mobility in such structures from the first principles accounting for a variety of scattering mechanisms.[2,6–11] Most models qualitatively describe the experimental results well, however, they usually fail quantitatively. Moreover, issues such as the maximum achievable mobility and the weight of various scattering mechanisms, are still under discussion. For example, in contrast to Pfeiffer's *et al.*[3] optimistic prediction that the mobility could rise by orders of magnitude in extremely pure structures, Saku *et al.*[11] have recently stated that a mobility limit of about 2×10^7 cm^2/Vs must always exist due to remote ionized donor impurities scattering—when a realistic carrier concentration and spacer thickness are being employed.

In this letter, we present results of a systematic study of low temperature 2DEG mobility in high purity selectively doped GaAs/AlGaAs heterostructures. We discuss both technological factors and structure design that determine the mobility. By varying structure parameters we distinguish between the different scattering mechanisms. Optimizing the structure leads to a record 2DEG mobility of 14.4×10^6 cm^2/Vs at 0.1 K; the highest value published thus far.

Our MBE system is a Riber 32 with a 3 in. diam substrate holder. The system is pumped with two cryopumps and valved with *all metal valves*. One cryopump is specially designed to have three stages, with the coolest one at 4.5 K. The chamber, continuously cooled by liquid nitrogen, reached (after baking it for two weeks at some 200 °C) a pressure of 1×10^{-12} Torr under idle conditions of all the effusion cells. GaAs (100) 2 in. substrates were *indium-free* mounted onto a 3 in. diam high purity Molybdenum holders.[12] Our experience taught us that the chamber's pressure, though being of great importance, does not limit the ultimate material purity in our system. Instead, impurities emanating from the substrate heater and source materials during epitaxy determine background impurity concentration. Figure 1 summarizes the evolution of the 4.2 K mobility as the As cell is being depleted for a 2 in. and 3 in. heater diameters. The 2 in. diam heater was inserted into the 3 in. holder in order to reduce the overall outgassing of the manipulator; consuming indeed some 30% less power at typical growth temperatures. One notices that the mobility increases steadily as the As source is being depleted, with the maximum 4.2 K mobility some 40% higher for the 2 in. heater.

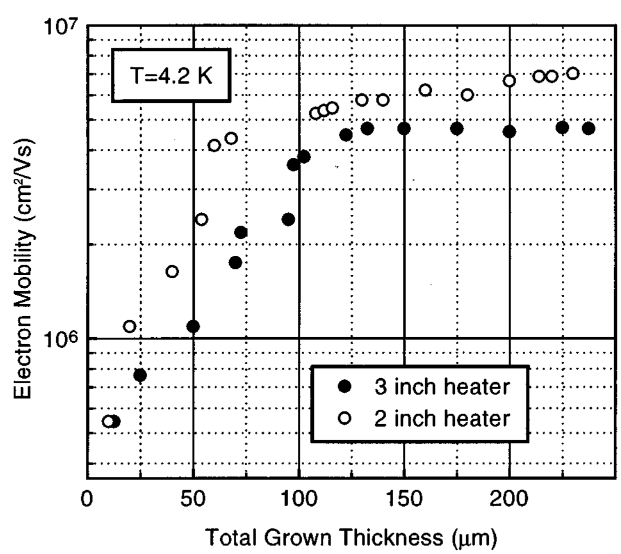

FIG. 1. Mobility of 2DEG, measured in the dark after illumination, as a function of the total thickness of grown material for two different substrate heaters.

[a]Electronic mail: human@wis.weizmann.ac.il

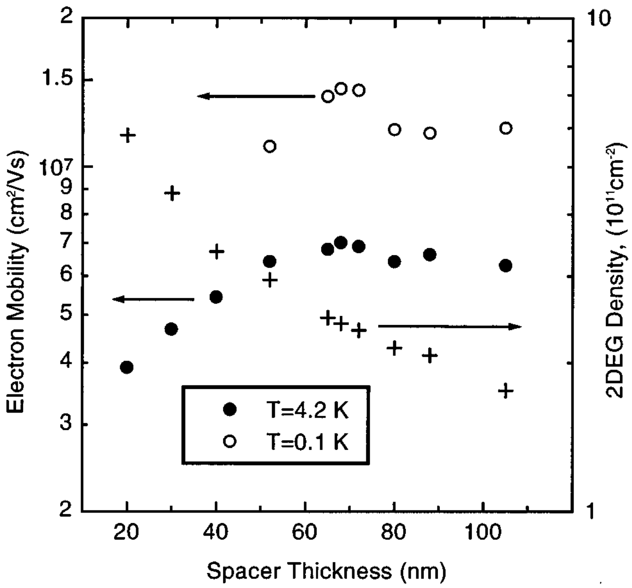

FIG. 2. Mobility (circles) and density (crosses) of 2DEG, measured in the dark after illumination, as a function of spacer thickness. The mobility, measured at two different temperatures, is shown for several structures.

