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Compressibility of a two-dimensional electron gas under microwave radiation

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Microwave irradiation of a two-dimensional electron gas (2DEG) produces a non-equilibrium distribution of electrons, and leads to oscillations in the dissipative part of the conductivity. We show that the same non-equilibrium electron distribution induces strong oscillations in the 2DEG compressibility, measured by local probes. Local probe measurements of the compressibility are expected to provide information about the domain structure of the zero resistance state of a 2DEG under microwave radiation.

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Microwave irradiation of a high-mobility two-dimensional electron system (2DEG) in GaAs/AlGaAs heterostructures results in oscillations of the dissipative part of the resistivity as a function of ω/ω_c, where ω is the microwave frequency and $\omega_c = eB/mc$ is the cyclotron frequency in magnetic field B.[1] Remarkably, in systems with a very high mobility at sufficiently high radiation power the amplitude of the oscillations becomes larger than the dark value of the resistivity and regions of zero resistance develop.[2,3] Experiments[4,5] have shown that the main features of the effect of microwave radiation on the transport properties of a 2DEG are independent of the sample geometry.

Theoretical studies of this phenomenon have been focused on the effect of microwave radiation on the electron spectrum[6–8] and on the electron distribution function.[9,10] As we have shown in Ref. 10, it is the latter effect that yields the leading microwave-induced contribution to the dissipative resistivity ρ_{xx}, explaining its ω/ω_c oscillations observed in the experiments.

The question we address in this communication is how the non-equilibrium electron distribution, responsible for the effect of microwaves on the longitudinal resistivity, affects the thermodynamic properties of the 2DEG, such as the compressibility χ. We find that χ exhibits ω/ω_c oscillations similar to those of the dissipative resistivity. We demonstrate that local measurements of the compressibility may be used as a probe of the spatial structure of the zero resistance state; hence, such measurements may verify the existence of domains suggested in Ref. 11.

The compressibility χ is defined as a static, low-wave-vector limit of the density-density response function $\Pi(\omega,q)$, i.e., $\chi = \Pi(0,q)$ is given by $\delta n_q/e\phi_q$, where δn_q is the electron density induced as a linear response to the application of a static self-consistent (screened) potential ϕ_q and $-e<0$ is the electron charge. Experimentally, the compressibility of a 2DEG in the limit of small q can be determined by measuring the capacitance between the 2DEG and a gate[12] or the electric field screening in double-layer systems.[13] On the other hand, a technique utilizing single-electron transistors has been developed[14] that allows one to measure the *local* compressibility at $q \sim L^{-1}$, where L is the spatial scale on which the screened potential $\phi(\mathbf{r})$ created by a local probe and the induced electron density $\delta n(\mathbf{r})$ change in the 2DEG plane.

Let us start by considering the local compressibility χ in the limit $ql_{\text{in}} \gg 1$, where $l_{\text{in}} = (D_c\tau_{\text{in}})^{1/2}$ is the inelastic relaxation length, τ_{in} is the electron-electron scattering time calculated in Ref. 10, and D_c is the diffusion coefficient. As shown at the end of the paper, in this limit we can neglect the inelastic-scattering induced damping of the ω/ω_c oscillations of χ. For a nonequilibrium state characterized by an electron distribution function $f(\varepsilon)$, we then have

$$\chi = -\int \nu(\varepsilon)\frac{\partial f(\varepsilon)}{\partial \varepsilon}d\varepsilon, \tag{1}$$

where $\nu(\varepsilon)$ is the density of states. In the equilibrium case, Eq. (1) reduces to the conventional formula $\chi_0 = \partial n_e/\partial\mu$, where n_e is the electron density and μ is the chemical potential.

