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Anomalous photomagnetoresistance effect in modulation-doped AlGaAs/GaAs heterostructures

S. Luryi
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

A. Kastalsky
Bell Communications Research, Murray Hill, New Jersey 07974

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A novel negative photoresistance effect at $Al_{0.3}Ga_{0.7}As$/GaAs interface in the presence of a magnetic field B is discovered and explained. At low temperatures ($T = 4.2$ K) illumination of the sample leads to a persistent electron accumulation in the GaAs channel (the well-known persistent photoconductivity effect). In the presence of $B \gtrsim 0.3$ T the dependence of the longitudinal resistance (as measured by the four-probe method) shows an anomalous behavior in that the resistance increases sharply with the increasing concentration n of carriers provided by light. In the same range of concentrations the longitudinal resistance at fixed n is proportional to B^2. It is shown that the observed behavior of the resistance is associated with photoexcitation of electrons from donor vacancy (DX) centers in the highly doped AlGaAs region resulting in the creation of a second conducting layer of high charge density and low mobility.

Modulation-doped AlGaAs/GaAs heterojunction structures possess a number of remarkable properties at low temperatures. Electrons transferred from donors in the heavily doped AlGaAs layer form a two-dimensional gas in the GaAs channel at the heterojunction interface. Because of the physical separation of the channel from ionized donors and also because of the high Fermi velocity of electrons in the two-dimensional channel, the electron mobility at the interface is exceptionally high.[1–3] Another peculiarity of this system is the persistent photoconductivity effect (PPC) arising under illumination at $T \lesssim 100$ K.[1–5] Two distinct mechanisms contribute to the PPC. One of these mechanisms is photogeneration of electrons and holes in GaAs and their subsequent separation by the electric field at the interface.[4,5] For the present work more important, however, is the other mechanism[1–3] which consists in the following. It is well known that typical shallow donors in AlGaAs form a deep level complex (called the DX center) with As vacancies.[6] Electrons photoexcited from the DX centers remain in the conduction band for a long time because their recapture by ionized donors is impeded by a potential barrier. In the presence of a heterojunction , these free electrons move into the GaAs channel (through alloyed contacts), and manifest themselves in the PPC.

In the present work we investigate the PPC effect in the presence of a magnetic field. It is shown that photoexcitation of DX centers can result in the formation of a second conducting layer in AlGaAs. The presence of such a layer which has a high electron density per unit area but a low mobility, brings about new photomagnetoresistance effects.

Experiments were carried out using molecular beam epitaxially (MBE) grown structures identical to those studied in Ref. 5. A pure GaAs buffer layer 1 μm thick on a semi-insulating, Cr-doped GaAs substrate is followed by an undoped $Al_{0.3}Ga_{0.7}As$ spacer layer (of thickness d varying from 60 to 190 Å) and a 500-Å Si-doped (2×10^{18} cm^{-3}) $Al_{0.3}Ga_{0.7}As$ layer. The measurements were done at liquid helium temperatures using Hall bridges. All samples showed consistently similar results with the only difference being in the initial electron concentration in the channel—determined by the spacer thickness. Below we present the typical data obtained for samples with $d = 190$ Å.

Most of the results were obtained by illuminating the sample through a silicon filter placed in the helium dewar in the proximity of the sample. This filter cuts off photons with energies above 1.35 eV and thus prevents electron-hole generation in bulk GaAs while ensuring maximum photoexcitation of silicon DX centers in AlGaAs.[6] Each measurement

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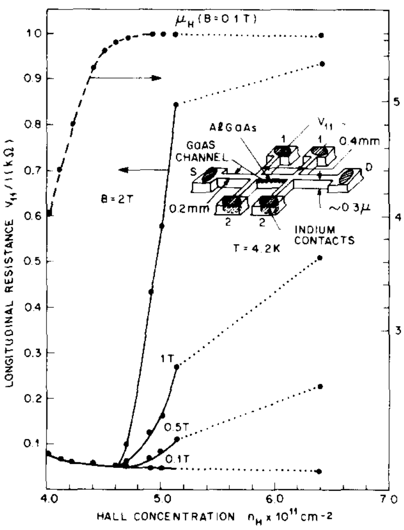

FIG. 1. Longitudinal resistance $r \equiv V_{11}/I$ (solid lines) and Hall mobility μ_H (broken line) as function of the Hall concentration n_H provided by illumination through a silicon filter. Additional data obtained by white-light illumination are indicated by dotted lines. Insert shows the sample geometry.

