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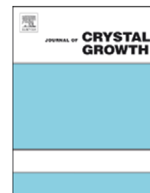

MBE growth of ultra-low disorder 2DEG with mobility exceeding $35\times10^6\,cm^2/V\,s$

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ABSTRACT

Two-dimensional electron gas (2DEG) in AlGaAs/GaAs heterostructures, grown by molecular beam epitaxy (MBE), has been a favorite template for numerous research in a field of quantum physics during last several decades. While in the early stages the main efforts were devoted to fabricate extremely high-mobility 2DEG by concentrating on the purity of the grown material, nowadays it became clear that the further progress in the field requires new approaches of heterostructures design and the growth procedure. Here we report on the MBE growth of AlGaAs/GaAs heterostructures using a short-period superlattice (SPSL) doping instead of the more standard n-AlGaAs doping. Such doping process allows the use of a low AlAs mole fraction spacer which, in turn, leads to a lower background of impurities as well as a better interface quality. Mobility exceeding $35\times10^6\,cm^2/V\,s$ was measured in samples with doping introduced on both sides of a quantum well (QW) where the 2DEG was imbedded in. Most importantly the SPSL doping allows introducing "correlations" between ionized donors and allows controlling the potential disorder landscape that governs the appearance of various fractional quantum Hall states.

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1. Introduction

Since the introduction of the concept of modulation doping by Dingle et al. in 1978 [1], the high-mobility two-dimensional electron gas (2DEG) AlGaAs/GaAs system has served as a favorite playground for extensive research in the field of quantum transport and mesoscopic physics. Interestingly, this system still exhibits the highest low-temperature electron mobility among numerous other heterostructure materials. Conventionally, the 2DEG is formed near the interface between a high-purity GaAs channel and an AlGaAs barrier (AlAs mol-fraction 30–40%) with a doping layer (uniform or 'delta'-doped) in the AlGaAs separated from the 2DEG by an undoped layer of AlGaAs (*spacer*). When the AlAs mol-fraction exceeds some 22%, as customarily done, silicon enters either as a substitutional, shallow donor, which donates an electron and remains positively charged, or as an interstitial impurity, deep within the energy gap, so-called DX center that is negatively charged [2]. Such deep level leads to freeze-out of free electrons in the donor layer at cryogenic temperatures, allowing a stable operation of numerous quantum devices that are defined by biased metallic gates patterned on the surface (quantum point contacts, quantum dots, etc.). However, due to the large binding energy of the electrons in the DX centers, the charge transfer efficiency (from the donors to the 2DEG) for a given spacer thickness is rather poor. Alternatively, illumination of the sample at low temperatures increases persistently the 2D electron density (by exciting electrons from the DX centers to shallow donor states); hence, the mobility also increases. However, in the absence of freeze-out the excited electrons that are being captured in the donor layer may create a 'parallel conducting' channel, which often leads to unstable and hysteretic effects when biasing metallic top-gates.

In this study, we report on developing of an alternative doping scheme in AlGaAs/GaAs modulation-doped structures, which allows obtaining both extremely high electron mobility without illumination and facilitating the fabrication of mesoscopic devices with relatively stable gate behavior. We also report our finding on the correlation between the classical transport parameters (electron mobility and low-field quantum scattering time) and the disorder landscape, which governs the appearance of fragile fractional quantum Hall states, particularly the $\frac{5}{2}$ state that has become recently a hot issue in quantum physics due to its predicted non-abelian statistics [3,4].

2. Experiment

Our modulation-doped GaAs/AlGaAs structures were grown in a Riber 32 MBE system on GaAs (1 0 0) substrates at a growth rate of about 0.8 μm/h (for GaAs). The substrate temperature was 630–640 °C except for the growth of doping layers where it was

