GIANT MAGNETORESISTANCE OSCILLATIONS CAUSED BY CYCLOTRON RESONANCE HARMONICS

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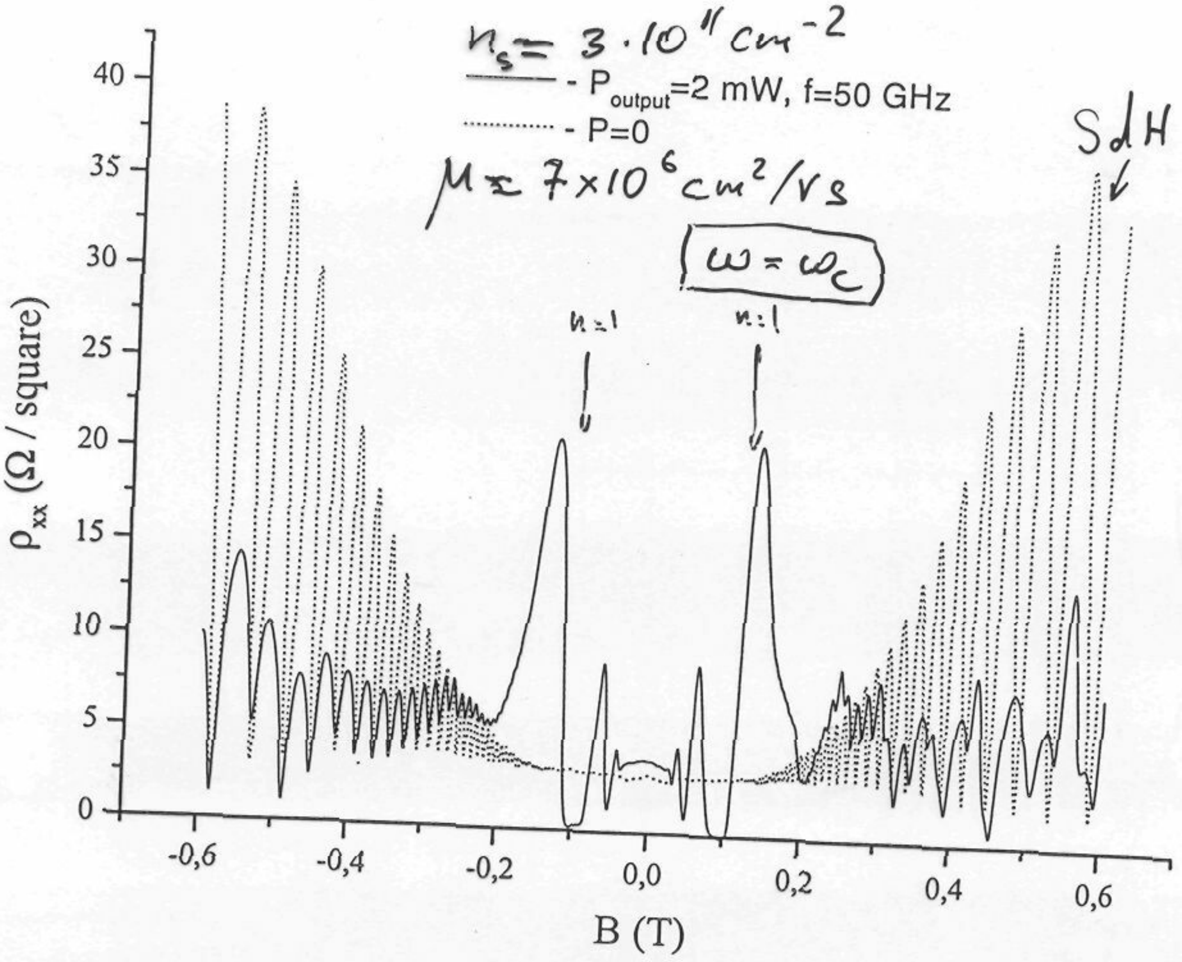


Characteristic features of the Giant Magnetoresistance Oscillations (GMO) and nearly Zero-Resistance States (ZRS)

1. The GMO positions approximately follow condition $\omega = n\ \omega_c = n\ eH/m^*c$
2. The GMO maximums (minima and ZRS) lye at $\omega < n\ \omega_c$ ($\omega > n\ \omega_c$)
3. Magnetoresistance in GMO is independent of filling factor of Landau levels.
4. GMO has triangle like form with rather steep drop in the vicinity of $\omega = n\ \omega_c$

Other characteristic features of the 2DES photoresnonse.

