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Low-Frequency Dispersion of the Effective Transverse Conductivity in Inhomogeneous Media in Strong Magnetic Field

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Abstract—On crystalline silicon specimens with a nonuniform carrier concentration distribution produced by an optical method, a dispersion of the effective transverse conductivity $\sigma_\perp^{\text{eff}}(\omega)$ is observed near the frequency $\omega \approx \omega_c = \tau_\perp^{-1} \equiv \varepsilon/4\pi\sigma_\perp^{\text{eff}}$. At $\omega < \omega_c$, an anomalous transverse effective conductivity is observed: $\sigma_\perp^{\text{eff}}(\omega)$ is greater than the transverse conductivity of a homogeneous specimen $\sigma_\perp^h(\omega)$ (in the frequency range studied in the experiment, $\sigma_\perp^h(\omega) = \text{const}$). Near $\omega \approx \omega_c$, the conductivity $\sigma_\perp^{\text{eff}}$ decreases, and, at $\omega > \omega_c$, it coincides with $\sigma_\perp^h$.

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1. In homogeneous conductors, a dispersion of the conductivity σ occurs at frequencies of the order of the inverse momentum relaxation time τ_p^{-1}. In an inhomogeneous conductor, an external electric field gives rise to local charge bunches. Near the inhomogeneities, local electric fields and gradients of the charge carrier concentration are formed, and they tend to dissipate the bunches. The characteristic time of such a bunch dissipation is the Maxwell relaxation time $\tau_M = \varepsilon/4\pi\sigma$ (ε is the dielectric constant of the material). At low frequencies, $\omega\tau_M \ll 1$ (ω is the frequency of the electric field), the effective conductivity σ^{eff} determined from the relation

$$\langle j \rangle = \sigma^{\text{eff}}(\omega)\langle E \rangle \tag{1}$$

(where $\langle j \rangle$ and $\langle E \rangle$ are the volume average values of the current density and field) is less than the average static conductivity: $\sigma^{\text{eff}}(\omega) \approx \sigma^{\text{eff}}(0) < \langle \sigma(0) \rangle$. At high frequencies, $\omega\tau_M \gg 1$ (but $\omega\tau_p \ll 1$; we assume that $\tau_M \gg \tau_p$, which is the usual case for semiconductors), a bunch has no time to form. In this case, $\sigma^{\text{eff}}(\omega) \approx \langle \sigma(0) \rangle$. For $\omega \sim \tau_M^{-1}$, a dispersion of conductivity (a low-frequency dispersion) was observed in the experiment described in [1]. The theory of this effect was developed in [2, 3].

2. In strong magnetic fields H: $\beta \equiv \mu H/c \gg 1$ (μ is the mobility and c is the velocity of light), the conductivity of a homogeneous specimen becomes highly anisotropic:

$$\sigma_{xx} \equiv \sigma_\perp \ll \sigma_{zz} \equiv \sigma_\parallel (\mathbf{H} \parallel 0z). \tag{2}$$

The Maxwell relaxation time also becomes anisotropic: $\tau_\perp = \varepsilon/4\pi\sigma_\perp \gg \tau_\parallel = \varepsilon/4\pi\sigma_\parallel$.

The dispersion of $\sigma_\perp^{\text{eff}}(\omega)$ was considered in [4] within the first approximation in the degree of inhomogeneity ξ (ξ is the ratio of the mean square fluctuation of the concentration to the mean concentration squared). A closer analysis [5] shows that at $\beta \gg 1$ the dispersion $\sigma_\perp^{\text{eff}}(\omega)$ should be observed at the frequencies

$$\begin{aligned} \omega \approx \omega_\perp &= \tau_\perp^{-1} = \frac{4\pi\sigma_\perp^{\text{eff}}}{\varepsilon}, \\ \omega \approx \omega_\parallel &= \tau_\parallel^{-1} = \frac{4\pi\sigma_\parallel^{\text{eff}}}{\varepsilon} \end{aligned} \tag{3}$$

($\omega_\perp \ll \omega_\parallel$). We note that $\sigma_\parallel^{\text{eff}} \approx \langle \sigma \rangle_{H=0}$.

