Осцилляции магнетосопротивления двумерного электронного газа, индуцированные терагерцовым излучением.

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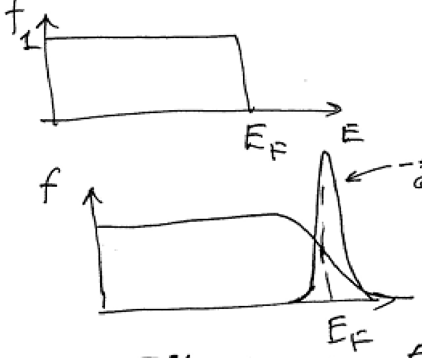
- **1. Двумерный электронный газ (ДЭГ).**

2. Осцилляции магнетосопротивления ДЭГ, индуцированные микроволновым излучением (MIRO).

- **3. Осцилляции магнетосопротивления ДЭГ, индуцированные терагерцовым излучением (TIRO).**

Двумерный электронный газ – двумерный металл

$$f(E) = \frac{1}{1+\exp(E-E_F)/kT}$$



$T = 0$

$$-\frac{\partial f}{\partial E} \xrightarrow[T\to 0]{} \delta(E-E_F)$$

$T \neq 0 \quad E_F \gg kT$

Обычный 3d металл: $E_F \simeq 10$ эВ $\gg$ 0.026 эВ (300K)

$$\nu_{3d}(E) = \frac{\sqrt{2}}{2\pi^2}\frac{m^{*3/2}}{\hbar^3}\sqrt{E}$$

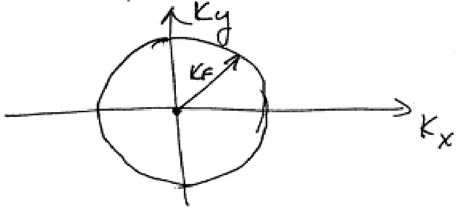
Поверхность Ферми (ПФ) $E(k) = E_F$

В 3d металле ПФ – сфера, если простой параб. и изотр. спектр

Двумерный металл $E_F \simeq (1-100)$ meV $\gg$ 0.36 мэВ (4.2K)

$$\nu_{2D}(E) = \frac{m^*}{\pi\hbar^2}$$

ПФ – окружность, если $E(k) = \frac{\hbar^2 k^2}{2m^*}$



$$\mathbf{E_F = N_s/\nu_{2D}}$$

$$\mathbf{k_F = \sqrt{2\pi N_s}}$$

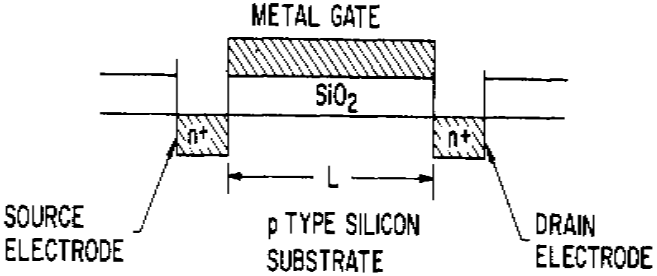
$$\boldsymbol{\sigma = (k_F l)\cdot(e^2/h)}$$