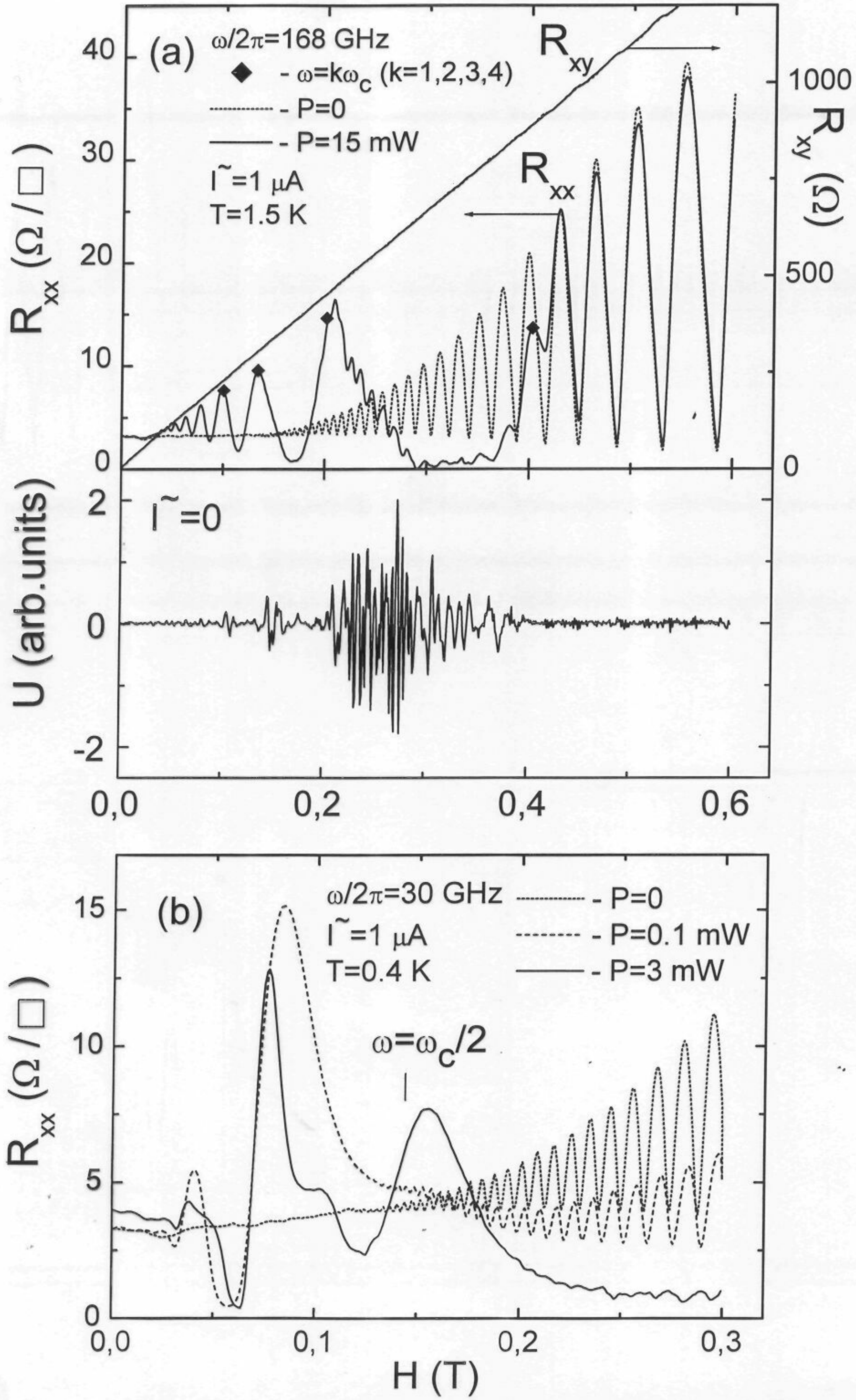
1.Hall resistance is practically independent of the microwave radiation.

2.At high microwave frequencies (large H) and moderate power, amplitude of SdH oscillations are only slightly affected by the microwaves at $\omega < \omega_c$ and at $\omega \approx 1.5\ \omega_c$.

3.At low microwave frequencies and high power,

(i) subharmonic $\omega = \omega_c/2$ appears

(ii) the magnetoresistance at $\omega < \omega_c$ is strongly suppressed.