3. As far as we know, so far no attempts had been made to experimentally observe the dispersion of $\sigma_\perp^{\text{eff}}(\omega)$. Presumably, this is related to two kinds of difficulties. First, it is difficult to fabricate an inhomogeneous structure of the "good semiconductor—bad semiconductor" type (see [6]). Second, the experiment requires ac measurements in a strong magnetic field in the closed Hall circuit regime, which is also quite complicated.

Meanwhile, such an experiment is of interest for the following reason. It is well known that, in a homogeneous specimen, the transverse conductivity $\sigma_\perp$ decreases with increasing magnetic field H (according to the elementary theory, $\sigma_\perp \sim \beta^{-2}$). In an inhomogeneous specimen, $\sigma_\perp^{\text{eff}}$ should decrease slower with H, namely: $\sigma_\perp^{\text{eff}} \sim \xi^{2/3}\beta^{-4/3}$ for three-dimensional inhomogeneities and $\sigma_\perp^{\text{eff}} \sim \xi\beta^{-1}$ for two-dimensional ones. This means that even for small values of ξ, in sufficiently strong magnetic fields H, the conductivity $\sigma_\perp^{\text{eff}}$ becomes greater than $\langle\sigma_\perp\rangle$, i.e., an anomalous transverse conductivity takes place (see [7] and references given there). This effect was first observed in the experiment described in [6]. An observation of the dispersion at the frequency $\omega \approx \omega_\perp$ would not only demonstrate the insignificance of inhomogeneities at high frequencies but also provide independent supporting evidence for the existence of the anomalous transverse conductivity.

4. The purpose of our experiments is to reveal the low-frequency dispersion of the effective transverse conductivity $\sigma_\perp^{\text{eff}}(\omega)$ of an inhomogeneous specimen in a strong magnetic field H. Below, we denote the transverse conductivity of a homogeneous specimen by $\sigma_\perp^h(\omega)$.

The measurements were carried out at a temperature of 4.2 K on Si : B crystalline specimens with the boron concentration $N \approx 6 \times 10^{15}$ cm^{-3} and mobility $\mu \approx 5 \times 10^4$ cm^2/V s. To obtain the closed Hall circuit regime, we used specimens in the form of a Corbino disk. A nonuniform distribution of the charge carrier concentration over the disk was formed by photoexcitation by an inhomogeneous radiation flux. A detailed description of the specimen and the method of photoexcitation can be found in [6].

The value of $\sigma_\perp$ at $\omega = 0$ and $H = 40$ kOe ($\beta \approx 20$) was about 10^{-10} Ω^{-1} cm^{-1}, which corresponds to $\tau_\perp \sim 10^{-2}$ s. Hence, the measurements were performed in the frequency band 20 s$^{-1} \le \omega \le 1000$ s^{-1}.

5. Figure 1 presents the equivalent circuit of the measuring setup. The ac voltage from the oscillator was supplied to the specimen (R_S, C_S). A load R_L was connected in series with the specimen. The voltage across the load, which was proportional to the current, was measured by a phase-sensitive voltmeter (PAR-124a). The parameters of the circuit are as follows: for the specimen, $R_S = f(H)$ and, at $H = 40$ kOe, $R_S \approx 3 \times 10^{10}$ Ω; $C_S \approx 0.4$ pF; for the load, $R_L = 10^5$ Ω; for the voltmeter, $R_V \gg R_L$; and the total capacitance is $C_V \approx 70$ pF. The low resistance of the oscillator ($\approx$50 Ω) shunts the capacitance of the lead to earth. The capacitance C_V is shunted by the resistance R_L (in the range of measurement $R_L \ll (\omega C_V)^{-1}$). The current through the specimen may be considerably affected only by the stray capacitance of the leads to each other, C_p. The main problem was to make the

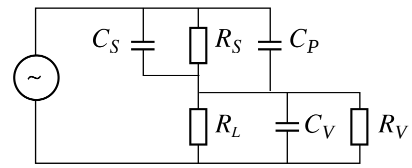

Fig. 1. Equivalent circuit of the measuring setup.

capacitance of C_p as small as possible. The value of C_p was determined from the experiment.

