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Absolute negative conductivity and zero-resistance states in two dimensional electron systems: A plausible scenario

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We present a model which provides a plausible explanation of the effect of zero-resistance and zero-conductance states in two-dimensional electron systems subjected to a magnetic field and irradiated with microwaves observed in a number of experiments and of the effect main features. The model is based on the concept of absolute negative conductivity associated with photon-assisted scattering of electrons on impurities. It is shown that the main features of the effect can be attributed to the interplay of different electron scattering mechanisms.

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1. Introduction. The possibility of the states in which the dissipative electric current in a nonequilibrium electron system (a system in which a majority of electrons have negative effective mass) flows in the direction opposite to the electric field, i.e., the usual (or absolute) conductivity of the system is negative, was discussed by Kroemer in the late 50s [1]. Rather realistic mechanisms of such an absolute negative conductivity (ANC) in two- and three-dimensional substantially nonequilibrium electron systems (2DESs and 3DESs) in magnetic field were considered more than three decades ago [2 – 4]. At the same time, the mechanism of ANC in a 2DES subjected to magnetic field and irradiated with microwaves associated with impurity scattering of 2D electrons accompanied by the absorption of microwave photons was proposed by one of us [5]. It was shown that the dissipative conductivity is an oscillatory function of the ratio of the microwave frequency Ω to the electron cyclotron frequency Ω_c. At Ω somewhat exceeding Ω_c or a multiple of Ω_c, the photon-assisted impurity scattering of 2D electrons with their transitions between the Landau levels (LLs) results in a contribution to the dissipative current flowing opposite to the electric field. At sufficiently strong microwave radiation, this scattering mechanism can dominate leading to ANC when $\Omega \gtrsim N\Omega_c$, where $N = 1, 2, 3, ...$ The transformation of the dissipative current vs electric field characteristic is schematically shown in Fig.1. The effect of vanishing electrical resistance (in the Hall bar configuration) and of vanishing electrical conductance (in the Corbino configuration) in a 2DES in magnetic field irradiated with microwaves has recently been observed by Mani et al. [6], Zudov et al. [7], and Yang et al. [8]. According to Anderson and Brinkman [9], Andreev et al. [10], and Volkov and co-workers [11] suggested that this effect, i.e., the appearance of ZR-states (and ZC-states), is attributed to ANC associated with photon-assisted impurity scattering of 2D electrons (put forward in [5, 12]) and an instability of homogeneous states in a conductive media with ANC. The latter was noted by Zakharov [13] and discussed in early papers on ANC in 2DESs (see, for example, [4]). The structure of the electric-field distributions corresponding to ZR- and ZC-states arisen as a result of the instability is determined by the shape of the current-voltage characteristic (in particular, by the value of E_0) and the features of the diffusion processes. Recent experimental findings [6 – 8] have stimulated a surge of experimental (for example, [14 – 17]) and theoretical papers (for example, [18 – 24]). Preliminary brief overviews can be found in [25, 26]. In particular, the results of early theoretical studies of ANC caused by photon-assisted impurity scattering were generalized by

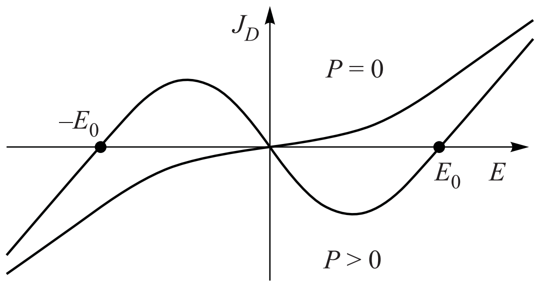

Fig.1. Schematic view of dissipative current-voltage characteristics $J_D = J_D(E)$ without ($P = 0$) and with ($P > 0$) microwave irradiation

the inclusions of the LL broadening and high microwave power effects [18 – 20]. A quasi-classical model which is valid at large filling factors and sufficiently strong electric field (or when a long-range disorder determines the dissipative current) was developed by Vavilov and Aleiner [21]. Possible role of photon-assisted acoustic phonon scattering was discussed in [22 – 24].