(a)
ω/2π=168 GHz
◆ - ω=kω$_c$ (k=1,2,3,4)
- P=0
- P=15 mW
I~=1 μA
T=1.5 K
R$_{xy}$
R$_{xx}$
R$_{xx}$ (Ω/□)
R$_{xy}$ (Ω)
I~=0
U (arb.units)
(b)
ω/2π=30 GHz
I~=1 μA
T=0.4 K
- P=0
- P=0.1 mW
- P=3 mW
ω=ω$_c$/2
R$_{xx}$ (Ω/□)
H (T)

Formulas of the self-consistent Born approximation
in the absence of Landau level mixing

$$D(\epsilon) = \sum_{n=0}^{\infty} \frac{2N_0}{\pi \Gamma_{\mathrm{n}}} \left[1 - \left(\frac{\epsilon - \epsilon_{\mathrm{n}}}{\Gamma_{\mathrm{n}}} \right)^2 \right]^{1/2} \tag{1}$$

$$\sigma_{\mathrm{xx}} = \frac{e^2}{\pi^2 \hbar} \sum_{n=0}^{\infty} \left(\frac{\Gamma_{\mathrm{n}}^{\mathrm{xx}}}{\Gamma_{\mathrm{n}}} \right)^2 \int_{\epsilon_{\mathrm{n}}-\Gamma_{\mathrm{n}}}^{\epsilon_{\mathrm{n}}+\Gamma_{\mathrm{n}}} \left(-\frac{df}{d\epsilon} \right) \left[1 - \left(\frac{\epsilon - \epsilon_{\mathrm{n}}}{\Gamma_{\mathrm{n}}} \right)^2 \right] d\epsilon \tag{2}$$

$$\sigma_{\mathrm{xy}} = -\frac{n_{\mathrm{s}} ec}{H} + \frac{e^2}{\pi^2 \hbar} \sum_{n=0}^{\infty} \frac{(\Gamma_{\mathrm{n}}^{\mathrm{xy}})^4}{\Gamma_{\mathrm{n}}^3 \hbar \omega_{\mathrm{c}}} \int_{\epsilon_{\mathrm{n}}-\Gamma_{\mathrm{n}}}^{\epsilon_{\mathrm{n}}+\Gamma_{\mathrm{n}}} \left(-\frac{df}{d\epsilon} \right) \left[1 - \left(\frac{\epsilon - \epsilon_{\mathrm{n}}}{\Gamma_{\mathrm{n}}} \right)^2 \right]^{3/2} d\epsilon \tag{3}$$

$D(\epsilon)$ is the density of states,

$\epsilon_{\mathrm{n}} = \hbar\omega_{\mathrm{c}}(n + 1/2)$ *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 $N_0 = 2eH/hc$.

Short-range scatterers

$\Gamma_n \equiv \Gamma = \left(\frac{2}{\pi}\hbar\omega_{\mathrm{c}}\frac{\hbar}{\tau}\right)^{1/2} \sim \sqrt{H}$