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480 °C in order to prevent silicon dopant segregation or diffusion toward the 2DEG channel. In contrast to conventional modulation-doped structures, where doping is done in the AlGaAs barrier layer, we 'delta doped' a thin GaAs layer being a part of a short-period GaAs/AlAs superlattice (SPSL) placed 90 nm below the surface. Such doping scheme was first proposed by Baba et al. [5] in 1983, later used in cryogenic transistors [6], and further modified by Friedland et al. [7,8] in high-mobility 2D structures. The main idea is based on separating the Si atoms from the AlAs containing layers, thus preventing the formation of DX centers [9]. Confining the doping in a thin quantum well (QW) quantizes and raises the electron energy and thus allows a better charge transfer to the 2DEG. Moreover, the parameters of the SPSL are so chosen to make it type II superlattice [10], namely, the ground state in the AlAs wells (X_z-minima, where z stands for growth direction) is lower than that (Γ minimum) in the GaAs wells. Consequently, the excess electrons that reside in the AlAs layers, being heavier than those in GaAs by a factor of ~3 [8], do not normally participate in the conduction process. Two different SPSL regions were grown: 6 ML AlAs–9 ML GaAs and 7 ML AlAs–10 ML GaAs (ML stands for monolayer), both leading to similar results. Note that the surface charges were separately compensated by adding a uniform doped $Al_{0.34}Ga_{0.66}As$ layer near the surface. The AlAs mole fraction was gradually decreased from 34% at the surface, throughout the spacer layer, to 20–25% near the 2DEG, in order to minimize the interface roughness and to decrease the aluminum cell temperature during the growth of the pure GaAs channel (Fig. 1). Note that the charge transfer (for SPSL doping) is governed by the electron energy level inside the QW independent of the AlAs mole fraction in the spacer.

We studied two types of structures, one with a single hetero-interface doped on one side (single hetero-interface doped, SHD), and another, with the 2DEG placed in a 28–31 nm wide QW with doping on both sides of the well (double hetero-interface doped, DHD). In the DHD design the electron density for the same spacer thickness is about twice higher than in the SHD design, resulting in improved screening and, hence, much higher mobility [11]. Low-temperature measurements were performed in both Van der Pauw (VdP, $4\times4\,mm^2$) and Hall bar ($1\times2.5\,mm^2$) configurations *in the dark* without prior illumination. The effect of disorder in the 2DEG system under high magnetic field was monitored by measuring the longitudinal magnetoresistance of the fractional quantum Hall states at 10–20 mK.

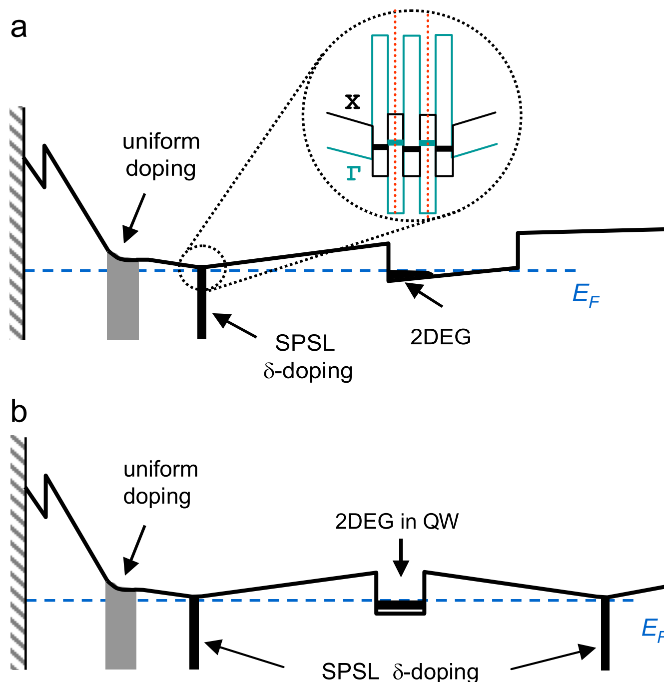

Fig. 1. Schematic diagram of the conduction band profile in single heterointerface-doped (SHD) (a) and in double heterointerface-doped (DHD) (b) structures. Magnification of the X and Γ band alignment in the AlAs/GaAs short-period superlattice (SPSL) of type II is shown in the inset. The red dashed lines mark the position of the silicon δ-doping.

3. Experimental results and discussion

Fig. 2 shows the low-temperature electron mobility as a function of the 2D electron density (n_s), in both SHD and DHD structures with spacer thicknesses d ranging from 60 to 100 nm. For the sake of comparison, some results for 2DEG with conventional doping (DX centers) were included as well. The mobility values were averaged between the $[1\bar{1}0]$ and $[110]$ directions (in the SPSL samples the anisotropy was below 10%). The highest mobility, measured in the SPSL samples at a temperature around 0.36 K, was $36\times10^6\,cm^2/V\,s$ in a DHD structure and $24\times10^6\,cm^2/V\,s$ in a SHD structure.