Microwave radiation changes both the electron distribution function $f(\varepsilon)$ and the oscillatory component of the electron density of states $\nu(\varepsilon)$. The microwave-induced correction to the compressibility $\delta\chi$ can therefore be split into three parts: (i) related to the change of the density of states only, (ii) related to the effect of microwaves on the distribution function only, and (iii) mixed term. We notice first of all that the contribution (i), which is the only one that remains if the influence of radiation on the distribution function is ignored, is exponentially suppressed[15] at $2\pi^2T \gg \omega_c$ because of the temperature smearing, see Eq. (1). We are thus left with the contributions (ii), (iii) to the compressibility $\chi = \chi_0 + \delta\chi$, which are governed by the deviation of the electron distribution function $f_{\text{mw}}(\varepsilon)$ from the equilibrium Fermi function $f_0(\varepsilon)$:

$$\delta\chi = -\int \nu_{\text{mw}}(\varepsilon)\frac{\partial}{\partial\varepsilon}[f_{\text{mw}}(\varepsilon) - f_0(\varepsilon)]d\varepsilon, \tag{2}$$

where $\nu_{\text{mw}}(\varepsilon)$ is the density of states in the presence of microwaves. Following the arguments of Ref. 10, contribution (iii) can be neglected as compared to (ii) at $\tau_{\text{in}} \gg \tau_q$, where τ_{in}

and τ_{q} are the inelastic scattering time and the quantum scattering time, respectively. In other words, we can replace $\nu_{\mathrm{mw}}(\varepsilon)$ in Eq. (2) by the dark density of states $\nu(\varepsilon)$.

The distribution function f_{mw} is the solution to the following kinetic equation:[10]

$$\frac{\mathcal{P}}{4\nu_0}\sum_{\pm}\nu(\varepsilon\pm\omega)[f_{\mathrm{mw}}(\varepsilon\pm\omega)-f_{\mathrm{mw}}(\varepsilon)] + \frac{\mathcal{Q}}{4\nu_0\nu(\varepsilon)}\frac{\omega_{\mathrm{c}}^2}{\pi^2}\frac{\partial}{\partial\varepsilon}\left[\nu^2(\varepsilon)\frac{\partial f_{\mathrm{mw}}(\varepsilon)}{\partial\varepsilon}\right] = f_{\mathrm{mw}}(\varepsilon)-f_0(\varepsilon), \tag{3}$$

written for $|\omega\pm\omega_{\mathrm{c}}|\tau_{\mathrm{tr}}\gg 1$ in terms of the dimensionless parameters $\mathcal{P}$ and $\mathcal{Q}$ characterizing the power of the microwave field $\mathcal{E}_\omega$ and the strength of the dc electric field $\mathcal{E}_{\mathrm{dc}}$,

$$\mathcal{P}=\frac{\tau_{\mathrm{in}}}{\tau_{\mathrm{tr}}}\frac{e^2\mathcal{E}_\omega^2 v_{\mathrm{F}}^2}{\omega^2}\frac{\omega_{\mathrm{c}}^2+\omega^2}{(\omega^2-\omega_{\mathrm{c}}^2)^2}, \quad \mathcal{Q}=\frac{2\tau_{\mathrm{in}}}{\tau_{\mathrm{tr}}}\frac{\pi^2e^2\mathcal{E}_{\mathrm{dc}}^2 v_{\mathrm{F}}^2}{\omega_{\mathrm{c}}^4}, \tag{4}$$

where v_{F} is the Fermi velocity, τ_{tr} is the transport (momentum relaxation) time, and ν_0 is the density of states at zero magnetic field. The first term on the left-hand side of the kinetic equation describes processes of absorption and emission of microwave quanta and the second term describes the diffusion of electrons over the energy spectrum due to the constant electric field. The right-hand side of Eq. (3) represents the inelastic relaxation of the electron distribution function toward the equilibrium function $f_0(\varepsilon)$.