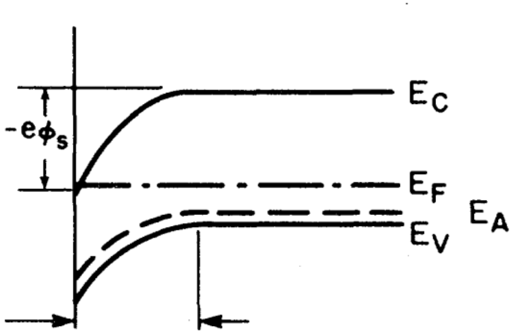
l – длина свободного пробега

l = (0.1 – 100) μm

First realized 2D electron systems

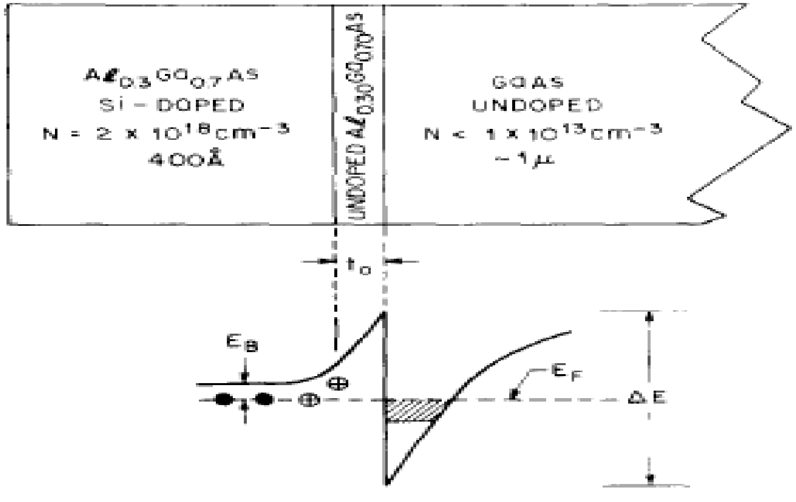
2D ES in MOSFET (1966)

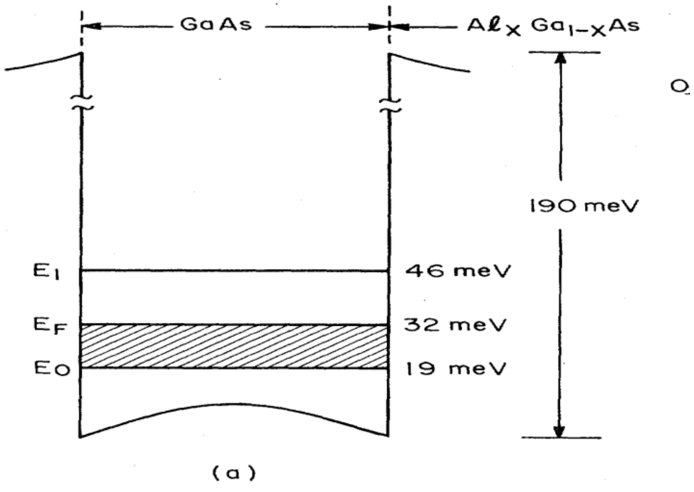




2DES in heterostructure (1978)

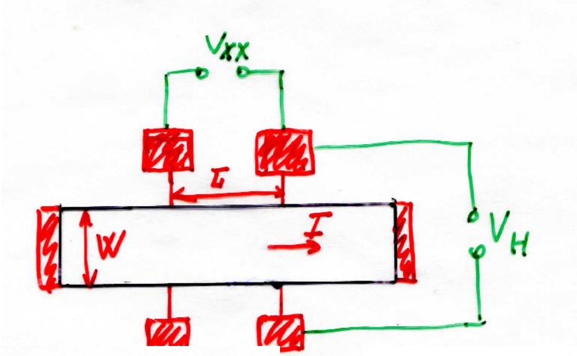
2DES in quantum well





ДЭГ в магнитном поле. Квазиклассика.

Холловский мостик



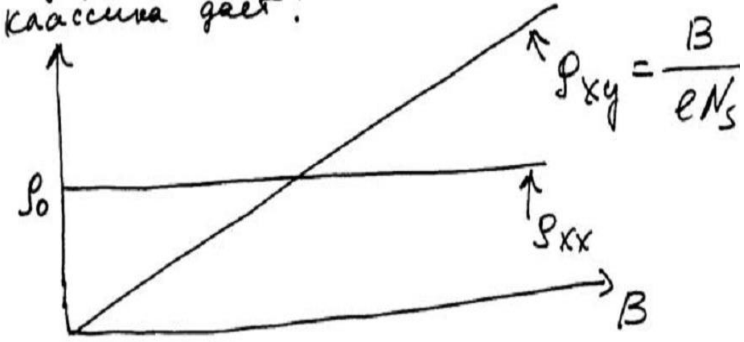
$$R_{xx} = \frac{V_{xx}}{I} = \frac{L}{W}\rho_{xx}$$

