Spatial correlation of ionized donors and its effect on scattering time and spin splitting in a two-dimensional electron gas

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We study the effect of spatial correlation of ionized donors on the single-particle scattering time and on spin splitting in a two-dimensional electron gas (2DEG). As the correlation is being reduced we observe a reduction in the scattering time and a collapse of the spin-splitted peaks into a single peak. We find these electronic properties to be much more sensitive than the momentum relaxation time (or mobility) in high mobility 2DEG. We compare our results with *Monte Carlo* simulations and find them to be in partial agreement. [S0163-1829(97)01223-X]

A two-dimensional electron gas (2DEG) is usually characterized by its electron's scattering times: the momentum relaxation time, τ_t, related to the mobility, $\mu = e\tau_t/m$, with e and m the electron's charge and effective mass, respectively; and the single-particle scattering time, τ_s, associated with the quantum lifetime (the time between two successive scattering events). In selectively doped structures these times can be very long ($\tau_t \sim 10^{-10}$ s, $\tau_s \sim 10^{-12}$ s) due to the spatial separation, via a *spacer* layer, between the parent donors, situated in the doped $Al_xGa_{1-x}As$ layer, and the 2DEG in the undoped GaAs. In high-purity material, and spacers thinner than some 30-nm, Coulomb scattering from the remote donors dominates scattering.[1] For a random distribution of ionized donors scattering times are inversely proportional to a donor density.[2] A comparison with experiments reveals, however, that the random impurity model is inadequate since predicted times are smaller than measured ones. Spatial correlation among ionized donors was proposed by Efros[3,4] as a mechanism that can substantially enhance scattering times in the 2DEG. Initial evidence by Colderidge[5] followed by a detailed experimental study by Buks *et al.*[6,7] showed indeed that correlation among donors play an important role in determining the mobility of the 2DEG.

In the presence of ordered potential experienced by 2DEG electrons, i.e., a constant potential or a periodic one, scattering is absent. Deviation from such a potential, in the form of random fluctuations, for example, results in scattering. These fluctuations can be of two kinds: fluctuations in the density of donor atoms and fluctuations in their charge state. The first is determined by the growth process and cannot be affected after growth. The second exists because the Si donor in $Al_xGa_{1-x}As$ can be found in one of two main configurations: a shallow donor state, positively charged, d^+, and a deep state, negatively charged, DX^-. The later depends on the ratio between the average densities of the two donor states. When this ratio approaches unity the two species are likely to be closely spaced and the net interaction between them is strong; resulting in *short-range order*, i.e., each positive donor tends to be surrounded by negative donor species. This *short-range order* tends to compensate the short-range random position fluctuations of the donors and leads to longer scattering times.[3,4] On the other hand, in the extreme case of only one type of donor specie scattering rates are maximized and approach those predicted by simplistic model of random impurity distribution. Buks *et al.* had developed a method (to be described later) to control donor's correlation in a *single* device by manipulating the ratio between the densities of d^+ and DX^- states. They measured the low-temperature (1.4-K) mobility as a function of the two donor species density ratio, or the resulting correlated potential, at different densities of 2DEG with a given spatial distribution of donors. The mobility was found to increase by up to a factor of six in a single structure and for the same 2DEG density as the correlation gets stronger. Based on their results they developed a model linking correlation between ionized donors and the measured mobility and found good agreement.

High-quality 2DEG systems are usually characterized by their low-temperature mobility, $\mu \geq 10^6$ cm^2/V s. The high mobility is achieved because the GaAs host material is very pure and large spacers between the donors and the 2D electrons are being utilized, suppressing these Fourier components of the scattering potential with momentum, $\mathbf{q}$, larger than $1/d$, where d is the spacer width.[1] Hence, the effect of short-range correlated fluctuations is also suppressed and the mobility is a less sensitive gauge to measure them. In such cases the effect of donor correlation on both the quantum time, τ_s, and spin level broadening (at higher magnetic fields) might be more profound. This was done by measuring the Shubnikov–de Haas (SdH) effect in high mobility samples. While τ_s affects the envelope of SdH oscillations at low B,[8] level broadening at higher B leads to a critical filling factor, ν_c, at which spin-splitted peaks collapse into a single peak in a form resembling a phase transition. Such a collapse was predicted to take place when disorder is large enough to induce a reduction of the electron-electron exchange enhancement that is contributing to the g factor.[9] Unlike the mobility, which is affected only by large $\mathbf{q}$'s, both τ_s and ν_c are expected to be affected by all $\mathbf{q}$ values of the scattering potential.