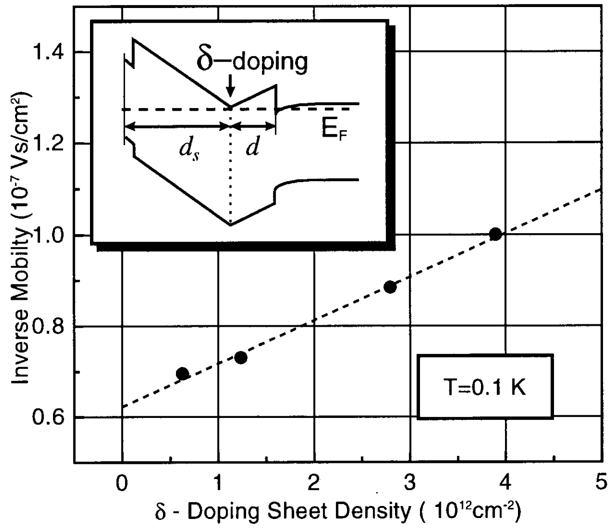

FIG. 3. Inverse electron mobility (points), measured at 0.1 K in the dark after illumination, for 2DEG samples with different δ-doping sheet density. The dashed line represents the best linear fit to the data. The inset shows schematically the band gap diagram of the selectively doped structures used in this experiment. In all structures d was fixed at 72 nm while d_s was varied from 25 to 180 nm.

Moreover, in contrast to the 3 in. heater, where the mobility saturates after approximately 130 μm of GaAs is grown, the 2 in. heater provides a weak but continuous increase of the mobility until complete As cell depletion. These results confirm that contamination from the As ingot are as important as those resulting from the substrate heater. Yet, our record mobility obtained with the 3 in. diam heater, being 4.7 $\times 10^6$ cm^2/Vs at 4.2 K and 8.3$\times 10^6$ cm^2/Vs at 0.3 K, is the highest reported for such a configuration. Hereafter, we describe only the 2DEG structures fabricated using the 2 in. diam heater.

We studied the effect of *spacer* thickness (undoped AlGaAs layer separating the doped region from the 2DEG) on the mobility and density of the 2DEG (see Fig. 2). All structures have a buffer layer composed of a 30 period GaAs/$Al_{0.37}Ga_{0.63}As$ superlattice followed by a 1.5 μm undoped GaAs layer grown at ~645 °C using a growth rate of 0.5 μm/h near the GaAs/AlGaAs interface. An $Al_{0.37}Ga_{0.63}As$ layer, some 30–300 nm thick, follows, with one or two δ-doped Si sheets inserted into it. The As_4-to-Ga beam equivalent pressure ratio was ~10. The dependence of the 2DEG density on spacer thickness agrees with previous works[3,5] and fits well Poisson's equation solution using the conduction band discontinuity $\Delta E_c \approx 0.67 \Delta E_g$. The mobility increases monotonously as the samples are cooled to about 0.8K and saturates thereafter, exceeding 10^7 cm^2/Vs for a spacer thickness in the range of 50–100 nm. The highest mobility $(14.4 \pm 0.2) \times 10^6$ cm^2/Vs, was measured at 0.1 K in a single δ-doped structure with a doping concentration of 6.3 $\times 10^{11}$ cm^{-2}, a 68 nm spacer thickness, a 250 nm total depth of the 2DEG from the surface and a 2DEG density of 2.4$\times 10^{11}$ cm^{-2}, measured after illumination. Note that the carrier concentration was determined via Hall measurement (4$\times$4 mm^2 *van der Pauw squares* or 0.8$\times$3.2 mm^2 *Hall bar* configurations, with currents below 100 nA) and verified via Shubnikov-deHaas (SdH) magnetoresistance oscillations. Absence of parallel conduction was confirmed by verifying that the longitudinal resistance in the integer quantum Hall regime drops to zero. Interestingly, in all our high mobility samples, we observe a negative magnetoresistance with a pronounced longitudinal resistance minimum at ~500 G. This effect is currently not understood since neither finite size effects nor weak localization can account for such a magnetic field. We have used the zero field resistance to calculate the mobility.