A theoretical model for ZR- and ZC-states should explain at least the following details observed experimentally: (a) the phase of the magnetic-field dependence of the resistance (dissipative conductivity), i.e., the positions of maxima and minima, (b) very slow dependence of the magnitude of the dissipative conductivity maxima and minima on the microwave power (tending to saturation in the range of elevated powers), (c) steep decrease in the maxima and minima magnitude resulting in vanishing of ANC and, hence, in vanishing ZR- and ZC-states with increasing temperature, and (d) relatively small magnitude of the minima and maxima in 2DESs with moderate electron mobility that makes impossible the attainment of ANC and its consequences.

In this letter, we discuss a scenario for the appearance of zero-resistance (ZR) as well as zero-conductance (ZC) states in 2DESs invoking the concept of ANC associated with photon-assisted impurity scattering complicated by electron-electron interaction and photon-assisted acoustic phonon scattering. The proposed scenario provides plausible explanations of main experimental facts.

2. ANC due to photon-assisted scattering. The effect of ANC in a 2DES system in magnetic field under microwave irradiation is associated with the following [5, 12]. The dissipative electron transport in the direction parallel to the electric field and perpendicular to the magnetic field is due to hops of the electron Larmor orbit centers caused by scattering processes. These hops result in a change in the electron potential energy $\delta\epsilon = -F\delta\rho$. Here F is the dc electric force acting on an electron which is determined by the net in-plane dc electric field including both the applied and the Hall components, and $\delta\rho$ is the displacement of the electron orbit center. If the electron orbit center displaces in the direction of the electric force ($\delta\rho > 0$ and $\delta\epsilon < 0$), the electron potential energy decreases. In equilibrium, the electron orbit center hops in this direction are dominant, so the dissipative electron current flows in the direction of the net dc electric field. However, in some cases, the displacements of the electron orbit centers in the direction opposite to the electric force (with $\delta\rho < 0$ and, hence, $\delta\epsilon > 0$) can prevail resulting in the dissipative current flowing opposite to the electric field. Indeed, if an electron absorbs a photon and transfers to a higher LL, a portion of the absorbed energy $N\hbar\Omega_c$ ($\hbar$ is the Planck constant) goes to an increase of the electron kinetic energy, hence, the change in the electron potential energy is $\delta\epsilon = \hbar(\Omega - N\hbar\Omega_c)$. If $(\Omega - N\hbar\Omega_c) > 0$, so that

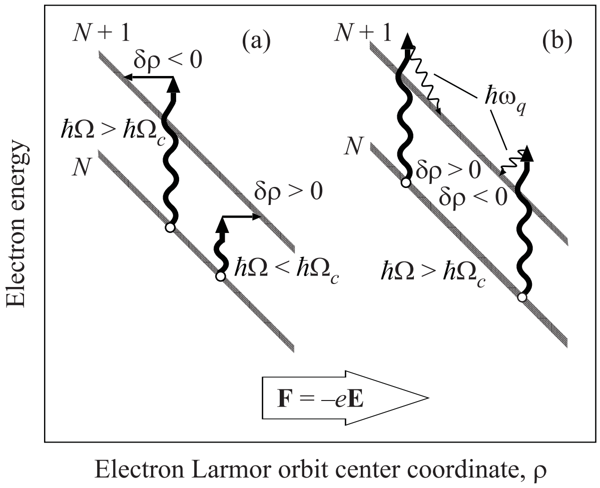

Fig.2. Inter-LL electron transitions: (a) photon-assisted impurity for both $\Omega > \Omega_c$ and $\Omega < \Omega_c$ and (b) photon-assisted acoustic phonon scattering mechanisms (only transitions for $\Omega > \Omega_c$ are shown)

$\delta\rho < 0$ (see Fig.2a), the potential energy of electrons increases with each act of their scattering.

3. Phase of the dissipative conductivity oscillations. Summarizing the results of previous calculations [5, 12, 21] (see also [20, 22]), the variation of the dissipative dc current under the effect of microwave radiation (photocurrent) can be presented as

$$J_{ph} \propto \sum_{N,M} \Theta_N I_N^M \frac{(N\Omega_c - M\Omega)}{[(\Lambda\Omega_c - M\Omega)^2 + \Gamma^2]^2} \tag{1}$$

if $FL \ll \hbar\Gamma$,

$$J_{ph} \propto \sum_{N,M} \Theta_N I_N^M (N\Omega_c - M\Omega) \exp\left[-\frac{\hbar^2(N\Omega_c - M\Omega)^2}{2F^2L^2}\right] \tag{2}$$