$$R_H = \frac{V_H}{I} = \rho_{xy}$$

$$\rho_{xx} = \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2}$$

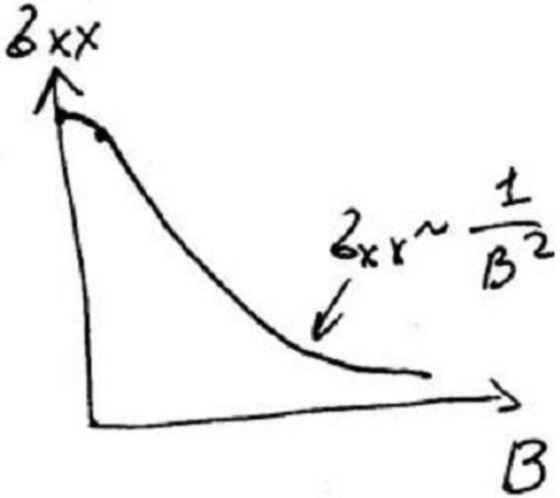
$$\rho_{xy} = \frac{\sigma_{xy}}{\sigma_{xx}^2 + \sigma_{xy}^2}$$

В двумерном изотропном металле классика дает:



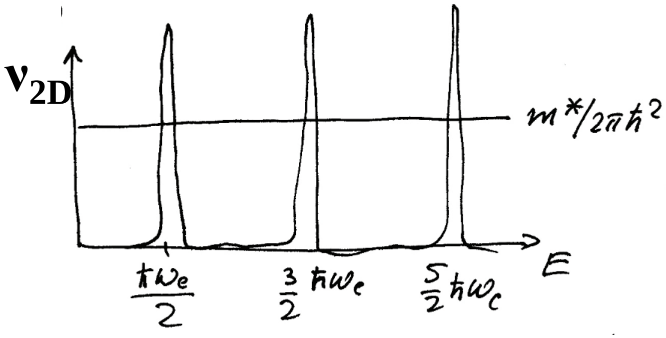
Диск Корбино

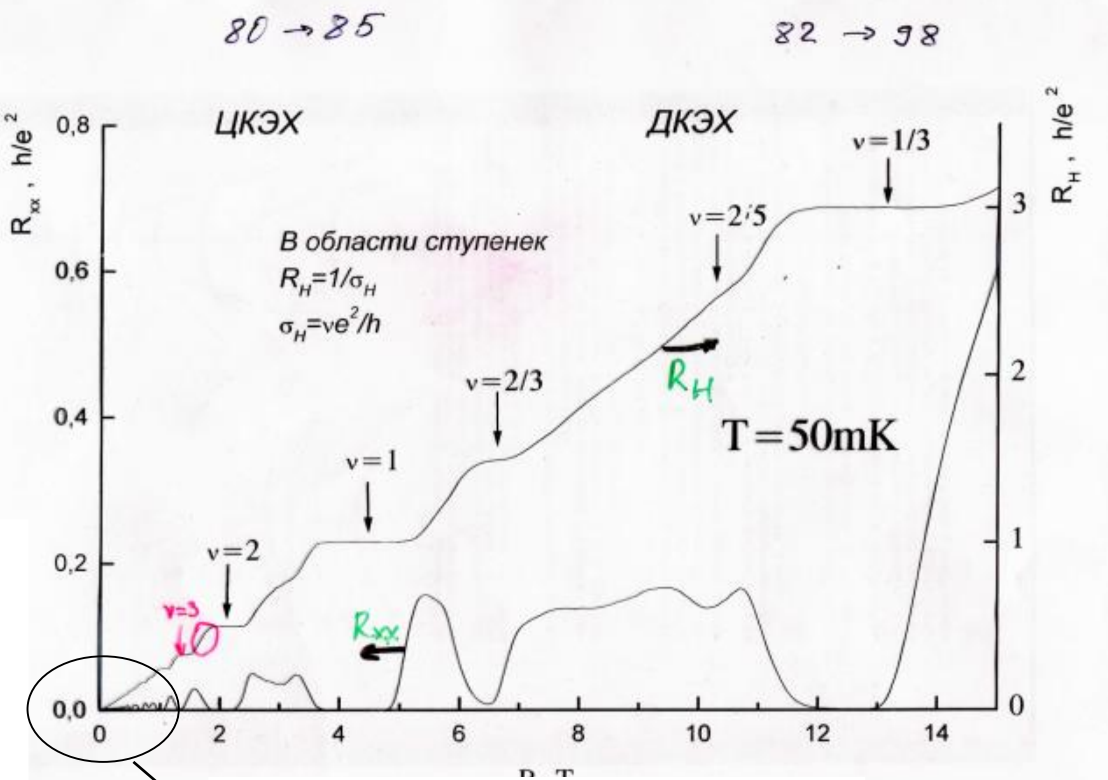
$\sigma_{xx} = A(I/V)$



ДЭГ в магнитном поле. Уровни Ландау. Квантовый эффект Холла.