The local relaxation-time approximation for inelastic collisions is justified in the calculation of the local compressibility by means of Eq. (2) if $q_1L\gg 1$, where $q_1=(\omega_c^3\tau_{\mathrm{tr}})^{1/2}/v_F$ is the characteristic momentum transfer in the electron-electron collision integral.[16] Under this condition one can neglect spatial variation of the distribution function in the collision volume. Since Eqs. (1) and (2) are valid for $l_{\mathrm{in}}\gg L$, we conclude that the local compressibility is given by Eqs. (1)–(4) provided that $l_{\mathrm{in}}\gg L\gg q_1^{-1}$. The window for L exists if $q_1l_{\mathrm{in}}\gg 1$, i.e., if $\omega_{\mathrm{c}}\tau_{\mathrm{in}}\gg 1$, which is satisfied in the experiments[1–5] by a large margin.

Below we consider the limit of overlapping Landau levels, when the electron density of states has a weak harmonic modulation

$$\nu(\varepsilon)=\nu_0\left(1-2\delta\cos\frac{2\pi\varepsilon}{\omega_c}\right), \quad \delta=\exp\left(-\frac{\pi}{\omega_c\tau_{\mathrm{q}}}\right). \tag{5}$$

From Eq. (3) we find:[10]

$$f_{\mathrm{mw}}(\varepsilon)\approx f_0(\varepsilon)+\delta\frac{\omega_{\mathrm{c}}}{2\pi}\left(\frac{\partial f_T}{\partial\varepsilon}\sin\frac{2\pi\varepsilon}{\omega_{\mathrm{c}}}\right)F(\mathcal{P},\mathcal{Q}), \tag{6}$$

where the dimensionless function F is given by

$$F(\mathcal{P},\mathcal{Q})=\frac{\mathcal{P}(2\pi\omega/\omega_{\mathrm{c}})\sin(2\pi\omega/\omega_{\mathrm{c}})+4\mathcal{Q}}{1+\mathcal{P}\sin^2(\pi\omega/\omega_{\mathrm{c}})+\mathcal{Q}}. \tag{7}$$

Substituting Eq. (6) into Eq. (2) for the compressibility and assuming (in conformity with the experiments) that the temperature is not too low, $2\pi^2T/\omega_{\mathrm{c}}\gg 1$, we find

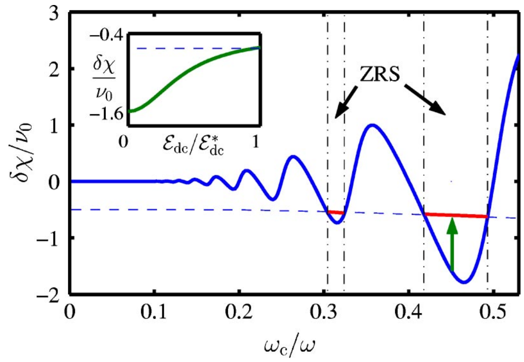

FIG. 1. The microwave-induced correction to the compressibility (solid line) of a 2DEG as a function of $\omega_{\mathrm{c}}/\omega$ at fixed $\omega\tau_q=2\pi$ and microwave power $\mathcal{P}|_{\omega_c=0}=1$. In the zero resistance state (ZRS), the electric field inside domains $\mathcal{E}_{\mathrm{dc}}^*$ fixes the compressibility at the level of $\delta\chi^*$ shown by a dashed line [see Eq. (9)]. Inside the domain wall, the electric field $\mathcal{E}_{\mathrm{dc}}$ is smaller than $\mathcal{E}_{\mathrm{dc}}^*$ and the compressibility depends on the local field as shown in the inset (for $\omega_{\mathrm{c}}/\omega=0.45$, this ratio is indicated by the arrow).

$$\delta\chi=-\nu_0\delta^2F(\mathcal{P},\mathcal{Q}). \tag{8}$$

Equation (8) is our main quantitative result. This equation describes the compressibility of a 2DEG with overlapping Landau levels, $\delta\lesssim 1$, at arbitrary electric dc and microwave fields. Most importantly, the compressibility exhibits oscillations as a function of $\omega/\omega_{\mathrm{c}}$.

