Increase in the low-temperature mobility of 2D electrons by constant exposure to light

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A theory which explains the increase in the low temperature mobility of a 2D electron gas in a GaAs/AlGaAs heterostructure as a result of a continuous exposure to light, which was observed in Ref. 1 [A. S. Plaut, I. V. Kukushkin, K. von Klitzing, and K. Ploog, Phys. Rev. **B42**, No. 6 (1990), in press] is derived.

The mobility of the 2D electron gas was observed in Ref. 1 to increase appreciably as a result of a continuous exposure of the structure to light; at the same time, the density of the 2D electron gas was found to decrease. Upon exposure of the structure to light the mobility exceeds the dark mobility by a factor of 5–10, while the density of

2D electron decreases by a factor of 2–3. Such a density dependence of the low-temperature mobility of the 2D electron gas is highly unusual since the mobility generally increases with increasing density of the 2D electron gas. This increase is due, on the one hand, to the increasing Fermi velocity and, on the other, to the increase in the screening of the scattering potential by the 2D electrons. The increase in the mobility observed in Ref. 1 due to the decrease in the density of the 2D electron gas can occur only if this decrease is accompanied by a considerable decrease in scattering which can exceed the factors mentioned above. It is clear that if the mobility is determined by the scattering by phonons, by the irregularities of the interface of GaAs/AlGaAs, or by the scattering by the irregularities of a solid solution, then the effect of these scatterers does not change upon reduction of the density of the 2D electron gas. If, on the other hand, the mobility is limited by the scattering by charged impurities, the electrons which escape from the 2D electron gas can migrate to these impurities and if these impurities are donors, then they can be made neutral. In this case, the scattering will decrease and the mobility will increase.

In the case of scattering by charged impurities, the mobility will increase.

In the case of scattering by charged impurities, the mobility of 2D electrons is given by the expression[2,3]

$$\mu^{-1} = \frac{2\pi m e^2}{\kappa^2 \hbar^2} \int_0^{2\pi} d\vartheta \int_{-\infty}^{\infty} dz \frac{e^{-2qz}}{(q+q_s)^2} N_i(z) F^2(q)(1-\cos(\vartheta)), \tag{1}$$

where m is the effective mass of 2D electrons, κ is the dielectric constant which is assumed to be the same in GaAs and AlGaAs, $N_i(z)$ is the concentration of the scattering impurities at a distance z from the plane of the 2D electron gas, $q = 2k_F \sin(\vartheta/2)$, $k_F = \sqrt{2\pi n_s}$ is the Fermi wave vector, and q_s is the reciprocal screening radius of the 2D electron gas, given by

$$q_s = \frac{2me^2}{\kappa^2 \hbar^2}.$$

The form factor $F(q)$ depends on the wave function of the 2D electrons. We used a variational Feng–Howard[4] wave function. The expression for the form factor corresponding to this wave function is given in Refs. 2, 4, and 5. It can be seen from expression (1) that a decrease in the impurity concentration N_i cannot adequately explain the effect observed in Ref. 1, since even if all the electrons which have escaped from the 2D electron gas will neutralize the charged scattering impurities, their concentration will decrease linearly with decreasing density of the 2D electron gas, n_s. The mobility, on the other hand, will be proportional to k_F^3, and hence, to $n_s^{3/2}$. The mobility can, however, increase when the density of the 2D electron gas decrease if the electrons which escape from the 2D channel populate its nearest donors, and if the average distance between the 2D electron gas and the charged donors is increased. Expression (1) shows that the mobility depends exponentially on the distance between the scattering centers and the 2D electrons. The mobility can therefore increase as the density of 2D electron gas decreases.

The arguments given above allow us to formulate the following model which describes the mobility of the 2D electron gas in heterostructures which were studied in Ref. 1. The electron mobility in a 2D channel at low temperatures is determined by the scattering by charged impurities. The impurity concentration is different in different regions of the structure: GaAs has a depletion region with an acceptor concentration $N_a \propto 2\text{–}5\times 10^{14}$ cm^{-3} in the immediate vicinity of the heterojunction and hence the 2D electron gas. An undoped spacer layer, whose residual concentration of donors, N_{sp}, may reach $10^{15}\text{–}10^{16}$ cm^{-3}, comes in contact with the heterojunction on the side of the solid solution AlGaAs. Then we have a strongly donor-doped region with a concentration $N_d \propto 10^{17}\text{–}10^{18}$ cm^{-3}. The thickness of the spacer layer s in the samples used in Ref. 1 is 250 Å. After the application of the initial light pulse, which causes the electrons to be transferred from the donors in AlGaAs to the 2D electron gas, the mobility is determined primarily by the scattering of closely spaced residual impurities in the spacer layer. The structure is then exposed to light which produces electron–hole pairs in AlGaAs. The electrons and holes are separated near the heterojunction: The holes recombine with the 2D electron gas, whose concentration decreases, while the electrons neutralize the charged donors. Some of the electrons in this case are captured by the donors, which are situated in the spacer layer, while the remaining electrons migrate to the strongly doped region of the structure. The electrons captured by donors we denote by P_s.