$$E_n = \hbar\omega_c\cdot(n + ½)$$

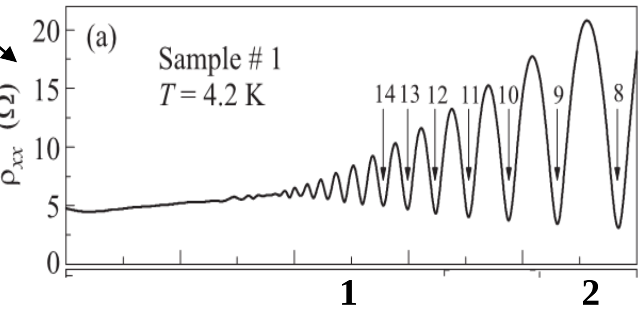




$$N = \frac{S}{2\pi l_H^2} = \frac{eB\cdot S}{2\pi\hbar c} = \frac{eBS}{hc} = \frac{\Phi}{\Phi_0}$$

$\Phi = B\cdot S$ - магнитный поток

$\Phi_0 = \frac{hc}{e}$ - квант магнитного потока



N - кратность вырождения уровня Ландау

N_B = eB/hc - емкость уровня Ландау

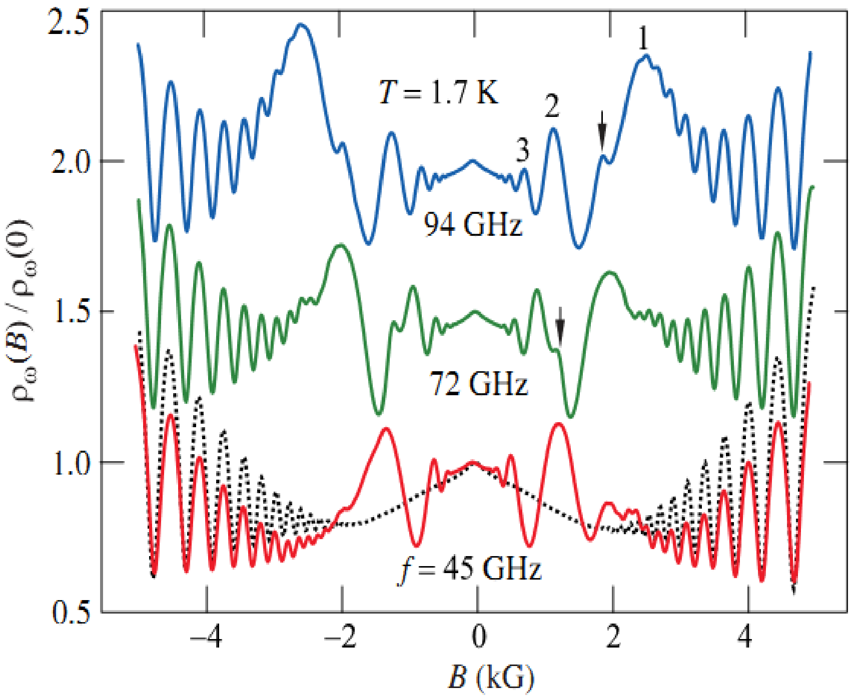
$\nu = N_s/N_B$ – фактор заполнения уровня Ландау

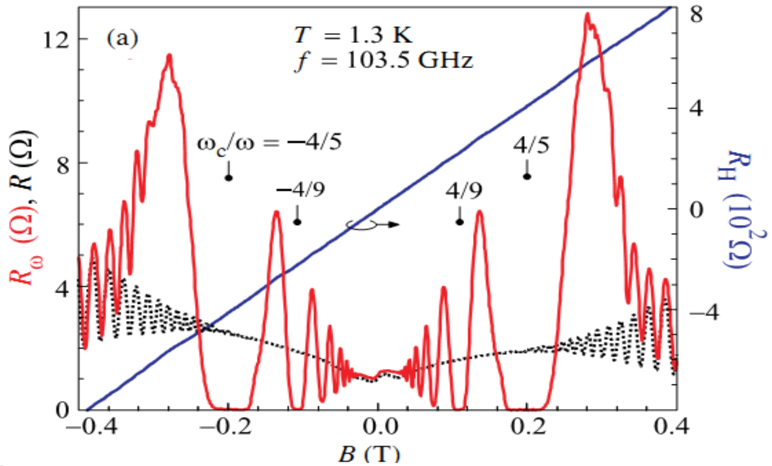
Осцилляции магнетосопротивления, индуцированные микроволновым излучением (MIRO)

