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-split 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.

A two-dimensional electron gas (2DEG) is usually characterized by its electron’s scattering times: the momentum relaxation time, $\tau_m$, related to the mobility, $\mu = e\tau_m/m$, with $e$ and $m$ the electron’s charge and effective mass, respectively; and the single-particle scattering time, $\tau_s$, associated with the quantum lifetime (the time between two successive scattering events). In selectively doped structures these times can be very long ($\tau_s \approx 10^{-10} \text{ s}$, $\tau_m \approx 10^{-12} \text{ s}$) due to the spatial separation, via a spacer layer, between the parent donors, situated in the doped Al$_x$Ga$_{1-x}$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 Coldridge\(^5\) 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$_x$Ga$_{1-x}$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, $\mu \approx 10^6 \text{ cm}^2/\text{V s}$. 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, $q$, 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, $\tau_s$, 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 $\tau_s$ affects the envelope of SdH oscillations at low $B$,\(^8\) level broadening at higher $B$ leads to a critical filling factor, $v_F$, 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 $q$’s, both $\tau_s$ and $v_F$ are expected to be affected by all $q$ 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 $\delta$ doping in the Al$_x$Ga$_{1-x}$As (Refs. 10 and 11) and the other had a uniformly doped, 30-nm-wide,
Al$_x$Ga$_{1-x}$As layer. In both samples the undoped Al$_x$Ga$_{1-x}$As spacer layer was a 30 nm wide ($x \approx 0.37$). 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$_x$Ga$_{1-x}$As layer).

Shubnikov–de Haas measurements are performed by measuring, via a four terminal configuration, the longitudinal resistance, $R_{xx}$, 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 $\tau_s$ from our data. We define a measure of the correlation in the $\delta$-doped sample via the dimensionless parameter $\eta = [n(d^-)-n(DX^-)]/[n(d^-)+n(DX^-)]$. In principal, the values of $\eta$ lie in the interval $[-1,1]$, however, experimentally $\eta$ 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 $V_C$ ($\ll 0$), since a unique $\eta$ cannot be calculated (it varies with distance from the 2DEG. The calculation of $\eta$ in the $\delta$-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 $\delta$-doped layer which is then used to calculate $\eta$.

We find $\tau_s$, 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 $\tau_s$ 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 $\tau_s$ in the $\delta$-doped sample we initially used the model developed by Buks et al.$^{6,7}$ Using this formulation we calculated the dependence of $\tau_s$ and the mobility on $\eta$ 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 $\tau_s$ is six times higher than the measured one while the measured mobility is $\mu_{measured}=2 \times 10^6$ cm$^2$/V s versus the predicted one $\mu_{predicted}=18 \times 10^6$ 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 $\tau_s$ using Monte Carlo simulations of the donor distribution in the $\delta$-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 scarring from unintentional impurities in the Al$_x$Ga$_{1-x}$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

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**FIG. 1.** Single-particle scattering time, $\tau_s$, as a function of correlation for different densities of 2DEG, for the $\delta$-doped sample (a), and for the uniform doped sample (b).

**FIG. 2.** Measured and predicted $\tau_s$'s based on the Buks et al. theory and on Monte Carlo simulations as a function of the correlation parameter $\eta$. The data are for 2DEG density $n_s=2.7 \times 10^{11}$ cm$^{-2}$. 
samples in Fig. 3, as a function of filling factor \( \nu \) (the number of filled Landau levels) at a given density \( n_s = 2.7 \times 10^{11} \text{ cm}^{-2} \). We show two extreme cases of correlations, \( \eta = 0.57 \) and \( \eta = 0.76 \) for the \( \delta \)-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 \( \rho_{xx}^\text{min} \), at a given \( \nu \), 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-split peaks into one peak occurs in the “ordered” systems at larger \( \nu \) values (\( \nu_c = 10 \) in the uniform doped sample and \( \nu_c = 8 \) in the \( \delta \)-doped sample) than in the “unordered” systems (\( \nu_c = 6 \) and \( \nu_c \approx 7 \)). We compare our results with the ones predicted by Fogler and Shklovskii. They calculate \( \nu_c \) using a parameter \( n_s \), which is the amount of uncorrelated donors. This parameter cannot be measured experimentally but the ratio between two \( n_s \)’s, representing different amounts of correlation, can be approximated by the inverse ratio of the respective quantum times. We thus infer \( \nu_{c2}/\nu_{c1} = (n_{s1}/n_{s2})^{\alpha} = (\tau_{s1}/\tau_{s2})^{\alpha} \), with \( \alpha = 0.39 \) for the \( \delta \)-doped sample. These values of \( \alpha \) agree well with the predicted value \( \alpha = 0.33 \) calculated by Fogler and Shklovskii for a \( \delta \)-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 \( (\rho_{xx} - \rho_{xx}^\text{min})/(\rho_{xx} + \rho_{xx}^\text{min}) \), where \( \rho_{xx} \) is the value of \( \rho_{xx} \) at the maximum of the spin up peak and \( \rho_{xx}^\text{min} \) 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 \( \delta \)-doped sample exhibits unexpected behavior at \( \nu = 3 \), contrary to the behavior of \( \tau_s \). The decrease in the visibility is accompanied by a development of a large asymmetry between the spin-up and spin-down peaks \( \nu_{c1}/\nu_{c2} = (\tau_{s1}/\tau_{s2})^{\alpha} \), with \( \alpha \approx 0.3 \) close to the predicted result.

In conclusion, we have shown that the correlation among charged donors can affect the single-particle scattering time, \( \tau_s \), 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-split peaks collapse at a higher filling factor for a highly correlated sample, and the critical filling factors are related to \( \tau_s \) via \( \nu_{c1}/\nu_{c2} = (\tau_{s1}/\tau_{s2})^{\alpha} \), with \( \alpha \approx 0.3 \) close to the predicted result.

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