In our experiment two different kinds of 2DEG samples were used, both patterned in the form of Hall bars. One sample had planar or δ doping in the $Al_xGa_{1-x}As$ (Refs. 10 and 11) and the other had a uniformly doped, 30-nm-wide,

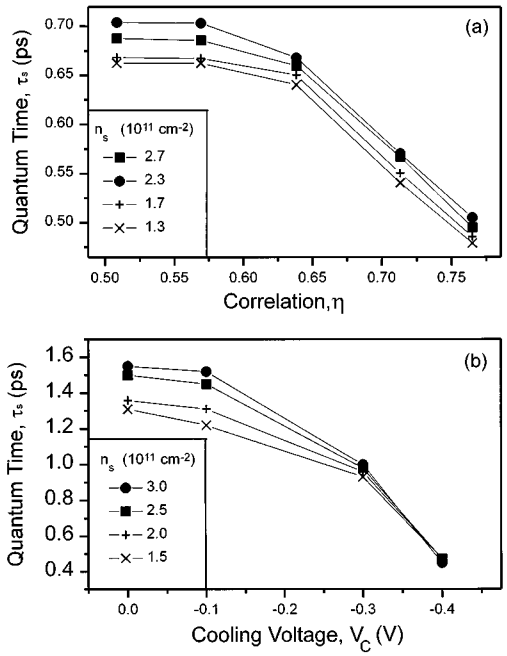

FIG. 1. Single-particle scattering time, τ_s, as a function of correlation for different densities of 2DEG, for the δ-doped sample (a), and for the uniform doped sample (b).

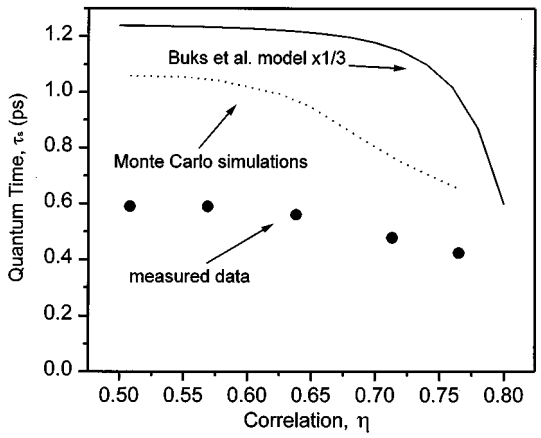

FIG. 2. Measured and predicted τ_s's based on the Buks *et al.* theory and on *Monte Carlo* simulations as a function of the correlation parameter η. The data are for 2DEG density $n_s = 2.7 \times 10^{11}$ cm^{-2}.

$Al_xGa_{1-x}As$ layer. In both samples the undoped $Al_xGa_{1-x}As$ spacer layer was a 30 nm wide ($x \cong 0.37$). Control over the ratio of the densities $n(d^+)/n(Dx^-)$ and over the density of the 2DEG, n_s, was achieved by using an evaporated metallic gate covering the whole sample. The configuration of charged donors was controlled via a similar method to that developed by Buks *et al.*[6,7] The sample was warmed to above the *freezing temperature*, T_f (about 130 K; a critical temperature below which every occupied Si donor is in a DX^- state. The negatively charged DX^- state is a metastable state which cannot be affected by an applied voltage at $T < T_f$. An applied fixed gate voltage, V_C during the cool down process, as the temperature is being reduced from $T > T_f$ to $T < T_f$ determines the ratio $n(d^+)/n(DX^-)$ at low temperature. The more negative V_C the larger is this ratio. At $T < T_f$, having a fixed $n(d^+)$ and $n(DX^-)$, the voltage applied to the same gate, now named V_g, is being used to control capacitively only n_s (with no free carriers in the $Al_xGa_{1-x}As$ layer).