$(\Gamma_{\mathrm{n}}^{\mathrm{xx}})^2 = (n + 1/2)\Gamma^2$

$(\Gamma_{\mathrm{n}}^{\mathrm{xy}})^4 = (n + 1/2)\Gamma^4$

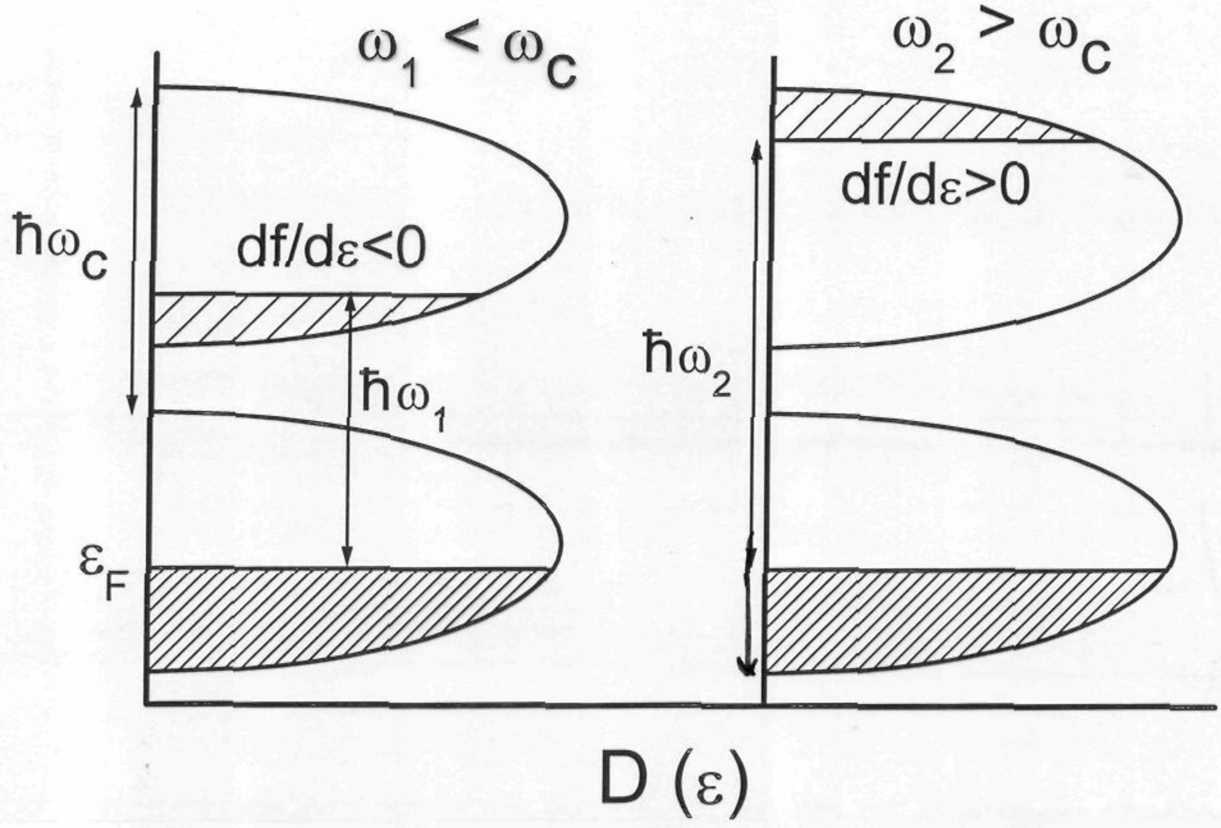
Long-range scatterers

$\Gamma_n^2 = 4 < (V(\mathbf{r}) - < V(\mathbf{r}) >)^2 >$

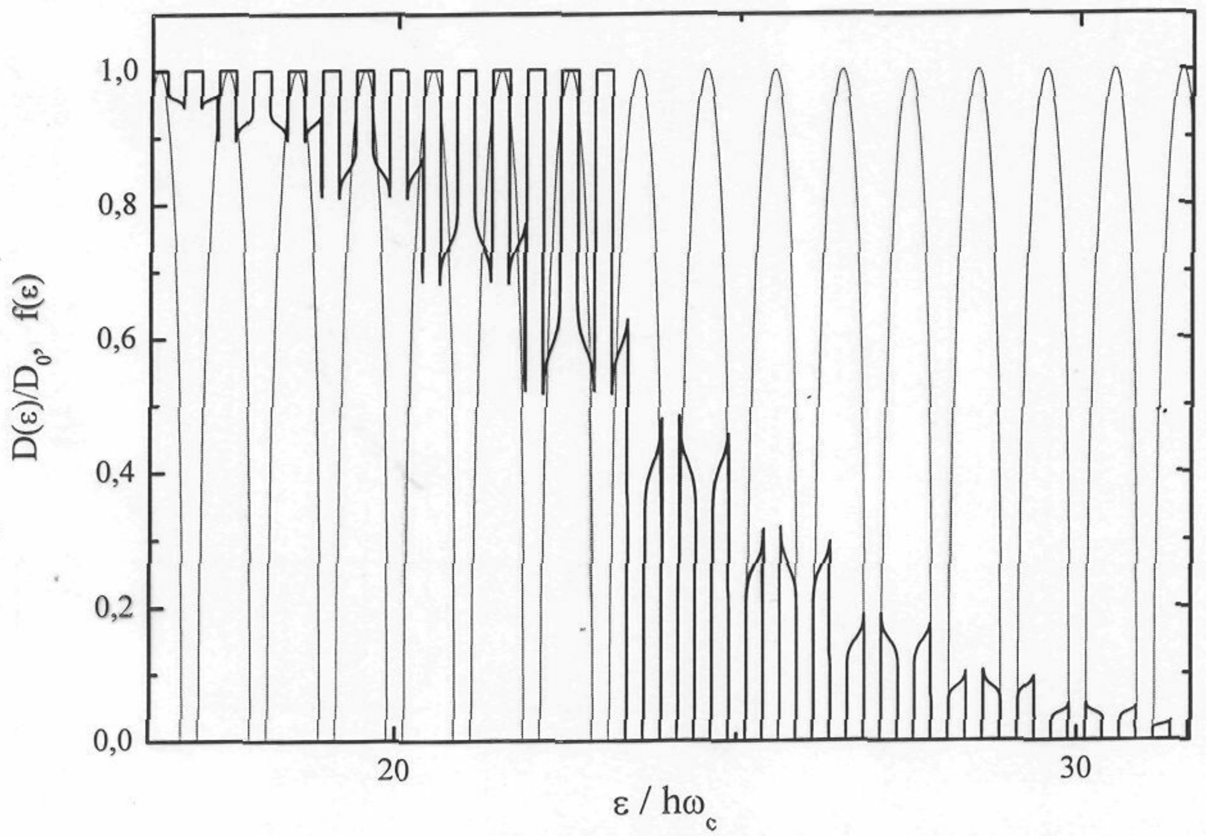
$(\Gamma_{\mathrm{n}}^{\mathrm{xx}})^2 = l^2 < (\nabla V(\mathbf{r}))^2 >$