In Fig. 3, we show the longitudinal magnetoresistance around one of the most fragile fractional filling factors measured in two samples with different mobilities. While the 2DEG with the lower mobility exhibits pronounced zeros at $\nu=\frac{7}{3}$, $\frac{5}{2}$ and $\frac{8}{3}$, the higher mobility 2DEG has only non-zero minima. Similar behavior was observed in large number of samples. These results are not really surprising since, for instance, Sajoto et al. [12] already showed in 1990 that features of fractional quantum Hall effect (FQHE) states in their samples were as clearly evident as in samples with 3–5 times higher low-field mobility (described in Ref. [13]). However, no explanation of that poor correlation between mobility and FQHE features had been provided. Moreover, for decades the low-temperature mobility has been used on countless occasions to quantify disorder in the 2DEG.

The results of this work clearly underline that it is not possible to predict the quality of FQHE states from the electron mobility alone. To explain this behavior we measured the relative contributions of the two main scattering mechanisms that limit the mobility: the unintentional background (BG) charged impurities in the channel (N_{BG}) and the remote ionized (RI) dopants

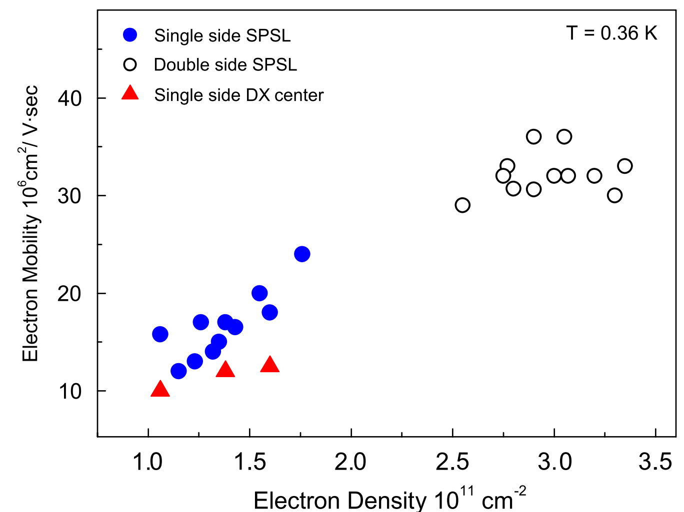

Fig. 2. Low-temperature (<300 mK) mobility measured in the dark at different electron densities and for different doping schemes. Note the almost two-fold increase in mobility for DHD structures compared with SHD structures with similar spacer thickness.

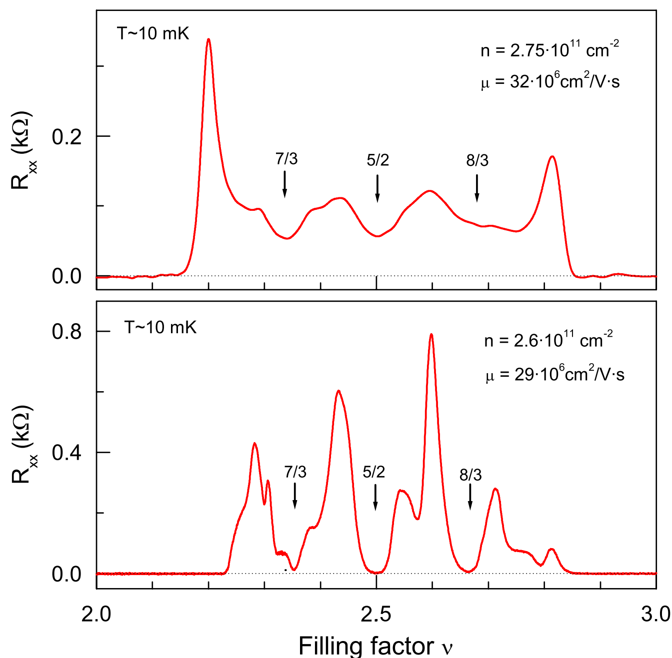

Fig. 3. Longitudinal resistance in the FQHE regime around filling $\frac{5}{2}$ measured on a Hall bar at $T = 10$ mK without prior illumination of the sample. The strength of the three fractional quantum states (namely, the minima in the longitudinal resistance) at fillings $\frac{7}{3}$, $\frac{5}{2}$ and $\frac{8}{3}$ served as a measure of the quality of the 2DEG.