We measured the current through the load as a function of frequency, $I(\omega)$, for different cases: in the absence of the specimen in the circuit ((I_0), in the presence of a homogeneous specimen (I_h), and in the presence of an inhomogeneous one (I_{nh}). For each case, the measurements were performed twice: one measurement with the phase shifter angle of the voltmeter $\phi = 90$ ($I^{(1)}$) and the other measurement with $\phi = 0$ ($I^{(2)}$), which provided the measurements of the reactive and resistive current components, respectively. From these measurements, we obtained the following results.

(i) The angle $\phi = 90$: the reactive currents in the absence of the specimen $I_0^{(1)}$, in the presence of a homogeneous specimen $I_h^{(1)}$, and in the presence of an inhomogeneous one $I_{nh}^{(1)}$; the stray capacitance of the circuit C_p ($\approx$0.6 pF), the capacitance of the circuit with a specimen, and the capacitance of the specimen C_S ($\approx$0.4 pF). This agrees well with the calculated value.

(ii) The angle $\phi = 0$: the currents $I_0^{(2)}$, $I_h^{(2)}$, and $I_{nh}^{(2)}$. At $\phi = 0$, the reactive current is not completely suppressed by the voltmeter. From the measurements, we determined the reactive component rejection ratio for the instrument: $k(\omega) = I_0^{(1)}(\omega)/I_0^{(2)}(\omega) \approx 20$.

Figure 2a shows the experimental dependences $I_h^{(2)}(\omega)$ and $I_{nh}^{(2)}(\omega)$. One can see that the difference between the currents vanishes with increasing ω. The increase in the currents at higher ω is unrelated to the conductivity dispersion. It is a consequence of the incomplete suppression of the reactive component. By introducing the corrections for the rejection ratio, we obtained the true active currents through the specimen, $I_h^{(a)}(\omega)$ and $I_{nh}^{(a)}(\omega)$. They are shown in Fig. 2b.

6. Proceeding to the discussion, we note the following facts. The voltage amplitude is independent of frequency. The currents $I_h^{(a)}(\omega)$ and $I_{nh}^{(a)}(\omega)$ are proportional to $\sigma_\perp^h$ and $\sigma_\perp^{\text{eff}}(\omega)$, respectively. The ratio of these currents is equal to the ratio of the corresponding conductivities because the homogeneous and inhomogeneous specimens are represented by the same Corbino disk under different photoexcitation conditions. The intensity of photoexcitation was selected so as to

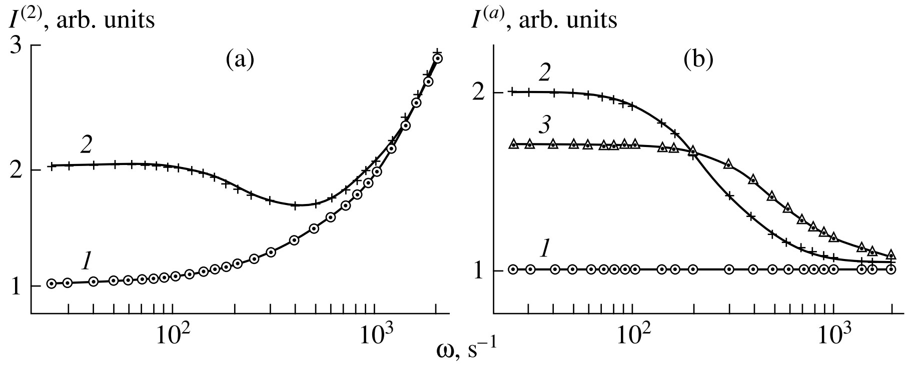

Fig. 2. (a) Frequency dependences of the currents for a homogeneous specimen (curve *1*) and an inhomogeneous one (curve *2*) at $\phi = 0$ and $H = 40$ kOe. (b) Frequency dependences of the active currents for the homogeneous (curve *1*) and inhomogeneous (curve *2*) specimens at $H = 40$ kOe. The value of $I_h^{(a)}$ at low frequencies ω is taken as the current unit. Curve *3* corresponds to $I_{nh}^{(a)}/I_h^{(a)}$ at $H = 30$ kOe.

provide the equality of these conductivities at $H = 0$ and $\omega = 0$. Therefore, the curves shown in Fig. 2b can be considered as the dependences $\sigma_\perp^{\text{eff}}(\omega)$ and $\sigma_\perp^h(\omega)$.