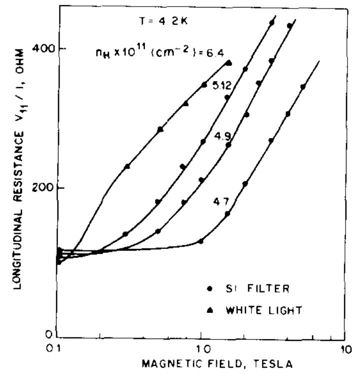

FIG. 2. Longitudinal resistance r against magnetic field B for different n_H. The curves represent an average over Shubnikov–de Haas oscillations.

was performed 1–2 min after the illumination which allowed the system to relax to a new quasi-equilibrium state characterized by the new persistent value of the Hall concentration n_H (per cm^{-2}) measured at $B = 0.1$ T.

Figure 1 shows the dependence of the longitudinal resistance $r \equiv V_{11}/I$ (where V_{11} is the voltage drop between the Hall bridge probes) as a function of the Hall concentration n_H at different magnetic fields. Solid lines correspond to n_H produced by illumination through the silicon filter. Additional points at $n_H = 6.4 \times 10^{11}$ cm^{-2} were obtained with white-light illumination.

The low magnetic field curve ($B = 0.1$ T) shows a weak monotonic decrease of the resistance corresponding to the increasing mobility μ_H from 450 000 cm^2/Vs at $n_H = 4.0 \times 10^{11}$ cm^{-2} to 560 000 cm^2/Vs at $n \approx 4.6 \times 10^{11}$ cm^{-2}. Further increase of the concentration does not enhance the mobility.

The situation is altered dramatically in higher magnetic fields. In the low-concentration region $n_H \lesssim 4.6 \times 10^{11}$ cm^{-2} the resistance remains unchanged, while at higher electron densities the resistance experiences a sharp rise (negative photoresistance). In this region r is linear with n_H and the slope $\partial r / \partial n_H \propto B^2$. The highest n_H obtained with Si-filtered light was 5.2×10^{11} cm^{-2}; upon reaching this point further illumination brought no change in the Hall parameters. Higher values of n_H were obtained by white-light illumination. The resultant points, however, do not in general, fall on the straight-line dependences, which reflects the fact that a different mechanism is involved.

Dependences of the longitudinal resistance r on the magnetic field at fixed values of n_H are shown in Fig. 2. The strong magnetoresistance effect is observed only in a certain range of B and n_H. At low concentrations (those corresponding to the rising mobility μ_H in Fig. 1) there is no effect. On the other hand, at higher concentrations $n_H \gtrsim 4.6 \times 10^{11}$ cm^{-2} (corresponding to saturated mobility) one sees a pronounced effect at $B \gtrsim 0.3$ T. For $B \gtrsim 1$ T we observe a clear quadratic dependence $r \propto B^2$. We remark that for the case of highest n_H (provided by white-light illumination) the observed dependence is rather different, $r \propto B^p$ with $p \approx 1$.

We have also measured the Shubnikov–de Haas (SdH) effect at each value of n_H provided by illumination. Typical results are presented in Fig. 3. As the concentration n_H increases into the anomalous region $n_H \gtrsim 4.6 \times 10^{11}$ cm^{-2}, the familiar oscillatory SdH curve is replaced by low-amplitude oscillations superimposed on a strong magnetoresistance curve. It should be noted that the critical n_H corresponding to the saturation of mobility and the onset of anomalous photomagnetoresistance varied from one sample to another in accordance with the initial electron concentration controlled by d.