(N_D) in the modulation-doped layers. Phonon scattering can be neglected at $T < 1$ K. Since RI scattering can be expressed as $\mu_{RI} \sim d^3 n_s^{1.5} N_D^{-1}$ (d stands for spacer thickness and n_s for 2DEG density) [14], it is possible to quantify relative contribution of RI scattering using the method first developed in Ref. [15]. Fig. 4 shows the dependence of the inverse electron mobility as a function of RI dopant density in a SHD structure with 80 nm spacer with a 2DEG sample grown as shown in Fig. 1 together with two test structures grown without surface charge compensating n-$Al_{0.34}Ga_{0.66}As$ layer and, thus, higher SPSL doping concentration. In these test structures the doping (N_D) and distance to the surface were chosen to establish nearly full donor ionization but still provide the same equilibrium density of the 2DEG. The extrapolation of the linear fit in Fig. 4 allows us to find maximum BG-limited mobility $\mu_{BG} \approx 16.5 \times 10^6\,cm^2/V\,s$ and hence to estimate the contribution of the RI scattering to be at most ~15%. This experiment clearly demonstrates that even in very high-purity structures the dominant scattering mechanism is that by background impurities whose concentration may be estimated as $\sim 1 \times 10^{13}\,cm^{-3}$, with a corresponding average distance between scattering centers ~500 nm. On the other hand, the RI impurities produce a weak disorder landscape with a characteristic correlation length determined by the spacer thickness (d~60–100 nm), which mostly contributes to small angle scattering. Thus, the absence of a clear correlation between the electron mobility and the quality of FQHE features may suggest that, despite the smaller amplitude of the disorder landscape due to the RI donors, its shorter correlation length produces a stronger impact on the FQHE.

To prove further this assumption, we studied the evolution of FQHE fractions as a function of disorder introduced by RI impurities. As discussed before, the SPSL doping scheme allows excess X-electrons in doping layer without facing a severe "parallel conduction" problem. We define γ as the ratio between the actual doping density and the minimum doping (N_D^{min}) that is determined experimentally to provide the equilibrium density of the 2DEG. In the over-doped samples Coulomb interactions are expected to introduce correlations among the ionized donors, and hence to modify the disorder potential experienced by electrons in the 2DEG. In samples with a large spacer the influence of 'ordering' among the ionized donors can be strong even for moderate over-doping.

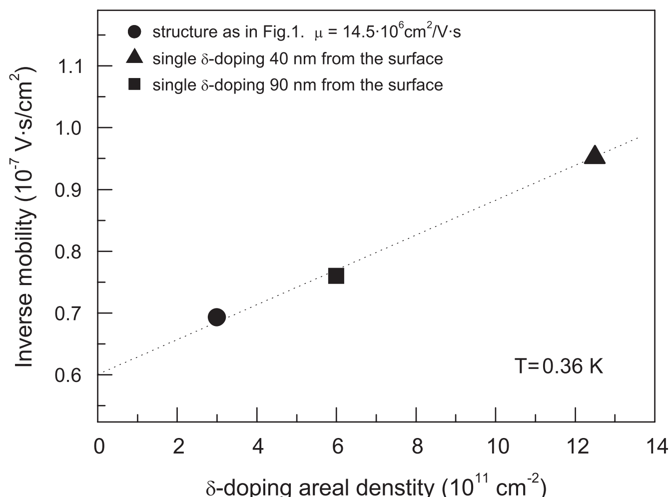

Fig. 4. Inverse electron mobility (points), measured at 0.36 K in the dark for 2DEG samples with fixed 80 nm spacer and with different δ-doping sheet density. The dashed line represents the best linear fit to the data.