From Fig. 2b, one can drive the following conclusions: $\sigma_\perp^h$ does not depend on ω; $\sigma_\perp^{\text{eff}}$ experiences a dispersion near $\omega = \omega_c \approx 200$ s^{-1}; at $\omega < \omega_c$, the ratio of the conductivities is $\sigma_\perp^{\text{eff}}(\omega)/\sigma_\perp^h(\omega) = 2$, and the anomalous transverse conductivity [6] is observed; at $\omega > \omega_c$, the aforementioned ratio is equal to unity; i.e., the anomalous transverse conductivity vanishes at high frequencies, as was predicted in [4, 5].

The measured value of $\sigma_\perp^{\text{eff}}(0)$ is equal to $2.2 \times 10^{-10}\ \Omega^{-1}$ cm^{-1}. The frequency ω_c is close to the value of $\omega_\perp$ from formula (3) in accordance with the results obtained in [5].

As noted above, the theory [5] predicts the second low-frequency dispersion at the frequency $\omega_\parallel$ (see formula (3)). This frequency lies beyond the limits of our measurements. Besides, the question as to whether this kind of dispersion should be observed in the case of homogeneity along H, which was studied in our experiment, requires special consideration.

Up to this point, we discussed the results of the measurements at $H = 40$ kOe ($\beta \approx 20$). Figure 2b also shows the curve (curve *3*) obtained for $H = 30$ kOe ($\beta = 15$). It is seen that the anomalous transverse conductivity decreases and the frequency ω_c increases with decreasing H. The conductivity $\sigma_\perp^{\text{eff}}$ observed for $\omega \ll \omega_c$ increases almost proportionally to the frequency ω_c.

In closing, we note one more fact. In the literature, it was repeatedly noted that, with increasing β, the transverse conductivity $\sigma_\perp$ decreases slower than predicted by the theory: $\sigma_\perp^h \sim \beta^{-2}$. This fact is confirmed by our experiments. This discrepancy may be possibly explained by the assumption that the specimen possesses its own inhomogeneities that weaken the $\sigma(H)$ dependence. The study of the frequency dependences should also verify this assumption. Curve *1* in Fig. 2b demonstrates that $\sigma_\perp^h(\omega) = \text{const}$. Therefore, the weakening of the $\sigma_\perp^h(H)$ dependence is not related to the presence of inhomogeneities.

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REFERENCES

1. A. N. Vystavkin, Yu. S. Gal'pern, and V. N. Gubankov, Fiz. Tekh. Poluprovodn. **2**, 1651 (1968) [Sov. Phys. Semicond. **2**, 1373 (1968)].
2. Yu. S. Gal'pern and A. L. Éfros, Fiz. Tverd. Tela **11**, 2301 (1969) [Sov. Phys. Solid State **11**, 1858 (1969)].
3. I. A. Chaikovskiĭ, G. M. Shmelev, and A. I. German, Phys. Status Solidi B **129**, 393 (1985).
4. Yu. M. Gal'perin and B. D. Laĭkhtman, Fiz. Tverd. Tela **13**, 2102 (1971) [Sov. Phys. Solid State **13**, 1760 (1971)].
5. I. A. Chaikovskiĭ and A. I. German, Phys. Status Solidi B **152**, 593 (1989).
6. L. S. Al'perovich, S. A. Grachev, Yu. A. Gurvich, *et al.*, Pis'ma Zh. Éksp. Teor. Fiz. **65**, 207 (1997) [JETP Lett. **65**, 224 (1997)].
7. O. E. Kvyatkovskiĭ, Zh. Éksp. Teor. Fiz. **85**, 202 (1983) [Sov. Phys. JETP **58**, 120 (1983)].

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