when $FL > \hbar\Gamma$ and $L > d_i$, and

$$J_{ph} \propto \sum_{N,M} \Theta_N I_N^M (N\Omega_c - M\Omega)\, K_0\left(\frac{|N\Omega_c - M\Omega| d_i}{v_H}\right) \tag{3}$$

when $FL > \hbar\Gamma$ and $L \ll d_i$ (smooth disorder). Here e the electron charge, Γ is the LL broadening, L is the magnetic length, d_i is the spacing between 2DES and the donor sheet, v_H is the Hall drift velocity, $K_0(z)$ is the McDonald function, and $\Theta_N = 1 - \exp(-N\hbar\Omega_c/T)$, where T is the electron temperature. Factor Θ_N is due to the contribution of scattering processes with both absorption and emission of microwave photons. Coefficients I_N^M are determined by the matrix elements of photon-assisted interaction of electrons with impurities (remote ones and those in 2DES) and surface roughness as well as by the amplitude of the ac microwave electric field $\mathcal{E}$ and the electron distribution function. As follows from (1)–(3), the microwave photocurrent reaches the maxima at $N\Omega_c - M\Omega = \Delta^{(+)}$ and minima at $N\Omega_c - M\Omega = -\Delta^{(-)}$ with $\Delta^{(+)} \simeq \Delta^{(-)} \sim \max\{\Gamma, FL/\hbar\}$. According to (1)–(3), the net dissipative current approximately coincides with its dark value at the resonances $N\Omega_c = M\Omega$. At $N\Omega_c - M\Omega = -\Delta^{(-)}$ and sufficiently strong microwave radiation (when $|J_{ph}| > J_{\rm dark}$), the net dissipative dc current $J_D = J_{\rm dark} + J_{ph}$ becomes directed opposite to the electric field resulting in the instability. This pattern of the oscillatory behavior of the microwave photocurrent is in line with qualitative reasonings in the previous section. It is consistent with the experimental results [6–8, 14–16].

As shown, the photon-assisted acoustic phonon scattering processes (see Fig.2b) also lead to an oscillatory dependence of the microwave photoconductivity. However, the phase of these oscillations is opposite to that in the case of photon-assisted impurity scattering [23, 24]. This can add complexity to the microwave photoconductivity oscillations and can even result in their suppression, particularly, at elevated temperatures (see Sec. 6).

4. Power nonlinearity. The dependence of the factor I_N^M microwave field is given by $J_M^2(\xi_\Omega)$, where $J_M(z)$ is the Bessel function and $\xi_\Omega \propto \mathcal{E}$ is proportional to the amplitude of classical oscillations of the electron orbit center in the microwave field (see, for example [19, 20]). The terms with $M > 0$ correspond to the transitions with the absorption and emission of M real microwave photons. Thus, the magnitudes of the microwave photoconductivity maxima and minima $\max\sigma_{ph}$ and $|\min\sigma_{ph}|$, where $\sigma_{ph} = J_{ph}/E$, are generally nonlinear functions of the microwave power $P \propto |\mathcal{E}|^2$. This is due to the effect of virtual photons absorption and emission on the electron scattering processes. At low microwave powers, $\max\sigma_{ph} \propto P$ and $|\min\sigma_{ph}| \propto P$. However, when $\xi_\Omega \propto \mathcal{E}$ approaches b_M, where b_M corresponds to maximum value of $J_M(z)$, the magnitude of $\max\sigma_{ph}$ fairly slow increases with microwave power P in line with experimental observations [6, 7] and others. This occurs at such powers that the amplitude of classical oscillations of the electron orbit center in the microwave field becomes of the order of L. The pertinent characteristic power $P_{\max}$ increases with Ω approximately as $P_{\max} \propto \Omega^3$ [19]. Another consequence of the nonlinear mechanism in question is that at high microwave powers the magnitudes of maxima and minima corresponding to higher resonances ($\Omega \sim N\Omega_c$ with $N > 1$) are not too small compared to those near the cyclotron resonance($\Omega \sim \Omega_c$).

Slowing down of the increase in $\max\sigma_{ph}$ and $|\min\sigma_{ph}|$ with increasing microwave power can be also associated with some heating of the 2DES. As shown below, an increase in the electron temperature leads to broadening of the LL and, consequently, to smearing of the resonances.