The mobility in the described model was calculated from Eq. (1) with a concentration $N_i(z)$ equal to that found in darkness:

$$N_i^d(z) = \begin{cases} N_d, & -\infty < z < -s \\ N_{sp}, & -s < z < 0 \\ N_a, & 0 < z < W_{depl} \end{cases},$$

and that found that after exposure to light:

$$N_i^l(z) = \begin{cases} N_d - \delta n_2, & -\infty < z < -s \\ N_{sp} - \delta n_1, & -s < z < 0 \\ N_a, & 0 < z < W_{depl} \end{cases}.$$

Here the z axis is directed at right angles to the heterojunction, the origin of the scale $z = 0$ is in the plane of the 2D electron gas, W_{depl} is the thickness of the depleted layer in GaAs, which is related to the density of the space charge (per unit area) N_{depl} by the relation

$$W_{depl} = N_{depl}/N_a,$$

and δn_1 and δn_2 are the change in concentration of the charged donors in the spacer layer and in the strongly doped AlGaAs, respectively. They are related to the decrease in the density of the 2D electron gas, δn_s, by the relation

$$\delta n_1 = P_s \delta n_s / s,$$

$$\delta n_2 = (1 - P_s)\delta n_s / h,$$

$$h = (n_s + N_{depl})/N_d.$$

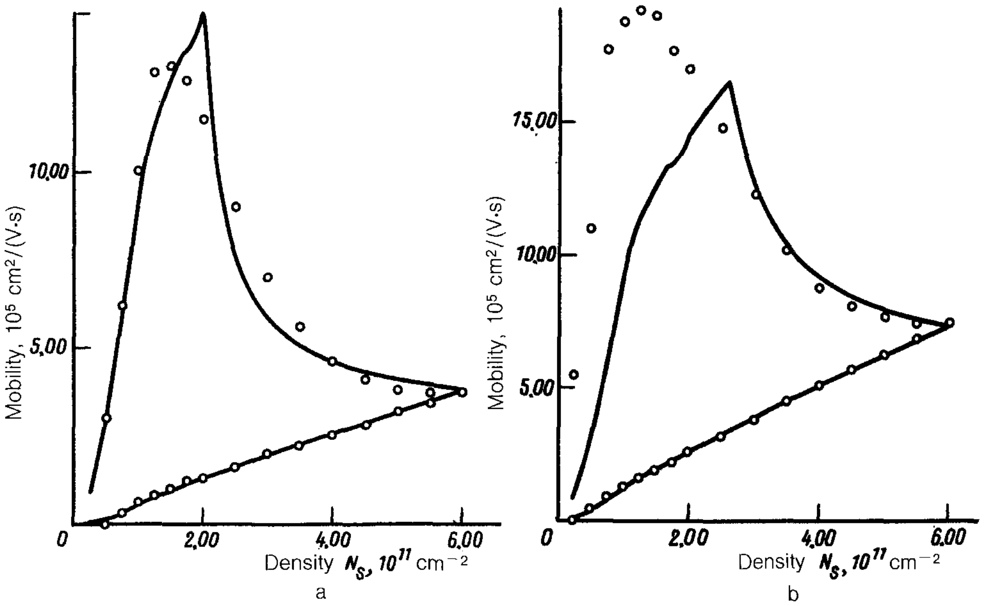

FIG. 1. Mobility of 2D electrons versus their density. Lower branch—The plot obtained in darkness; upper branch—the plot obtained upon exposure to light. Solid line—calculation result; O—experimental data.[1] The parameters of the samples are shown in the text.

mechanism for the suppression of magnetism by the superconductivity should be discussed, however, only when the nature of high-T_c superconductivity is understood.

The results of calculation of the mobility are shown in Fig. 1, which is a plot of the mobility versus the density of the 2D electron gas in darkness (lower branch) and when exposed to light (upper branch) for two samples which were used in Ref. 1. In the calculation we used the following parameter values; $s = 250$ Å, $N_a = 2\times10^{14}$ cm^{-3}, and $N_{\rm depl} = 3\times10^9$ cm^{-2} (Ref. 1). The remaining parameters were found from the best fit of the theory to the experimental data: (a) $N_{sp} = 8.1\times10^{16}$ cm^{-3}, $P_s = 0.5$ and (b) $N_{sp} = 3.8\times10^{16}$ cm^{-3}, $P_s = 0.24$. We see that the results of the calculations are in good agreement with the experiment. The discrepancy stems primarily from the assumption that the electrons, which neutralize the donors, are distributed uniformly.

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