Pis'ma v ZhETF, vol. 77, iss. 10, pp. 681 – 685

Giant magnetoresistance oscillations caused by cyclotron resonance harmonics

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Submitted 17 April 2003

For high-mobility two-dimensional electrons at a GaAs/AlGaAs heterojunction, we have studied, both experimentally and theoretically, the recently discovered giant magnetoresistance oscillations with nearly zero resistance in the oscillation minima which appear under microwave radiation. We have proposed a model based on nonequilibrium occupation of Landau levels caused by radiation which describes the oscillation picture.

PACS: 73.40.–c, 73.43.–f

Recent observations, in high-quality two-dimensional electron systems, of microwave-stimulated giant magnetoresistance oscillations (MSGMO) [1, 2] with positions corresponding to subharmonics of the cyclotron resonance [3] and especially the discover of zero-resistance states in the MSGMO minima [4, 5] attract a great attention to this spectacular phenomenon [6 – 14]. Observation of zero-resistance states was a reason to assume [4, 5] their collective origin, like photon-stimulated superconductivity [4]. Alternative approach to explanation of zero-resistance states is based on the peculiarities of electron motion in crossed electric and magnetic fields, when electron drift along electric field can occur only as a result of scattering events. In recent preprint [7], it has been demonstrated that MSGMO with negative magnetoresistance in minima can result from transitions between broadened Landau levels caused by photon absorption and accompanied by elastic scattering on short-range scatterers. Similar effect was shown rather long ago [15] to give a sequence of photocurrent peaks of different signs for unbroadened Landau levels and nonlinear conditions with respect to electric field. For bulk semiconductors and quantising magnetic fields, photocurrent oscillations with negative conductivity in minima were predicted in Ref. [16] for δ-type photoelectron energy distribution function. A link between states with negative dissipative conductivity and the zero-resistance states was proposed in Ref. [8] (see also Ref. [11]). It implies that negative dissipative resistivity gives rise to instability in a system which finally breaks its symmetry and produces inhomogeneous states with nearly zero average resistance. This result allows to associate theoretical states with negative dissipative resistivity and the experimental zero-resistance states. The inhomogeneous states are characterized by high local current density even at zero net current through a sample. One more approach to explanation of MSGMO based on edge magnetoplasma instability was considered in preprint [13].

In this paper, we reproduce previous experimental observations [1, 2, 4, 5] of MSGMO with some additional data and compare them with our calculations, based on results of self-consistent Born approximation (SCBA), which are capable of explaining the main features of MSGMO in terms of nonequilibrium occupation of broadened Landau levels under microwave radiation. Additionally, our model predicts appearance of the second harmonic in the Shubnikov-de Haas oscillations under appropriate choice of microwave frequency and sample parameters.

We have measured a Hall bar sample with conducting channel of a L-shape. Channel width was equal to 0.2 mm, the distances between neighboring potential probes were either 0.4 or 0.6 mm. Magnetoresistance per square R_{xx} and Hall resistance R_{xy} have been measured by the standard technique exploiting the low-frequency AC current excitation and phase sensitive detection of a voltage between potential probes with the use of a Lock-in amplifier. We used the frequency 9.2 Hz and amplitude of the current 1 μA, well within ohmic regime. Results for R_{xx} and R_{xy} presented in this paper do not depend on pairs of potential probes used for measurements. The sample has been produced from a GaAs/AlGaAs wafer of the standard architecture containing a two-dimensional electron system at a single remotely doped GaAs/AlGaAs heterojunction with the spacer width about 55 nm. The most pronounced MSGMO were observed after illumination of the sample until saturation of electron density at about

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$n_s = 3 \cdot 10^{11}\mathrm{cm}^{-2}$. The corresponding mobility of electrons was $\mu = 7 \cdot 10^6\mathrm{cm}^2/\mathrm{V\,s}$. The sample was placed in the close ended rectangular waveguide of the WR-62 type with cross-section sizes 16×8 mm which entered a ^{3}He refrigerator. The two arms of the L-shaped sample were parallel to the long and the short sides of the rectangular. The microwave radiation in the frequency range 10–170 GHz was produced by a set of oscillators. The microwave power reached the low temperature end of the waveguide was estimated to be always below 2 mW. At frequencies greater than 50 GHz, transmission coefficient between oscillator output and the low-temperature part of the waveguide was rather low falling down to values of the order of 0.01.