$l = (\hbar c/eH)^{1/2}$ is the magnetic length

$(\Gamma_{\mathrm{n}}^{\mathrm{xy}})^4 = 4(n + 1/2)\, l^2 < (\nabla V(\mathbf{r}))^2 >^2$



$\omega_1 < \omega_c$
$\omega_2 > \omega_c$
$\hbar\omega_c$
$df/d\varepsilon<0$
$df/d\varepsilon>0$
$\hbar\omega_1$
$\hbar\omega_2$
ε_F
$D(\varepsilon)$



1,0
0,8
0,6
0,4
0,2
0,0
$D(\varepsilon)/D_0$, $f(\varepsilon)$
20
30
$\varepsilon / h\omega_c$

Basic equations to determine nonequilibrium distribution function

(all transitions except ones accompanying one photon ($\hbar\omega$) absorption or emission are neglected)

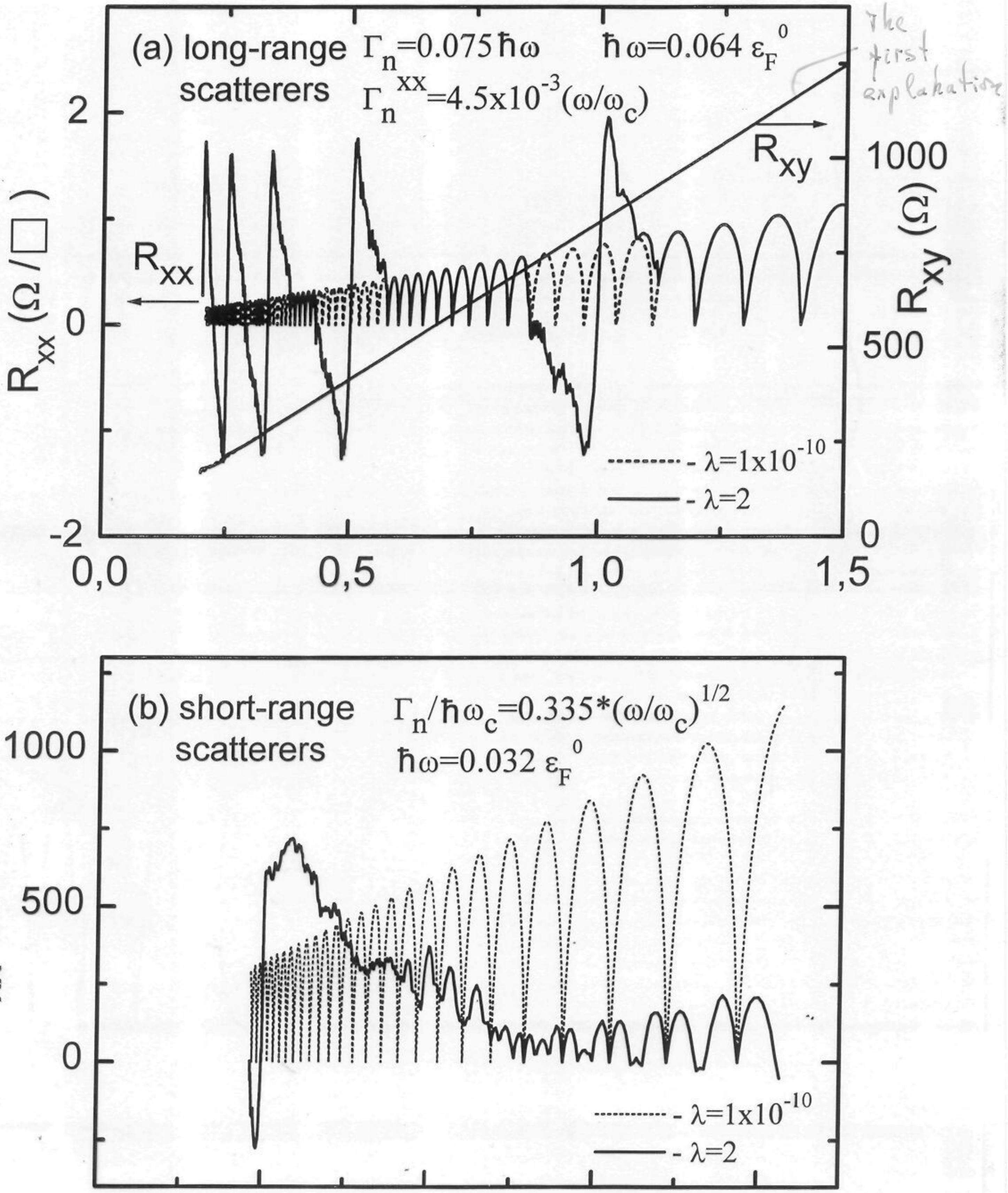
$$f(\epsilon) = \frac{\lambda f(\epsilon - \hbar\omega)}{\lambda + 1 - f(\epsilon - \hbar\omega)}$$