5. Temperature effects. As seen from (1), the microwave photoconductivity σ_{ph} markedly decreases due to the processes with emission of microwave photons. This effect becomes essential when the electron temperature increases from $T < N\hbar\Omega_c \sim \hbar\Omega$ to $T > N\hbar\Omega_c \sim \sim \hbar\Omega$. The microwave photoconductivity maxima and minima also strongly depend on the LL broadening. The latter can be rather sensitive to the temperature. In particular, at moderate microwave powers P, for the Lorentzian shape of the LLs, one obtains the following temperature dependence:

$$\frac{\max\sigma_{ph}}{\sigma_{\rm dark}} \simeq \frac{|\min\sigma_{ph}|}{\sigma_{\rm dark}} \propto P\,\frac{1 - e^{-\hbar\Omega/T}}{\Gamma^3(T)}. \qquad (4)$$

Here the dark conductivity and photoconductivity stem from the scattering processes involving inpurities, while the value σ_{ph} depends on the sharpness of the resonances and, hence, on the net LL broadening. The net LL broadening is determined by the impurity (and roughness) scattering processes and by the electron-electron interaction. The LL broadening due to electron-electron interaction steeply increases with the electron temperature. Taking into account that in the experimental situations the 2DES Fermi energy $E_F \gg \hbar\Omega_c$, one can use the following temperature dependence [27]: $\Gamma_e(T) \propto (T/E_F)^2 \ln(\sqrt{E_F Ry^*}/T)$, where Ry^* is the effective Rydberg. For $f = \Omega/2\pi = 50$ GHz, the factor associated with the emission of microwave photons in (4) reduces approximately by half with the temperature increasing from 1 K to 3–4 K. Setting $E_F = 10$ meV, we find that $\Gamma_e|_{T=3\,{\rm K}}/\Gamma_e|_{T=1\,{\rm K}} \simeq 9$. Hence, according to (4), in a 2DES with high electron mobility (in the absence of magnetic field) in which Γ is determined primarily by the electron-electron scattering so that $\Gamma \simeq \Gamma_e$, the span of the dissipative conductivity oscillations, i.e., the values $\max\sigma_{ph}$ and $|\min\sigma_{ph}|$ can decrease by several orders of magnitude when the temperature increases by a few K. However, in 2DESs with moderate electron mobility (limited, say, by residual impurities and interface roughness) in which $\Gamma_i \gtrsim \Gamma_e$, an increase in Γ with increasing temperature and, hence, a decrease in $\max\sigma_{ph}$ and $|\min\sigma_{ph}|$ can be less pronounced as confirmed by experimental data.

Since photon-assisted acoustic phonon scattering provides the microwave photoconductivity maxima and minima at $N\Omega_c \lesssim M\Omega$ and $N\Omega_c \gtrsim M\Omega$, respectively, i.e., approximately at the point where photon-assisted impurity scattering yields, on the contrary, the microwave photoconductivity minima and maxima, the former mechanism can interfere with the latter one modifying the oscillations and even effectively suppressing them. This is possible if photon-assisted acoustic phonon scattering becomes essential with increasing temperature [23, 24]. A marked intensification of this mechanism occurs when $T \gtrsim \hbar s/L = T_{ac}$, where s is the speed of sound. In the experimental situations, $T_{ac} \simeq 0.5$ K.

6. Effect of high electron mobility. Although the oscillations of microwave photoconductivity as a function of the cyclotron frequency (i.e., the magnetic field) were observed in 2DESs with the electron mobility in rather wide range, sufficiently deep microwave photoconductivity minima which can result in ANC were observed only in the samples with fairly high electron mobility. In the framework of the model under consideration, this can be explain as follows. The relative amplitude of the microwave photoconductivity oscillations is very sensitive to the LL broadening. In sufficiently perfect 2DESs with weak scattering of electrons on residual impurities immediately in the 2DES and on the interface roughness, the LL broadening is determined primarily by the electron-electron interaction. Indeed, when the electron sheet concentration Σ_e is about the sheet concentration of remote impurities Σ_i, the ratio of quantities Γ_i and Γ_e can be estimated roughly as $\Gamma_i/\Gamma_e \propto (\Sigma_i/\Sigma_e)\exp(-2d_i/L)$. The exponential factor in this formula is due a spatial separation of electrons and donors which gives rise to an exponential decrease in the matrix element of electron-impurity interaction. Hence, at $d_i > L$, one obtains $\Gamma_i \ll \Gamma_e$. In the experiments with 2DESs having high electron mobility, $d_i/L \simeq 1.4$, so that the latter exponential factor is about of 0.06. Since the electron-electron scattering processes are effectively suppressed with decreasing temperature [27], the microwave maxima and, what is more important, minima are well pronounced and can surpass the dark conductivity at low temperatures and when the microwave radiation is strong enough. This leads to ANC in some ranges of magnetic field when certain relations between Ω and Ω_c are met. In contrast, in the samples with moderate electron mobility, a significant contribution to the LL broadening is provided by residual impurities and interface roughness. This prevents the attainment of a sufficiently large ratio $|\min \sigma_{ph}|/\sigma_{dark}$ necessary for ANC.