In the absence of the dc field, the oscillations of χ have the same properties as the oscillations of the dissipative part of the linear conductivity $\sigma_{\mathrm{ph}}=\sigma_{\mathrm{D}}[1+2\delta^2(1-F(\mathcal{P},0))]$, see Ref. 10 (here σ_{D} is the Drude conductivity). In particular, the temperature dependence of the amplitude of oscillations is determined by the inelastic scattering time τ_{in}.[17] Note also that at $\omega=k\omega_{\mathrm{c}}$ with integer k the microwave-induced corrections to both the compressibility and the conductivity vanish.

The above picture of oscillations of the compressibility holds if the linear conductivity is positive, $\sigma_{\mathrm{ph}}>0$. However, if the dissipative part of the *linear* conductivity is negative, the electron system becomes unstable and breaks down into domains.[11] The magnitude of electric field $\mathcal{E}_{\mathrm{dc}}^*$ inside the domains is set by the condition that the dissipative electric current $j_{\mathrm{d}}=\sigma_{\mathrm{D}}\mathcal{E}_{\mathrm{dc}}[1+2\delta^2(1-F(\mathcal{P},\mathcal{Q}))]$ is zero. This condition can be rewritten as $F(\mathcal{P},\mathcal{Q}^*)=(1+2\delta^2)/2\delta^2$, where $\mathcal{Q}^*$ is expressed in terms of $\mathcal{E}_{\mathrm{dc}}^*$ according to Eq. (4). Correspondingly, in the zero-resistance state the correction to the compressibility is given by

$$\delta\chi^*=-\nu_0\frac{1+2\delta^2}{2}, \tag{9}$$

which yields the compressibility for overlapping Landau levels close to $\nu_0/2$.

These results are illustrated in Fig. 1, where we plot the compressibility as a function of $\omega_{\mathrm{c}}/\omega$ for fixed values of $\mathcal{E}_\omega$ and for $\omega\tau_{\mathrm{q}}/2\pi=1$. This choice of $\omega\tau_{\mathrm{q}}$ corresponds to typical experimental values[2–5] $\omega/2\pi\sim 100$ GHz and $\tau_{\mathrm{q}}\sim 10$ ps.

The oscillatory contribution $\delta\chi$ is seen to develop with increasing magnetic field, Eq. (8). At sufficiently strong magnetic fields, zero resistance states appear, domains are formed, and the compressibility inside the domains is given by $\delta\chi^*$, Eq. (9).

When crossing a domain wall, the normal component of the dc electric field changes from $-\mathcal{E}^*_{\rm dc}$ on one side of the wall to $\mathcal{E}^*_{\rm dc}$ on the other, thus vanishing in between. To estimate the compressibility inside the domain wall, we note that Eq. (8) gives the local compressibility provided the spatial scale on which the dc electric field varies exceeds the inelastic relaxation length. The latter gives the characteristic width of the domain wall, so that we still can use Eq. (8) for the estimate. Then the local compressibility is determined by the strength of the local electric field $\mathcal{E}_{\rm dc}$ and $\chi-\chi_0$ changes between $\delta\chi$, Eq. (8), at $\mathcal{Q}=0$ in the middle of the domain wall and $\delta\chi^*$, Eq. (9), away from the wall, as shown in the inset to Fig. 1 for $\omega_{\rm c}=0.45\omega$.

We recall that Eq. (8) is applicable in the regime of overlapping Landau levels, $\delta=\exp(-\pi/\omega_{\rm c}\tau_{\rm q})\ll 1$, when only the first harmonic $g_1\delta$ of the electron density of states $\nu(\varepsilon)/\nu_0 =1+2\Sigma_{l=1}^{\infty} g_l\delta^l\cos(2\pi l\varepsilon/\omega_{\rm c})$ is important (coefficients g_l are given by[8] $g_l=L^1_{l-1}(2\pi l/\omega_{\rm c}\tau_{\rm q})/l$ and L^m_l are the Laguerre polinomials). This approximation, Eq. (5), works well up to the point where the Landau levels become separated, $\omega_{\rm c}\tau_{\rm q}/2\pi \simeq 1.5$.[8] For typical parameters of experiments performed up to date, $\omega\tau_{\rm q}/2\pi\lesssim 1$, the approximation is thus sufficient in the whole range of magnetic fields, $\omega_{\rm c}<\omega$, where the microwave-induced oscillations take place.[18] For larger values of $\omega\tau_{\rm q}$, when Landau levels get separated already at $\omega_{\rm c}<\omega$, the compressibility as a function of the magnetic field still has the same qualitative features as in Fig. 1. In particular, the amplitude of oscillations of $\delta\chi$ increases as B increases. However, the peaks of $\delta\chi$ become narrower and plateaus between the peaks appear. The quantitative analysis is similar to one developed in Ref. 10 and is not presented in this Communication.