Here $\lambda = W_{induced}/W_{sponteneous}$

$$\int_{-\infty}^{\infty} (f(\epsilon) - f_0(\epsilon))\, D(\epsilon) d\epsilon = 0$$

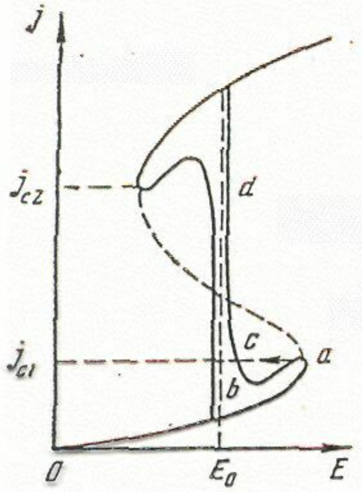
In the absence of relaxation processes

$$\sum_{n=-\infty}^{\infty} (f(\epsilon + n\,\hbar\omega) - f_0(\epsilon + n\,\hbar\omega))\, D(\epsilon + n\,\hbar\omega) = 0$$

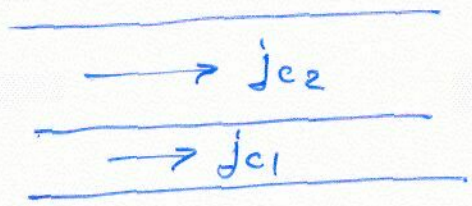


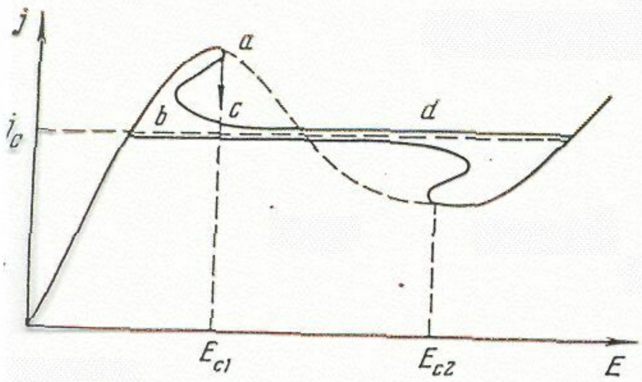
(a) long-range scatterers
Γn=0.075 ħω
Γn^xx=4.5x10^-3(ω/ωc)
ħω=0.064 εF^0
The first explanation
Rxx
Rxy
Rxx (Ω/□)
Rxy (Ω)
- λ=1x10^-10
- λ=2
2
0
-2
1000
500
0
0,0
0,5
1,0
1,5
(b) short-range scatterers
Γn/ħωc=0.335*(ω/ωc)^1/2
ħω=0.032 εF^0
Rxx (Ω/□)
1000
500
0
- λ=1x10^-10
- λ=2
0
1
2
3
4
ωc / ω

RELATION BETWEEN TYPE OF I-V CHARACTERIC
IN A HOMOGENEOUS STATE,
DOMAIN STRUCTURE
AND I-V CHARACTERISTIC IN INHOMOGENEOUS STATE

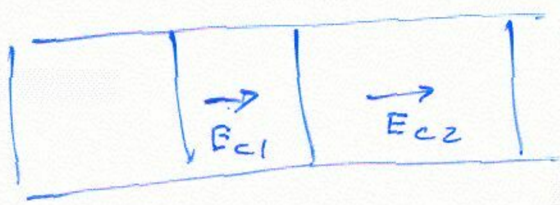


S-type





N-type



Dynamical symmetry breaking as the origin of the zero-dc-resistance state in an ac-driven system.

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Under a strong ac drive the zero-frequency linear response dissipative resistivity $\rho_d(j=0)$ of a homogeneous state is allowed to become negative. We show that such a state is absolutely unstable. The only time-independent state of a system with a $\rho_d(j=0)<0$ is characterized by a current which almost everywhere has a magnitude j_0 fixed by the condition that the nonlinear dissipative resistivity $\rho_d(j_0^2)=0$. As a result, the dissipative component of the dc electric field vanishes. The total current may be varied by rearranging the current pattern appropriately with the dissipative component of the dc-electric field remaining zero. This result, together with the calculation of Durst *et. al.*, indicating the existence of regimes of applied ac microwave field and dc magnetic field where $\rho_d(j=0)<0$, explains the zero-resistance state observed by Zudov *et. al.* and Mani *et. al.*.