Typical experimental data are shown in Fig.1. In the absence of microwave radiation, magnetoresistance

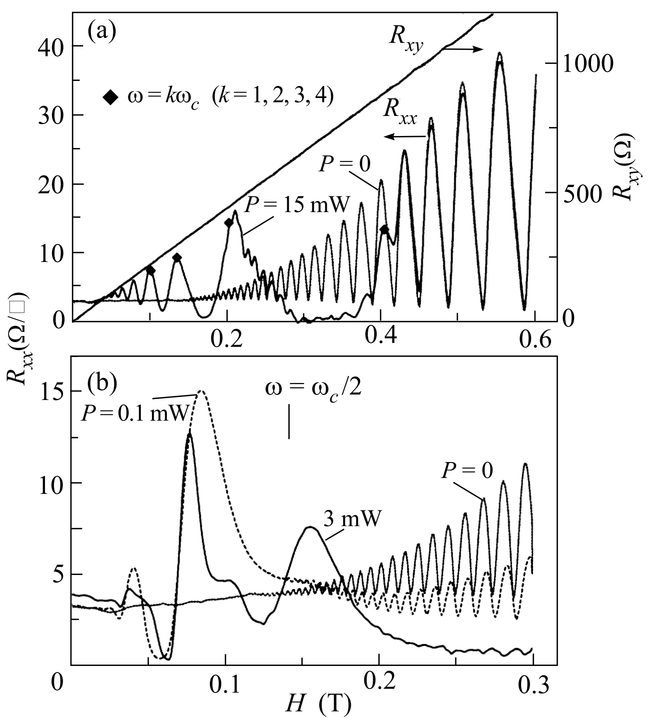

Fig.1. Magnetoresistance R_{xx}, Hall resistance R_{xy} measured with excitation current $I^{\sim} = 1\,\mu$A versus magnetic field H in the absence of microwave radiation (dotted lines) and under microwave radiation (dashed and solid lines). Data in Figs.(a) and (b) have been measured at frequencies 168 GHz and 30 GHz, respectively at temperature $T = 0.4$ K. Power P shown in Figs. corresponds to the oscillator output. Positions of magnetic fields corresponding to subharmonics of the cyclotron resonance are marked in Fig.a by diamonds. $n_s = 2.84 \cdot 10^{11}\,\mathrm{cm}^{-2}$

R_{xx} demonstrates at $H \geq 0.15$ T standard Shubnikov-de Haas oscillations periodic in the inverse magnetic field with the period determined by areal density of electrons n_s in a two-dimensional system. Corresponding oscillations in R_{xy} become visible only at magnetic fields higher than 0.4 T. Microwave radiation suppresses Shubnikov-de Haas oscillations at low magnetic fields and gives rise to new oscillations (microwave stimulated giant magnetoresistance oscillations) also periodic in the inverse magnetic field with the period determined by microwave frequency (compare Fig.1a and Fig.1b). Positions of MSGMO follow those of subharmonics of the cyclotron resonance $\omega = k\omega_c^{(k)} \equiv k\,(eH^{(k)}/m^*c)$. Here $m^* = 0.067m_e$ is the effective mass of electrons in GaAs. The main minima and maxima of MSGMO are shifted to different sides from the corresponding subharmonic. Additional weaker oscillation arises at comparatively low-frequency and high-power radiation at $\omega < \omega_c$ and can be associated with the cyclotron resonance harmonic $\omega = \omega_c/2$ (see Fig.1b). In the main MSGMO minima, the magnetoresistance can become rather close to zero (see also Refs. [4, 5]). MSGMO peaks have characteristic asymmetric triangular-like form with a steep drop at low-magnetic-field side. At the same time, the microwave radiation has practically no effect on the Hall resistance (in Fig.1a the solid R_{xy} curve measured in the presence of the microwaves is practically indistinguishable from the "dark" dotted curve).