The measurement of the local compressibility χ may be used to study the strength of the local dc electric fields in the zero resistance state. Indeed, assuming that the microwave power is uniformly distributed over the area of the sample, we relate the variation of the compressibility between different points of a 2DEG to the variation of the local field $\mathcal{E}_{\rm dc}$ at these points. The strength of the field $\mathcal{E}_{\rm dc}$ can be found from the measured value of χ by using Eqs. (4) and (8). As the electric field decreases from $\mathcal{E}^*_{\rm dc}$ inside the domains to zero in the middle of the domain wall, the magnitude of the microwave-induced correction to the compressibility $|\delta\chi|$ increases and reaches a maximum at $\mathcal{E}_{\rm dc}=0$. Thus, the local minima of the compressibility χ mark the boundaries between the domains of the electric field in the zero resistance state of a 2DEG under microwave radiation. The length scale that determines the shape of the minima represents the width of the domain walls.

Finally, we discuss the compressibility in nonequilibrium state of 2DES for arbitrary value of $ql_{\rm in}$. In the presence of electrostatic potential $\phi(\mathbf{r})$, the term $e\vec{\mathcal{E}}_{\rm dc}\partial_\varepsilon$ representing the effect of uniform dc electric field on electron distribution function acquires a more general form $e[\nabla\phi(\mathbf{r})-\vec{\mathcal{E}}_{\rm dc}]\partial_\varepsilon+\nabla$, see Ref. 8. Corrrespondingly, the second term in the left-hand side of Eq. (3) has to be rewritten as

$$\frac{\mathcal{Q}}{4\nu_0\nu(\varepsilon)}\frac{\omega_c^2}{\pi^2}\partial_\varepsilon[\nu^2(\varepsilon)\partial_\varepsilon f_{\rm mw}] \to \frac{D_c\tau_{\rm in}}{\nu_0\nu(\varepsilon)}(e[\nabla\phi-\vec{\mathcal{E}}_{\rm dc}]\partial_\varepsilon+\nabla) \times[\nu^2(\varepsilon)(e[\nabla\phi-\vec{\mathcal{E}}_{\rm dc}]\partial_\varepsilon+\nabla)f_{\rm mw}]. \tag{10}$$

with $f_{\rm mw}=f_{\rm mw}(\varepsilon,\mathbf{r})$ and $D_c=v_F^2/2\omega_c^2\tau_{\rm tr}$. The substitution of Eq. (10) ensures that function $f_0(\varepsilon-e\phi(\mathbf{r}))$ is a solution of kinetic equation for arbitrary electrostatic potential $\phi(\mathbf{r})$.

The compressibility χ is related to a linear-in-ϕ term in the solution of the resulting kinetic equation by $\chi = (\partial/e\partial\phi_q)\int d\varepsilon\,\nu(\varepsilon)f_{{\rm mw},q}(\varepsilon)|_{\phi_q\to 0}$, where $f_{{\rm mw},q}(\varepsilon)$ is the Fourier transform of $f_{\rm mw}(\varepsilon,\mathbf{r})$. Solving the kinetic equation along the lines of Ref. 10 for $q\ll q_1$ (which allows us to write the inelastic collision integral in the local form in real space), we obtain for the correction to the compressibility related to the oscillations of $f_{{\rm mw},q}(\varepsilon)$ in ε:

$$\chi-\chi_0=\frac{q^2}{q^2+l_{\rm in}^{-2}}\delta\chi, \tag{11}$$

where $\delta\chi$ is given by Eq. (8). We note the appearance of $l_{\rm in}^{-2}$ term in the denominator of Eq. (11). This term originates from the relaxation of the nonequilibrium electron distribution function $f_{\rm mw}(\varepsilon)$ due to the inelastic scattering, which occurs on length $l_{\rm in}=(D_c\tau_{\rm in})^{1/2}$. As a result of such relaxation, the nonequilibrium component of the compressibility at $q \ll l_{\rm in}^{-1}$ is suppressed. However, the compressibility in equilibrium is given by Eq. (1) even for $q=0$ because a shift of the chemical potential does not lead to the relaxation of the Fermi distribution function ($l_{\rm in}^{-1}=0$).

We conclude that the local relation $\delta n(\mathbf{r})=\chi_{\rm loc}e\phi(\mathbf{r})$ holds only if the L on which $\phi(\mathbf{r})$ changes satisfies the condition $L\ll l_{\rm in}$, otherwise the oscillatory part of the $\delta n(\mathbf{r})$ is suppressed as $l_{\rm in}^2/L^2$. Therefore, the most favorable conditions for measuring the microwave-induced oscillations of the local compressibility by scan probe microscopy should be realized when the size of the probe and the distance between it and the 2DEG are smaller than or comparable with $l_{\rm in}$. The technique used in Ref. 14 makes these conditions feasible: $l_{\rm in}$ is estimated[10] to be in the micrometer range under the experimental conditions,[1–5] whereas the spatial resolution in the local compressibility measurements[14] was in the range of a few tenths of a micrometer.

To summarize, we have shown that the compressibility χ of a 2DEG exhibits oscillations governed by the ratio $\omega/\omega_{\rm c}$, similar to the oscillations of the photoconductivity $\sigma_{\rm ph}$. The key features of the effect of microwave radiation on the compressibility are: (i) the period and the phase of the oscillations of χ are the same as for the oscillations of $\sigma_{\rm ph}$; (ii) the amplitude of the oscillations in χ and $\sigma_{\rm ph}$ have the same dependence on the electron temperature and microwave power; (iii) at $\omega=k\omega_{\rm c}$ with integer k the microwave radiation affects neither $\sigma_{\rm ph}$ nor $\delta\chi$; (iv) the zero resistance state corresponds to a plateau in the compressibility. Local measurements of the compressibility may be used to make a real space snapshot of the domain structure in the zero resistance state.

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[15] In this respect the compressibility is different from the conductivity, which contains the factor $\nu^2(\varepsilon)$ in the integrand, $\sigma \propto -\int d\varepsilon \nu^2(\varepsilon) \partial f/\partial\varepsilon$. The correction to σ due to the effect of microwaves on $\nu(\varepsilon)$ (Refs. 6–8), though smaller by the factor $\tau_q/\tau_{\rm in}$ than the correction related to the change of $f(\varepsilon)$—(Refs. 9 and 10)—survives at high temperatures, $2\pi^2 T \gg \omega_c$.

[16] In fact, q_1 is the smallest characteristic momentum transfer since the integration over momenta in $\tau_{\rm in}^{-1}$ yields $\ln(\kappa/q_1)$, where $\kappa \gg q_1$ is the inverse static screening length, i.e., all momenta between q_1 and κ contribute "logarithmically" to the relaxation rate.

[17] The inelastic time $\tau_{\rm in}$ due to the electron-electron scattering can be estimated as $\tau_{\rm in} \propto E_{\rm F}/T^2$, where $E_{\rm F}$ is the Fermi energy of the 2DEG, see Ref. 10.

[18] In particular, the approximation of the harmonic modulation of the density of states, Eq. (5), is still applicable for the largest values of magnetic field in Fig. 1, i.e., at $\omega_c = \omega/2$, when the amplitudes of the first few harmonics $g_l \delta^l$ are $g_1\delta = 0.37$, $g_2\delta^2 = 0.14$, and $g_3\delta^3 = 0.05$.