The dominant scattering mechanisms at low temperatures are: remote ionized (RI) donors, unintentional background impurities (BIs) in GaAs and the AlGaAs spacer, and interface roughness (IR). Phonon scattering is negligible at 0.1 K. If all remote parent donors, with density N_{RI}, separated by spacer d from the 2DEG are positively ionized (thus, no donor correlation[10]), the RI scattering rate is expected to scale linearly with N_{RI} and with $1/d^{2.5}$ for large spacer thickness.[7] For a given BI density the mobility grows with the 2DEG density as $\sim n_s^{0.8}$ (due to screening).[9] The IR scattering rate scales with electric field at the interface, namely, with n_s.[6,11] The inverse mobility can be expressed via a Mathiessen rule $\mu^{-1} = \mu_{\mathrm{RI}}^{-1} + \mu_{\mathrm{BI}}^{-1} + \mu_{\mathrm{IR}}^{-1}$.

In order to study the relative contribution of RI scattering we measured a set of *single δ-doped* heterostructures, all with a spacer thickness $d = 72$ nm, but with different donor densities (inset of Fig. 3). The doping (N_{RI}) and distance to the surface (d_s) were carefully chosen to establish nearly full donor ionization after illumination (due to Fermi level pinning at the surface), but still provide the same equilibrium density of the 2DEG (as we increase N_{RI} we decrease the distance to the surface to ensure full donor ionization). As seen in Fig. 3 we find a linear dependence of the inverse mobility on donor concentration, with a maximum extrapolated intrinsic mobility (for $N_{\mathrm{RI}} \rightarrow 0$) of $(1.6 \pm 0.1) \times 10^7$ cm^2/Vs and RI limited mobility that fits

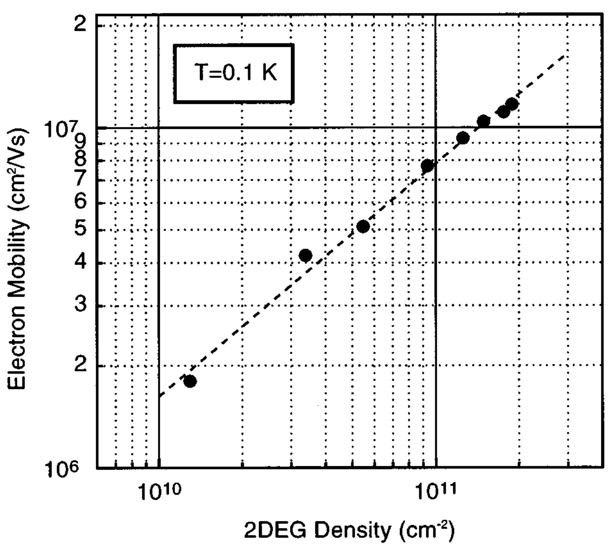

FIG. 4. Dependence of the mobility on the 2DEG density measured in the dark at 0.1 K. 2DEG carrier density was varied via a controllable illumination by an infrared light emitting diode relying on persistency of the effect. The dashed line represents the best power law fit to the data.

$\mu_{\mathrm{RI}} \approx (1.1\times 10^8)\times(10^{12}/N_{\mathrm{RI}})$ cm^2/Vs. In the best structures, with $N_{\mathrm{RI}} \approx 6\times 10^{11}$ cm^{-2}, one finds the remote donors to be responsible for merely $\sim$10% of the scattering rate.

Changing the 2DEG density in a single device might help in distinguishing between BI and IR scattering. To minimize remote donor scattering, which also depends on the carrier density, we carried out these measurements on a structure with a relatively thick (85 nm) spacer and 0.1 K mobility of 11.8×10^6 cm^2/Vs (in such structures RI scattering contributes $\sim$5% to the scattering rate). Figure 4 shows the dependence of the mobility on 2DEG density varied by a controllable infrared illumination. The mobility exhibits a monotonous growth $\mu \propto n_s^{\alpha}$ with $\alpha \approx 0.68$. This dependence agrees well with previous observations[3] and with theoretical predictions for background impurity dominant scattering,[9] rather than interface roughness scattering. In turn, IR scattering is usually associated with an anisotropy of the mobility along the $[\bar{1}10]$ and $[110]$ directions.[11,13] Indeed, we observed such an anisotropy which can be as high as 40% in 2DEG structures grown at lower temperatures and/or with too high an As_4 flux. In such samples the mobility versus density dependence generally saturates at high 2DEG densities. In contrast, in our best 2DEG structures, with mobility exceeding 10^7 cm^2/Vs at 0.1 K, we find only 5%–10% anisotropy, suggesting the contribution of interface roughness is small.

Evidently, in our best 2DEGs, mobility is still limited by background impurities ($\sim$90% of the scattering rate), while the remote donor scattering rate accounts for only $\sim$10%. A further increase of electron mobility is thus possible, both by improving the efficiency of the substrate heater and by utilizing a purer As source. Optimization of the heterostructure and inducing spatial correlation among charged donors is also expected to increase the mobility.

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