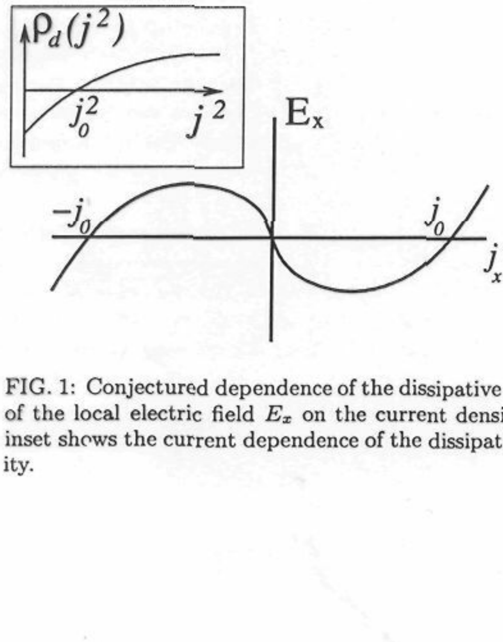


FIG. 1: Conjectured dependence of the dissipative component of the local electric field E_x on the current density j_x. The inset shows the current dependence of the dissipative resistivity.

value j_0 defined in Eq. (4) is unstable with respect to inhomogeneous current fluctuations.

(*ii*) The only possible time independent state is one in which the current $\boldsymbol{j}$ has magnitude j_0 everywhere except at isolated singular points (vortex cores) or lines (domain walls), implying vanishing dissipative electric field, $\boldsymbol{j}\cdot\boldsymbol{E}=0$.

An immediate consequence of (*ii*) is that by adjusting the details of the current pattern, any net dc current less than a threshold value (which we discuss below) can be sustained at vanishing electric field, so that *any microscopic mechanism of non-equilibrium drive resulting in* $\rho_d(j^2=0)<0$ *leads to the observed [1, 2] zero dissipative differential resistance*:

$$\frac{dV_x}{dI_{dc}}=0. \qquad (5)$$

Writing $\boldsymbol{j}(r,t)=\boldsymbol{j}_i+\delta\boldsymbol{j}(r,t)$, linearizing in $\delta\boldsymbol{j}$, and taking the divergency of both sides of Eq. (8), we find

$$\frac{\partial\nabla\cdot\delta\boldsymbol{j}}{\partial t}=\left(\nabla\left(\widetilde{\widehat{\rho}}_d+\widehat{\rho}_H\right)^{-1}\nabla\hat{U}\right)\nabla\cdot\delta\boldsymbol{j}, \qquad (9)$$

with $\widehat{\rho}_H=\rho_H\begin{bmatrix}0 & 1\\ -1 & 0\end{bmatrix}$ the usual Hall resistivity tensor,

$$\widetilde{\widehat{\rho}}_d=\rho_d\mathbf{1}+\alpha_j\boldsymbol{j}_i\otimes\boldsymbol{j}_i, \qquad (10)$$

and

$$\frac{d\rho_d(j^2)}{}\Big| \ldots$$

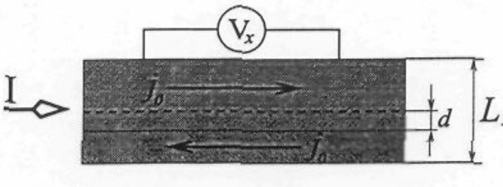


FIG. 2: The simplest possible pattern of the current distribution – domain wall. The net current, I, is accommodated by a shift of the position of the domain wall by the distance d, see text.

of those for which $[\boldsymbol{j}_0\times\boldsymbol{z}]\cdot\nabla\hat{U}\delta n=0$, i.e. with the

EXISTING PROBLEMS

(The questions which I do not like)

1. The role of other relaxation processes.
2. Cyclotron against magnetoplasmon resonance.
3. Domain structure for different geometries.

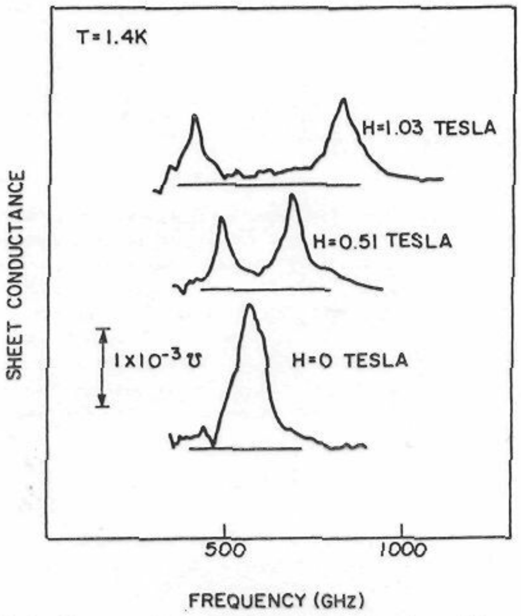


FIG. 3. Sheet conductance of array as a function of frequency. Magnetic field normal to the surface is a parameter.

resonance splits in two. As the magnetic field is raised, one mode approaches the cyclotron resonance, and the low-frequency mode tends toward zero but at an ever decreasing rate (Fig. 4).