For all samples the channel concentration after each illumination was found to be strictly independent of the magnetic field in the entire range of B and n_H, as indicated by the SdH analysis (straight lines in the dependences of the Landau numbers versus B^{-1}). The measured Hall concentration was also nearly independent (within 5%) of B for all concentrations obtained by illumination. Lowering of the temperature to 2.5 K produced no effect on the characteristics in Fig. 2. We can conclude, therefore, that no activation-type processes are involved.

In our view, all the unusual phenomena described above can be explained by a simple model which assumes that under illumination in AlGaAs appears a second conducting layer of high electron concentration and low mobility. Excitation of DX centers by Si-filtered light provides free electrons in the conduction band of AlGaAs which do not recombine with the donors but move through the alloyed indium contacts into the GaAs channel. The charging up of the channel has two consequences: firstly, it increases the potential energy of the quantum well at the interface, and secondly, it enhances the electron mobility in the channel through increasing the Fermi level E_F. The process ends when E_F coincides with the bottom of the conduction band in AlGaAs. From this point on (which defines n_{cr}) the addi-

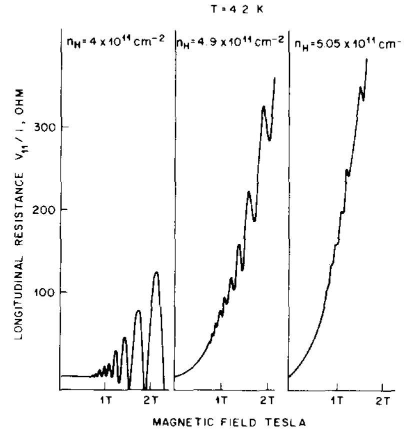

FIG. 3. Shubnikov–de Haas oscillations measured at different n_H provided by Si-filtered illumination.

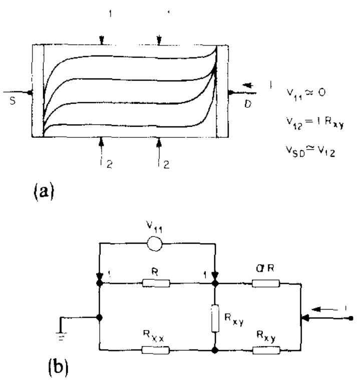

FIG. 4. Illustration of the mechanism responsible for the observed phenomena. (a) Equipotentials in a high-mobility sample placed in a transverse magnetic field; (b) equivalent circuit of the four-probe measurements in a two-layer structure.

tional illumination leads to a much slower rise in the channel concentration and a sharp rise in the free-electron concentration in AlGaAs. Further increase in the channel Fermi level occurs only in virtue of an electron degeneracy in bulk AlGaAs, which explains the mobility saturation.[5] The existence of a second conducting layer in equilibrium with the high-mobility channel has a dramatic effect on the magnetoresistance of the system, as we shall now discuss.

The longitudinal resistance R of the AlGaAs layer is much larger than that of the GaAs channel, R_{xx}. Indeed, even though the ratio of the concentration N per unit area in AlGaAs to that in the channel n is of order 10 the corresponding ratio of mobilities in 1:2000. The contribution of the second conducting layer to the Hall parameters is hence negligible,[7] so that $n_H \approx n$. It is therefore surprising that its contribution to the longitudinal resistance at higher magnetic fields becomes important.

The crux of the matter consists in the fact that in a magnetic field the high-mobility channel possesses an additional series resistance $R_{xy} = B/en$ (the Hall resistance) which can be much higher than its longitudinal resistance R_{xx}. This forces an additional fraction of the total current I to flow through the AlGaAs channel of high resistance R. The voltage drop across this resistance is recorded by the longitudinal probes. Experimentally, in the "quantum" limit $\mu B \gg 1$ (which is well satisfied in our case for $B \gtrsim 1$ T) the following two inequalities hold:

$$R \gg R_{xy} \gg R_{xx}. \tag{1}$$

As will be shown below, in the limit (1) the measured resistance $r \equiv V_{11}/I$ is given by

$$r = R_{xy}^2/\alpha R + R_{xx}, \tag{2}$$

where α is a geometrical factor of order unity. This expression explains all our results. In the absence of illumination ($R = \infty$) one measures the longitudinal channel resistance, $r = R_{xx}$. Illumination of the sample beyond n_{cr} provides free electrons in the AlGaAs layer and a finite value of R. Remaining with the limits of (1) one can have a situation where the first term in (2) becomes dominant, because of the small value of R_{xx}. Precisely this occurs in our experiments for $B \gtrsim 1$ T. In this limit it is evident that $r \propto B^2$ for a fixed R controlled by illumination, cf. Fig. 2. On the other hand, at a fixed strong magnetic field the measured resistance r is proportional to conductivity of the AlGaAs layer which explains the observed negative photoresistance.