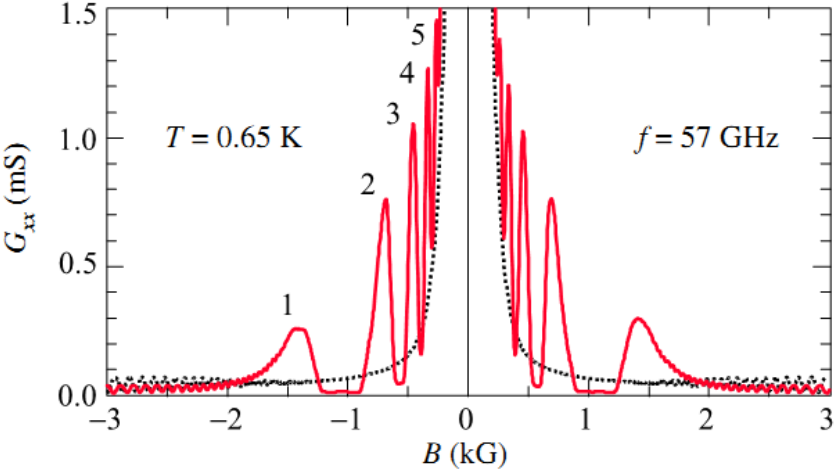
Zudov, M.A et al, Phys.Rev. **B 64**, 201311(R). (2001)

R.Mani et al, Nature,**420**, 646 (2002)

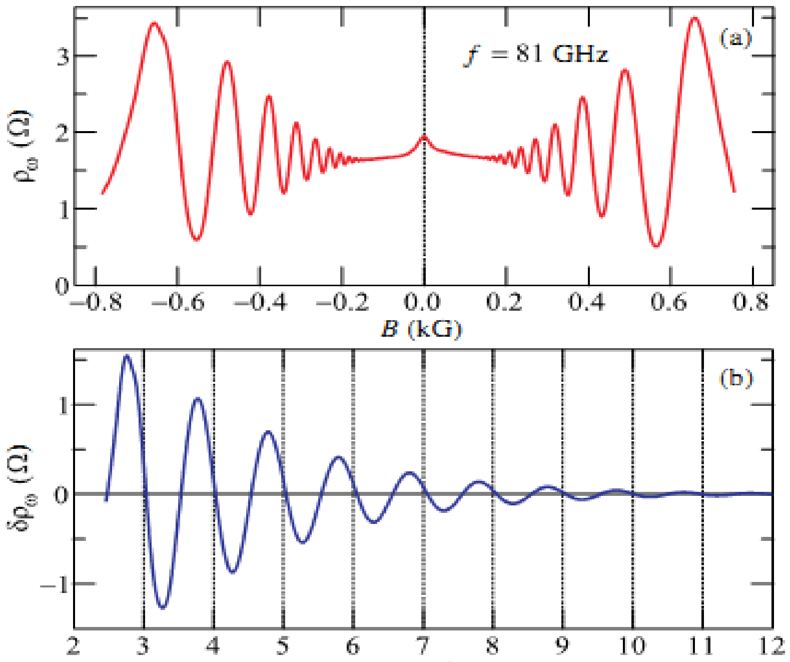
Zudov, M.A et al 2003, Phys.Rev. Lett,
90, 046807 (2003) ; **91,** 096803 (2003).