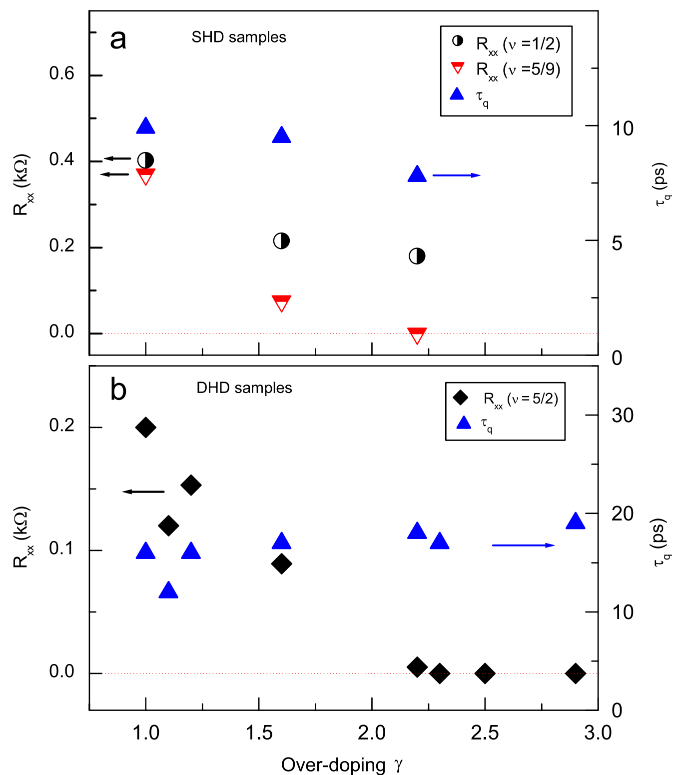

Fig. 5. The longitudinal resistance at filling factors $\frac{1}{2}$ and $\frac{5}{9}$ (a) or $\frac{5}{2}$ (b), and the quantum lifetime (a and b) as a function of over-doping at 10 mK. (a) Data for SHD samples and (b) DHD samples.

To illustrate the effect of over-doping Fig. 5a shows the dependence of the longitudinal magnetoresistance on γ at $\nu = \frac{1}{2}$ and at $\nu = \frac{5}{9}$ FQHE states in SHD structures with electron densities $n_s \sim 1.2 \times 10^{11}$–$1.4 \times 10^{11}\,cm^{-2}$. Similarly, Fig. 5b illustrates how the magnetoresistance evolves with γ at $\nu = \frac{5}{2}$ in DHD structures with densities $n_s \sim 2.5 \times 10^{11}$–$3.1 \times 10^{11}\,cm^{-2}$. The trend is unequivocally

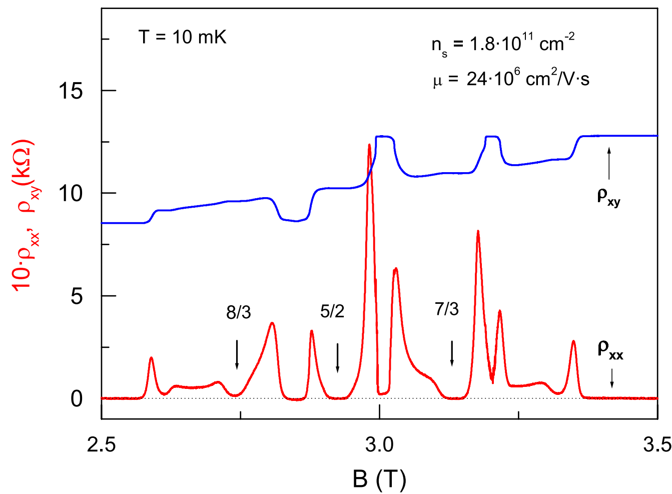

Fig. 6. Hall and longitudinal resistance measured without prior illumination of the SHD sample at $T = 10\,\text{mK}$ in a four terminal configuration in a Hall bar. The three main fractions, $\frac{8}{3}$, $\frac{5}{2}$ and $\frac{7}{3}$, are highlighted.

clear. Increased over-doping drastically reduces the minima in the longitudinal magnetoresistance. The mobility, however, is barely affected by over-doping (not shown). The same holds for the quantum lifetime, which was plotted as a function of over-doping in Fig. 5.

Note that DHD structures are not a must for obtaining fragile fractions such as the $\frac{5}{2}$ FQHE state. Employing the over-doping scheme in a SHD structure with a spacer thickness of 64 nm allowed the observation of clear plateaus in the Hall resistance and corresponding zeros in the longitudinal resistance at $\nu = \frac{7}{3}$, $\frac{5}{2}$ and $\frac{8}{3}$ at fields as low as 3 T (see Fig. 6).

4. Conclusions

In summary, using careful bandgap engineering and an unconventional approach for modulation doping in a short-period superlattice, low disorder 2DEG exhibiting well-developed fragile FQHE states were obtained. The samples allowed the fabrication of relatively stable quantum point contact devices [4]. The technique improved considerably the properties of both single interface 2DEG as well as double side-doped QW structures. However, neither the low-field mobility (as high as $36 \times 10^6\,\text{cm}^2/\text{V s}$) nor the quantum lifetimes (around 15 ps) were found to be relevant parameters that predict the quality of the FQHE states. Experiments in which the amount of over-doping was altered suggested that the disorder landscape generated by the RI impurities affects strongly the appearance of the FQHE.

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