In order to relate the variation of R to that in the channel concentration we assume for simplicity that the mobility in AlGaAs does not vary with the free-electron concentration there, N. In a simple model which takes into account both the variation of the Fermi level and the change in the electrostatic potential of the quantum well due to electron redistribution, we find

$$N = \tilde{l}(n - n_{cr})^{3/2}, \tag{3}$$

where

$$\tilde{l} = \frac{l}{3\pi^2}\left(\frac{m_2}{m_1}\right)^{3/2}\left(2\pi + \frac{2m_1 e^2 L}{\hbar^2 \epsilon}\right)^{3/2}, \tag{4}$$

l is the width of the conducting channel in AlGaAs, L is the mean separation between the two channels, and $m_1 = 0.067m_0$ and $m_2 = 0.092m_0$ are the effective masses in GaAs and $Al_{0.3}Ga_{0.7}As$, respectively. For the sample with $d = 190$ Å we have $l \approx 200$ Å, $L \approx 400$ Å, and $\tilde{l} \approx 2 \times 10^{-4}$ cm. This large value of $\tilde{l}$ accounts for the fact that small variations in n are accompanied by large increments in N. For instance, the observed maximum increase of n_H over n_{cr} by $\delta n_H \approx 5 \times 10^{10}$ cm^{-2} corresponds to $N \approx 2 \times 10^{12}$ cm^{-2}. Since $R^{-1} \propto N$, the observed superlinear behavior of the negative photoresistance (Fig. 1) is explained by Eqs. (2) and (3).

In the case of white-light illumination (points $n_H = 6.4 \times 10^{11}$ cm^{-2} in Figs. 1 and 2) the obtained relationship (3) does not hold. In this case the additional channel concentration results from electron-hole generation and separation in GaAs with holes trapped in bulk GaAs compensating the increments in both n and N.

We now return to the derivation of Eq. (2). Consider a rectangular sample with idealized source (S) and drain (D) contacts at the opposite sides, carrying a current I. It is easy to see that the total voltage drop V_{SD} can never be less than the Hall voltage IR_{xy}. Indeed, since the contacts themselves are equipotentials, the total number of equipotentials one has to cross on going longitudinally from S to D is greater than their number in any transverse section. Figure 4(a) illustrates this general topological property for our case of a very small channel resistivity. In this case the Hall angle is nearly 90°, i.e., the current flows along equipotentials, the voltage drop measured by the internal longitudinal probes is almost vanishing, $V_{11} \approx 0$, but $V_{SD} \approx V_{12} = IR_{xy}$. A similar consideration is also applicable to the second conducting layer in AlGaAs. However, the corresponding contribution to the resistance there is not important since $R \gg B/Ne$. On the other hand, in the high-mobility channel, where $R_{xx} \ll B/ne$, the series Hall resistance appears and is dominant at every contact carrying current. In particular, the internal probes represent such contacts, since the indium alloy penetrates both conducting channels (see the insert in Fig. 1). When part of the current is diverted into AlGaAs and causes a voltage drop between the internal probes, this voltage is applied to the channel again through the series Hall resistance R_{xy}.