Shubnikov–de Haas measurements are performed by measuring, via a four terminal configuration, the longitudinal resistance, ρ_{xx}, as a function of magnetic field B at 300 mK. According to established theory[8] the envelope of these oscillations is proportional to $\exp[-\pi/\omega_c\tau_s]$, where $\omega_c = eB/m$ is the cyclotron frequency. Using Dingle plots[5] we extract τ_s from our data. We define a measure of the correlation in the δ-doped sample via the dimensionless parameter $\eta = [n(d^+) - n(DX^-)]/[n(d^+) + n(DX^-)]$. In principal, the values of η lie in the interval $[-1,1]$; however, experimentally η cannot be negative. When $\eta = 0$ the correlation is the strongest and it decreases as $\eta \to 1$. In the uniformly doped sample the disorder is characterized by the *cooling voltage* V_C ($\leqslant 0$), since a unique η cannot be calculated (it varies with distance from the 2DEG. The calculation of η in the δ-doped sample is done like in Refs. 6 and 7. We measure the 2DEG electron density, n_s, as a function of the gate voltage, V_g, and find the depletion voltage, V_D [where $n_s(V_D) = 0$]. Knowing V_D we use the Poisson equation to find the net charge density in the δ-doped layer which is then used to calculate η.

We find τ_s, in Figs. 1(a) and 1(b), to be weakly dependent on n_s with a significant drop when the correlation has been eliminated. The change in τ_s is much larger in the uniform doped sample since both the correlation and the ''effective spacer,'' separating the randomly distributed d^+-layer from the 2DEG, decrease. In order to explain quantitatively the behavior of τ_s in the δ-doped sample we initially used the model developed by Buks *et al.*[6,7] Using this formulation we calculated the dependence of τ_s and the mobility on η for $n_s = 2.7 \times 10^{11}$ cm^{-2} and found both to be much higher than the measured experimental results (solid line in Fig. 2). As seen, the calculated τ_s is six times higher than the measured one while the measured mobility is $\mu_{\text{measured}} = 2 \times 10^6$ cm^2/V s versus the predicted one $\mu_{\text{predicted}} = 18 \times 10^6$ cm^2/V s for the strongest correlation. For samples with a thin spacer,[6,7] where mobility is lower, the agreement between theory and experiment is very good. Since the discrepancy might result from use of a *continuous model*, we calculated τ_s using *Monte Carlo* simulations of the donor distribution in the δ-doped donor layer, as was done by Van der Wel *et al.*[12] The results plotted in Fig. 2 (dotted line) indeed are in much better agreement with the experimental data. The remaining discrepancy (of up to a factor of two) might result from not accounting for possible scattering from unintentional impurities in the $Al_xGa_{1-x}As$ spacer layer or due to the damage caused to the 2DEG during the fabrication process.

We now describe the effect of correlation on the broadening of the Landau levels, consequently affecting spin splitting of the Landau levels. The longitudinal magnetoresistance at high magnetic field, $\rho_{xx}(B)$, is shown for the two

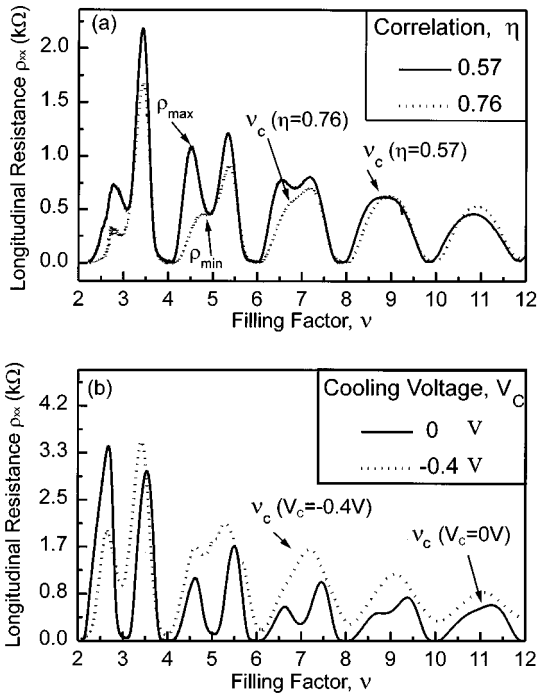

FIG. 3. The longitudinal resistance, ρ_{xx}, for δ-doped (a) and uniform doped (b) samples as a function of the filling factor, ν, for the two extreme cases of correlation. The parameters used to define the *visibility*, $\rho_{\max}$ and $\rho_{\min}$, are indicated. The position of the critical filling factor, ν_c, when spin splitting collapses is also indicated.