To model the response of this system, we consider the disc of 2D electrons to be an oblate spheroid with small thickness, t. The internal field, E^-, is related to the external field, E^0, oriented in the plane of the disc, by

$$E^- = E^0 - LP \quad . \tag{1}$$

L is the depolarization factor for the thin oblate spheroid[9] and P the internal polarization:

$$LP = \frac{\pi}{4a\epsilon i\omega}(t\sigma_v)E^- \quad . \tag{2}$$

Here σ_v is an effective 3D conductivity, ϵ the dielectric constant in which the disc is imbedded, and a is the disc radius.

In the limit as $t \rightarrow 0$, $t\sigma_v$ approaches the 2D surface conductivity, σ_s, with appropriate units of mho/square ($1\text{mho} = 1\Omega^{-1}$). Further, we note that in the system shown in Fig. 2, the fringing fields that contribute to the depolarization field in the 2D limit are divided between free space and GaAs and we replace ϵ in (2) by $(\epsilon_0+\epsilon_1)/2$ where ϵ_0 and ϵ_1 are dielectric constants of free space and GaAs, respectively.

Then we have

$$E^- = \frac{E^0}{1+\pi\sigma_s/2a(\epsilon_0+\epsilon_1)i\omega} \tag{3}$$

and the average sheet conductivity

$$\sigma = f\frac{\sigma_s}{1+\pi\sigma_s/2a(\epsilon_0+\epsilon_1)i\omega} \quad , \tag{4}$$

where f is the fraction of the area covered by discs.

Assuming a classical Drude relaxation of the conductivity of the 2D electron gas

$$\sigma_s = \frac{n_s e^2\tau}{m}\frac{1}{1+i\omega\tau} \quad , \tag{5}$$

we obtain the σ

$$\text{Re}(\sigma) = f\frac{n_s e^2\tau}{m}\frac{1}{1+\omega^2\tau^2(1-\omega_0^2/\omega^2)} \quad . \tag{6}$$

n_s, e, τ, and m are the 2D electron density, charge, scattering time, and mass, respectively.

ω_0 is the resonance frequency for the disc given by

$$\omega_0^2 = \frac{n_s e^2\pi}{am^*2(\epsilon_0+\epsilon_1)} \quad . \tag{7}$$

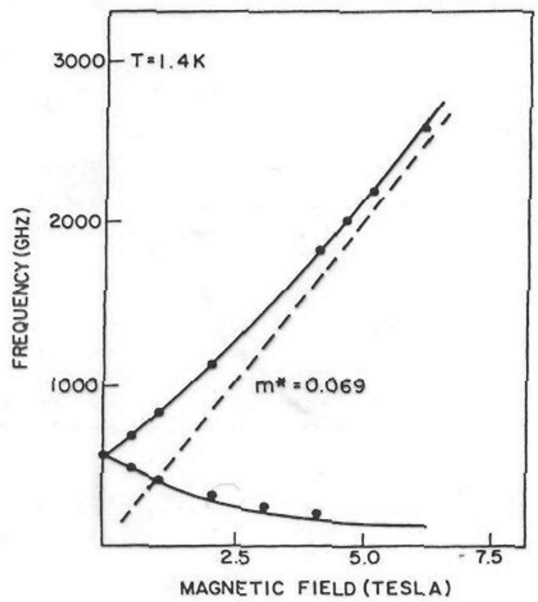
In deriving (6) we have ignored interaction between discs.

Using the electron density for the starting material $n_s = 5.5\times10^{11}/\text{cm}^2$ gives $\omega_0/2\pi \cong 690$ GHz whereas the resonance occurs at 575 GHz. The scattering rate in the starting material is $1/2\pi\tau \sim 16$ GHz compared with a rate deduced from the linewidth in Fig. 3 at $H = 0$ of 50 GHz.

To account for the discrepancy in measured ω_0 we must reduce the electron density of the disc by approximately 30%. We substantiate this interpretation by measuring the effective density in the surface from the integrated strength of the $H = 0$ line.

$$\int_0^\infty \text{Re}(\sigma)\,d\omega = \left(\frac{\pi a^2}{b^2}\right)\left(\frac{\pi}{2}\frac{n_s e^2}{m}\right) \quad . \tag{8}$$

The factor $\pi a^2/b^2$ is the filling factor, f, shown in (6).



$$\omega_\pm = \pm\frac{\omega_c}{2} + \sqrt{\omega_c^2 + \frac{\omega_c^2}{4}}$$

$$\omega_0^2 = \frac{\pi e^2 n_s}{2\epsilon m^* d}$$

$\omega_0/2\pi \simeq 20$ THz