The above arguments can be expressed by an equivalent circuit shown in Fig. 4(b). For the sake of simplicity, we have drawn it asymmetrically, placing all the series resistances on one side. The geometrical factor $\alpha \approx 2$ is determined by the ratio of the sample lengths outside and inside the interval probes 1–1. From the equivalent circuit we find

$$r = \frac{R_{xx} + R_{xy}(R_{xy} + 2R_{xx})/\alpha R}{1 + (2R_{xy} + \alpha R_{xy} + \alpha R_{xx})/\alpha R + R_{xy}(R_{xy} + 2R_{xx})/\alpha R^2}. \quad (5)$$

In the limit of $R \ll R_{xx}, R_{xy}$ (which we do not realize experimentally) we have, naturally, $r = R$. In the opposite limit, Eq. (5) reduces to (2).

To summarize, we have discovered and analyzed a new photogalvanomagnetic effect in modulation-doped AlGaAs/GaAs heterostructures. The effect occurs at low temperatures in moderate (~ 1 T) magnetic fields and consist in a strong persistent negative photoresistance. On the other hand, at a fixed persistent concentration of electrons provided by illumination, the longitudinal magnetoresistance of the sample, as measured by a four-probe method, is strong and proportional to B^2. We have shown that the observed phenomena are due to the formation under light of a second conducting layer of high electron concentration and low mobility. Even though a pronounced manifestation of the described phenomena requires the condition $\mu B > 1$, no quantum effects (such as quantization of electron energy by the magnetic field or the quantum well at interface) are important. To be sure, the dimensional quantization underlies the high channel mobility and also affects redistribution of electrons between the two layers. The main peculiarity of the AlGaAs/GaAs system we have studied lies in the possibility of creating the second conducting channel by photoexcitation of *DX* centers.

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Infrared excitation spectrum of 40.4-meV acceptor level in neutron-irradiated gallium-doped silicon

David W. Fischer and W. C. Mitchel

Air Force Wright Aeronautical Laboratories, Materials Laboratory (AFWAL/MLPO), Wright-Patterson AFB, Ohio 45433

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An infrared absorption spectrum has been obtained for the shallow A_2 acceptor level formed by neutron irradiation of Si:Ga. After a 600 °C anneal, absorption peaks were observed at 213.1, 244.9, and 286.9 cm.$^{-1}$ These peaks appear to correspond to lines 1, 2, and 4 of a group III-like acceptor spectrum originating from a ground state with a 40.4-meV binding energy. Hall effect measurements confirm the presence of an acceptor level at this energy.

Evidence for the existence of a shallow acceptor level at 40.4 meV in neutron-irradiated Si:Ga has been obtained by infrared absorption spectroscopy and Hall effect measurements. Absorption peaks are found at 213.1, 244.9, and 286.9 cm^{-1}, corresponding to lines 1, 2, and 4 of the typical group III $p_{3/2}$ spectrum [1,2] but originating from a ground state of 40.4-meV binding energy.

Neutron transmutation doping (NTD) is used as a means of homogeneously introducing phosphorus (by transmuting the ^{30}Si isotope to ^{31}P) into extrinsic *p*-type silicon photoconductor material to compensate the residual boron impurity.[3] One of the disadvantages of the NTD process is that it also causes large amounts of radiation induced defects such as vacancies, interstitials, and defect complexes in the silicon lattice. Most such defects can be removed by high-temperature (850 °C) annealing.[3] Three new shallow acceptor levels have been previously reported in neutron irradiated and annealed Si:Ga; the A_1 and A_2 acceptors at 26 and 40 meV,[4–6] and the Ga *X* center at 57 meV.[6] The A_1 and A_2 levels have only been observed in Hall effect measurements. It appears that the 40.4-meV level reported here in absorption is the same as the Hall effect A_2 level.

The samples used for the absorption experiment were cut from a gallium-doped float zone (FZ) silicon crystal grown by Westinghouse. The gallium concentration was approximately 5×10^{16} cm^{-3}. Two samples were used, each $10 \times 10 \times 2$ mm thick. One was an as-grown sample which served as a control reference for the absorption measurements. The other sample was neutron irradiated at the University of Missouri Research Reactor (MURR) at a fluence of 1.8×10^{17} neutrons cm^{-2}, then annealed at temperatures of 450, 550, and 600 °C for one hour each. Absorption spectra were recorded on a Digilab model FTS-20C Fourier transform spectrophotometer at a resolution of 1 cm^{-1} and