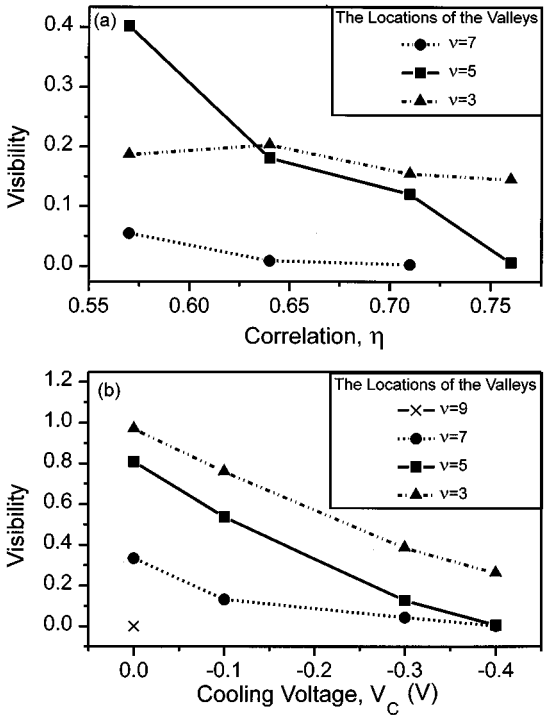

FIG. 4. The *visibility* as function of the correlation is plotted for the two samples, the δ-doped sample (a), and the uniform doped sample (b). The different filling factors point to different valleys of ρ_{xx}.

samples in Fig. 3, as a function of filling factor ν (the num-ber of filled Landau levels) at a given density ($n_s = 2.7 \times 10^{11}$ cm^{-2}). We show two extreme cases of correlations, $\eta = 0.57$ and $\eta = 0.76$ for the δ-doped sample [Fig. 3(a)], and $V_C = 0$ and $V_C = -0.4$ V for the uniform doped sample [Fig. 3(b)]. In the ''ordered'' systems ($\eta = 0.57$ or $V_C = 0$ V) the peaks in ρ_{xx}, at a given ν, are narrower than those in the ''disordered'' systems ($\eta = 0.76$ and $V_C = -0.4$ V). Similarly, as qualitatively expected, the collapse of spin-splitted peaks into one peak occurs in the ''ordered'' systems at larger ν values ($\nu_c = 10$ in the uniform doped sample and $\nu_c = 8$ in the δ-doped sample) than in the ''unordered'' systems ($\nu_c = 6$ and $\nu_c \cong 7$). We compare our results with the ones predicted by Fogler and Shklovskii.[9] They calculate ν_c using a parameter n_i which is the amount of uncorrelated donors. This parameter cannot be measured experimentally but the ratio between two n_i's, representing different amounts of correlation, can be approximated by the inverse ratio of the respective quantum times. We thus infer $\nu_{c2}/\nu_{c1} = (n_{i1}/n_{i2})^{\alpha} \cong (\tau_{s2}/\tau_{s1})^{\alpha}$, with $\alpha = 0.39$ for the δ-doped sample. These values of α agree well with the predicted value $\alpha = 0.33$ calculated by Fogler and Shklovskii[9] for a δ-doped sample having the same range of mobilities and densities as in our samples.

Since the energy broadening of the peaks is difficult to measure (the magnetic field varies along each peak), we define a *visibility* as $(\rho_{\max} - \rho_{\min})/(\rho_{\max} + \rho_{\min})$, where $\rho_{\max}$ is the value of ρ_{xx} at the maximum of the spin up peak and $\rho_{\min}$ is the value of the valley between two peaks associated with the same Landau level. One expects a greater *visibility* as correlation gets stronger. Indeed, as shown in Fig. 4, the *visibility* as a function of the disorder for different filling factors shows this effect. The increase of the *visibility* with magnetic field (or $1/\nu$) is expected since the energy separation between two successive spin levels is proportional to the magnetic field. Zero *visibility* indicates the collapse of spin splitting (see Fig. 3). The δ-doped sample exhibits unexpected behavior at $\nu = 3$, contrary to the behavior of τ_s. The decrease in the *visibility* is accompanied by a development of a large asymmetry between the spin-up and spin-down peaks[13] [Fig. 3(a)], making the *visibility* not necessarily a unique characterizing parameter. We also note that the collapse of the spin splitting occurs rather abruptly around $\nu = \nu_c$; this resembles a kind of phase transition.[9]

In conclusion, we have shown that the correlation among charged donors can affect the single-particle scattering time, τ_s, by a factor as large as three. The experimental results were found to be in partial agreement with theoretical prediction based on *Monte Carlo* simulations. We find that spin-splitted peaks collapse at a higher filling factor for a highly correlated sample, and the critical filling factors are related to τ_s via $\nu_{c1}/\nu_{c2} = (\tau_{s2}/\tau_{s1})^{\alpha}$, with $\alpha \sim 0.3$ close to the predicted result.[9]

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