Our calculations of magnetoconductivity tensor components σ_{xx} and σ_{xy} are based on formulas obtained within self-consistent Born approximation in the absence of Landau level mixing (see review [17] and Refs. therein):

$$D(\epsilon) = \sum_{n=0}^{\infty} \frac{2N_0}{\pi\Gamma_n}\left[1 - \left(\frac{\epsilon - \epsilon_n}{\Gamma_n}\right)^2\right]^{1/2} \equiv \sum_{n=0}^{\infty} \frac{2N_0}{\pi\Gamma_n} Z_n^{1/2}(\epsilon), \tag{1}$$

$$\sigma_{xx} = \frac{e^2}{\pi^2\hbar}\sum_{n=0}^{\infty}\left(\frac{\Gamma_n^{xx}}{\Gamma_n}\right)^2 \int\limits_{\epsilon_n-\Gamma_n}^{\epsilon_n+\Gamma_n}\left(-\frac{df}{d\epsilon}\right) Z_n(\epsilon)d\epsilon, \tag{2}$$

$$\sigma_{xy} = -\frac{n_s ec}{H} + \frac{e^2}{\pi^2\hbar}\sum_{n=0}^{\infty}\frac{(\Gamma_n^{xy})^4}{\Gamma_n^3\hbar\omega_c}\int\limits_{\epsilon_n-\Gamma_n}^{\epsilon_n+\Gamma_n}\left(-\frac{df}{d\epsilon}\right) Z_n^{3/2}(\epsilon)d\epsilon. \tag{3}$$

Here $D(\epsilon)$ is the density of states, $\epsilon_n = \hbar\omega_c(n + 1/2)$ is the energy of the n-th spin-degenerate Landau level with the width Γ_n and the total number of states on the level $N_0 = 2eH/hc$. Contributions of this level to σ_{xx} and σ_{xy} are characterized by parameters Γ_n^{xx} and Γ_n^{xy}, respectively. Our modification of Eqs. of Ref. [17] is the use of nonequilibrium distribution function $f(\epsilon)$ which would be formed, at zero temperature, as a result of direct one-photon transitions (induced and spontaneous), i.e., transitions accompanied by the energy change by $\hbar\omega$ and the nearly zero momentum variation equal to the photon momentum. We neglect all other excitation and relaxation processes. Such function can arise if the life time of a photo-excited electron is the shortest time in the problem. This condition is normally justified if the energy of this electron is less than the energy of optical phonon (see, for example, Ref. [18]), which is well fulfilled in our experiment. As can be shown, the distribution function obtained under these conditions is appropriate for calculations of the magnetoconductivity in accordance with Eqs.(2), (3).

At zero temperature, it is easy to write down condition of the steady state which relates values of the distribution function $f(\epsilon)$ at energies differing by $\hbar\omega$:

$$f(\epsilon) = \frac{\lambda f(\epsilon - \hbar\omega)}{\lambda + 1 - f(\epsilon - \hbar\omega)}. \quad (4)$$

Here parameter λ characterizes microwave intensity. This relation is applicable at non-zero densities of states $D(\epsilon)$ and $D(\epsilon - \hbar\omega)$. If $D(\epsilon) = 0$ or $D(\epsilon - \hbar\omega) = 0$ we set $f(\epsilon) = f_0(\epsilon)$, where f_0 is the Fermi distribution function at $T = 0$. Eq. (4) and condition $\int_{-\infty}^{+\infty} f(\epsilon)D(\epsilon)d\epsilon = n_s$ define nonequilibrium distribution function which was used for calculations of the conductivity. Fig.2 demonstrates that, in some ranges of energy, photon-stimulated

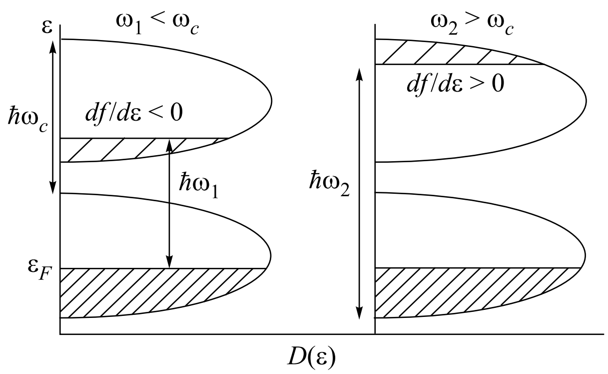

Fig.2. Schematic of the electron redistributions between two neighboring broadened Landau levels which are caused by microwave radiation of two frequencies $\omega_1 < \omega_c$ (left panel) and $\omega_2 > \omega_c$ (right panel). Partly occupied states are shaded. The lowest level contains the Fermi energy ϵ_F at zero temperature. Assumptions concerning relaxation processes are discussed in the text