We believe that main experimental facts on ZR- and ZC-states and related effects can be explained in the framework of the concept based on ANC caused by photon-assisted impurity scattering of electrons and affected by electron-electron and photon-assisted acoustic phonon interactions.

1. H. Kroemer, Proc. IRE **47**, 231 (1959).
2. V.I. Ryzhii, JETP Lett. **7**, 28 (1968).
3. V.F. Elesin, ZhETF **55**, 799 (1968) [Sov. Phys. JETP **28**, 410 (1969)].
4. A.D. Gladun and V.I. Ryzhii, ZhETF **57**, 978 (1969) [Sov. Phys. JETP **30**, 534 (1970)].
5. V.I. Ryzhii, Fiz. Tverd. Tela **11**, 2577 (1969) [Sov. Phys.-Solid State **11**, 2078 (1970)].
6. R.G. Mani, J.H. Smet, K. von Klitzing et al., Nature **420**, 646 (2002).
7. M.A. Zudov, R.R. Du, L.N. Pfeiffer, and K.W. West, Phys. Rev. Lett. **90**, 046807 (2003).
8. C.L. Yang, M.A. Zudov, T.A. Knuuttila et al., Phys. Rev. Lett. **91**, 096803 (2003).
9. P.W. Anderson and W.F. Brinkman, cond-mat/0302129 (2003).
10. A.V. Andreev, I.L. Aleiner, and A.J. Millis, Phys. Rev. Lett. **91** 056803, (2003).
11. F.S. Bergeret, B. Huckestein, and A.F. Volkov, Phys. Rev. **B67**, 241303 (2003).
12. V.I. Ryzhii, R.A. Suris, and B.S. Shchamkhalova, Fiz. Tekh. Poluprovodn. **20**, 2078 (1986) [Sov. Phys.-Semicond. **20**, 1299 (1986)].
13. A.L. Zakharov, ZhETF **38**, 665 (1960) [Sov. Phys. JETP **11**, 478 (1960)].
14. S.I. Dorozhkin, JETP Lett. **77**, 681 (2003).
15. S.A. Studenikin, M. Potemski, P.T. Coleridge et al., Solid State Comm. **129**, 314 (2003).
16. R.G. Mani, J.H. Smet, K. von Klitzing et al., Phys. Rev. **B69**, 161306 (2004)
17. R.L. Willett, L.N. Pfeiffer, and K.W. West, Phys. Rev. Lett. **93**, 026804 (2004).
18. A.C. Durst, S. Sachdev, N. Read, and S.M. Girvin, Phys. Rev. Lett. **91**, 086803 (2003).
19. V. Ryzhii and R. Suris, J. Phys.: Cond. Mat. **15**, 6855 (2003).
20. X.C. Lei and S.Y. Liu, Phys. Rev. Lett. **91**, 226805 (2003)
21. M.G. Vavilov and I.L. Aleiner, Phys. Rev. **B69**, 035303 (2004).
22. V. Shikin, JETP Lett. **77**, 236 (2003).
23. V. Ryzhii and V. Vyurkov, Phys. Rev. **B68**, 165406 (2003).
24. V. Ryzhii, Phys. Rev. **B68**, 193402 (2003).
25. R. Fitzgerald, Physics Today **56**, 24 (2003).
26. A.C. Durst and S.M. Girvin, Science **304**, 1752 (2004).
27. A.V. Chaplik, ZhETF **60**, 997 (1971) [Sov. Phys. JETP **33**, 997 (1971)].