interlevel transitions can give rise to inverted population of electron states ($df/d\epsilon > 0$) leading to negative contributions to the conductivity σ_{xx}. The inversion is possible only if $\omega > \omega_c$. The inverted occupation shown in the right panel of Fig.2 is obviously independent of the position of the Fermi energy on the lower level, i.e., of the filling factor of Landau levels. Our computation shows (see Fig.3) that appearance of energy regions with inverted population of broadened Landau levels can lead

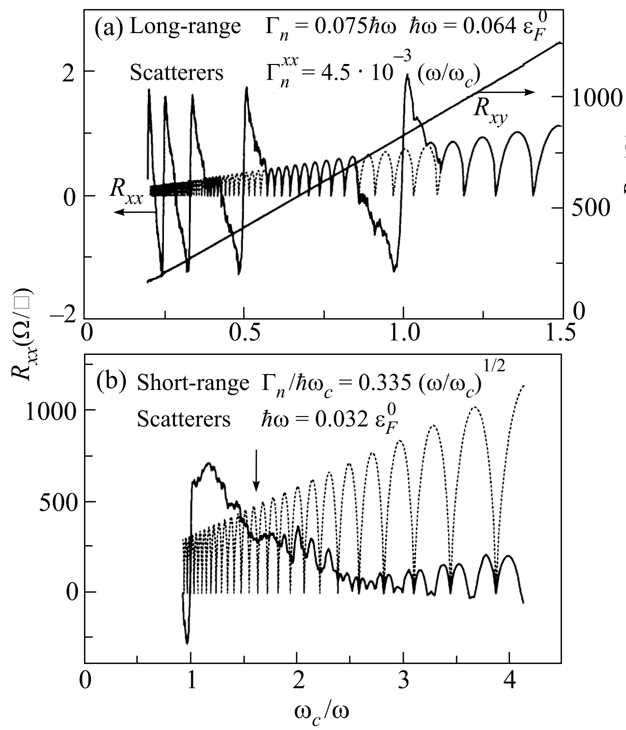

Fig.3. Calculated magnetoresistance R_{xx} and Hall resistance R_{xy} versus ratio ω_c/ω proportional to magnetic field for two very different intensities of microwave radiation, characterizing by parameter $\lambda = 1\cdot 10^{-10}$ (dotted line) and $\lambda = 2$ (solid line). The solid and dotted R_{xy} lines overlap. (a) and (b) – correspond to two limiting cases of the scatterer range, different values of the microwave frequency, and different values of Landau level width (corresponding parameters are shown in the Figure)

to the negative sign of σ_{xx} and, consequently, to the negative magnetoresistance $R_{xx} = \sigma_{xx}/(\sigma_{xx}^2 + \sigma_{xy}^2)$. We have considered two limiting cases of the short- and long-range scatterers when analytical formulas are available for dependencies of parameters Γ_n, Γ_n^{xx}, and Γ_n^{xy} on n and magnetic field [17]. For the short-range (long-range) scatterers there is only one (two) independent parameter (s). Fig.3 shows results of our calculations. To get data corresponding to the absence of radiation we have set parameter λ to very low value $\lambda = 1 \cdot 10^{-10}$. The results obtained under radiation provide MSGMO with both, form of the oscillations and their positions, in reasonable agreement with the experiment (namely, the minimum (maximum) associated with particular subharmonic lies at $\omega > k\omega_c^{(k)}$ ($\omega < k\omega_c^{(k)}$)). The main difference from the experiment is in the fact that calculated magnetoresistance in the MSGMO minima is negative. Elimination of this discrepancy lies beyond our model applicable for macroscopically homogeneous systems and could be referred to results of Ref. [8]. Additionally, there are at least two more mechanisms leading to suppression of the negative conductivity which are finite temperature and all kinds of relaxation processes. These arguments show that the calculated regions of negative magnetoresistance can be associated with the experimental minima of MSGMO. For $\omega = k\omega_c^{(k)}$ our model predicts absence of the photoresponse in magnetoresistance. But this is valid only for the two limiting cases of short-range and long-range scatterers, when the width of a Landau level Γ_n is independent of a level number n [17]. For the intermediate-range scatterers, points where $R_{xx}|_{P=0} = R_{xx}|_{P\neq 0}$ should depend on the radiation power P and be shifted from the positions of the subharmonics, which is consistent with our experimental data where these points appear always at lower magnetic fields than the corresponding subharmonics. Additional shift of these points can result from relaxation processes.

It is necessary to discuss a role of different unknown parameters which enter our model. Absolute values of Γ_n, Γ_n^{xx}, Γ_n^{xy}, and λ affect only amplitude and detailed form of the Shubnikov – de Haas oscillations and MSGMO. Neither of these parameters influences positions of the oscillations. Explanation of the experimentally established absence of the photoresponse in the Hall resistance is closely related to absolute values of parameters Γ_n, Γ_n^{xx}, and Γ_n^{xy}. Within SCBA this result appears rather naturally for the case of long-range scatterers (in Fig.3a the solid and dotted R_{xy} lines overlap) and needs very narrow Landau levels in the other limiting case. A problem arises with absolute values of the magnetoresistance even in the absence of microwaves (see also results of Ref. [7] obtained within SCBA for short-range scatterers). In comparison with experiment, SCBA gives either too high or too low values of magnetoresistance for two limiting cases of short-range and long-range scatterers, respectively. But it seems to be possible to get reasonable absolute values of the magnetoresistance together with the absence of the photoresponse in the Hall resistance for intermediate-range scatterers. Comparison of the lower limit for the range of potential fluctuations, given by the spacer width, with the cyclotron radius in magnetic fields involved shows that in our experimental conditions intermediate-range scatterers are of great importance.

Important aspect of the experimental results is existence of MSGMO in very weak magnetic fields where Shubnikov-de Haas oscillations are not observed. Obviously, appearance of MSGMO proves existence of the Landau quantization in corresponding magnetic fields. We explain absence of the Shubnikov – de Haas oscillations in these fields by inhomogeneous broadening of the oscillations picture caused by long-range carrier density fluctuations in a sample. MSGMO are much less affected by this broadening because of larger period of these oscillations measured in filling factors of Landau levels. Inhomogeneous broadening is not included in our model and Shubnikov – de Haas oscillations and MSGMO coexist at the same magnetic fields.

It is interesting to note that, in addition to MSGMO, results of our calculations describe some additional features of the experimental data. In the case of comparatively narrow Landau levels, the Shubnikov – de Haas oscillations are only slightly modified by microwave radiation at $\omega \lesssim \omega_c$ and in-between $k = 1$ minimum and $k = 2$ maximum of MSGMO (compare Figs 1a and 3a). At rather wide Landau levels, experimentally realized at weaker magnetic field, our model describes strong suppression of the magnetoresistance at $\omega \ll \omega_c$ in very good agreement with our observations (compare Figs. 1b and 3b) and leads to appearance of additional minima related to the $\omega = \omega_c/2$ harmonic (shown by arrow in Fig.3b). Note that the latter effect appears in our model without two-photon processes. Our model predicts that, for appropriate choice of Landau level width, microwave frequency and power, great second harmonic can appear in the Shubnikov-de Haas oscillation picture (in Fig 3b it occurs at $\omega_c/\omega > 2.5$).

In summary, we have shown that experimentally measured photoresponse of two-dimensional electrons on microwave radiation, including MSGMO, is consistent with our theory considering conventional magnetotransport effects under conditions of nonequilibrium occupation of electronic states.

The author is very thankful to Professor K. von Klitzing and Dr. J. H. Smet for kind opportunity to carry out the experimental part of this research in the Max-Planck-Insitut für Festkörperforschung (Stuttgart, Germany) and to Dr. V.Umansky for providing the author with nice GaAs/AlGaAs material. The author gratefully acknowledges valuable discussion with S. V. Iordansky and partial support of this work by INTAS and RFBR.

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