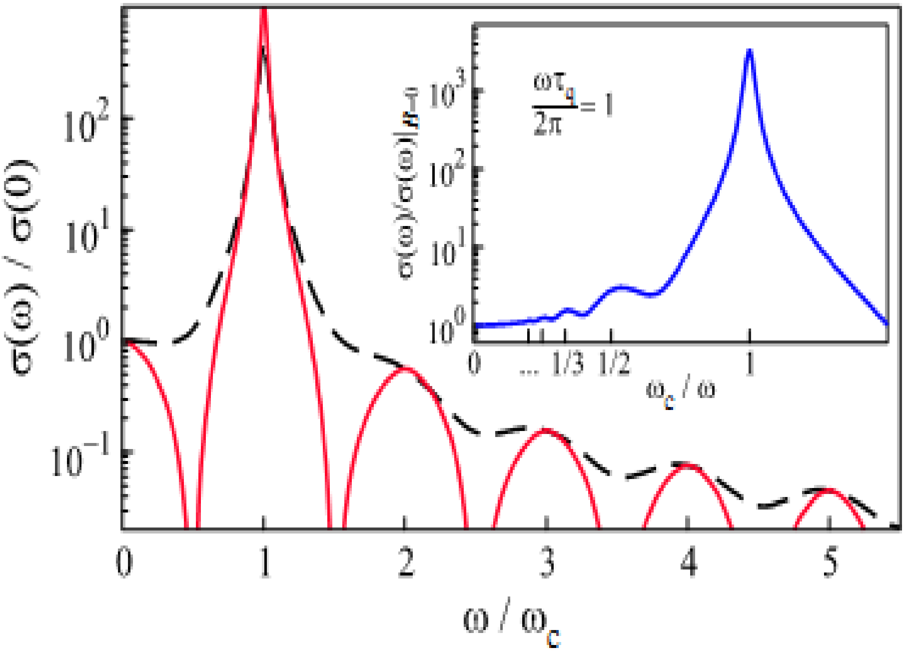


Гармоники циклотронного резонанса



$\varepsilon_{ac} = \omega/\omega_c$

FIG. 6 (color online). (a) Magnetoresistivity oscillations with va ing B at fixed $f = 81$ GHz. (b) Microwave-induced correction $\delta\rho_\omega$ the resistivity as a function of ϵ_{ac}, obtained by subtracting the slowly varying background. The data were obtained at $T \simeq 1.5$ K in a 100 μm wide Hall-bar sample with $n_e \simeq 3.0 \times 10^{11}$ cm^{-2} and $\mu \simeq 1.2 \times 10^7$ cm^2/V s.



Теоретические модели. Сдвиговая.

I. A. Dmitriev, A. D. Mirlin, D. G. Polyakov, and M. A. Zudov, Rev. Mod. Phys. 84, 1709 (2012).

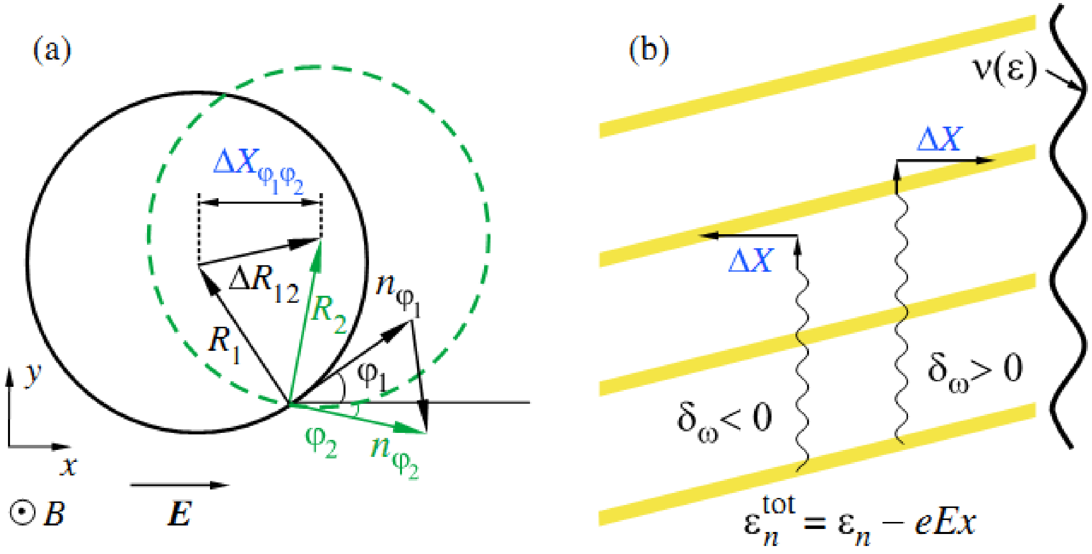
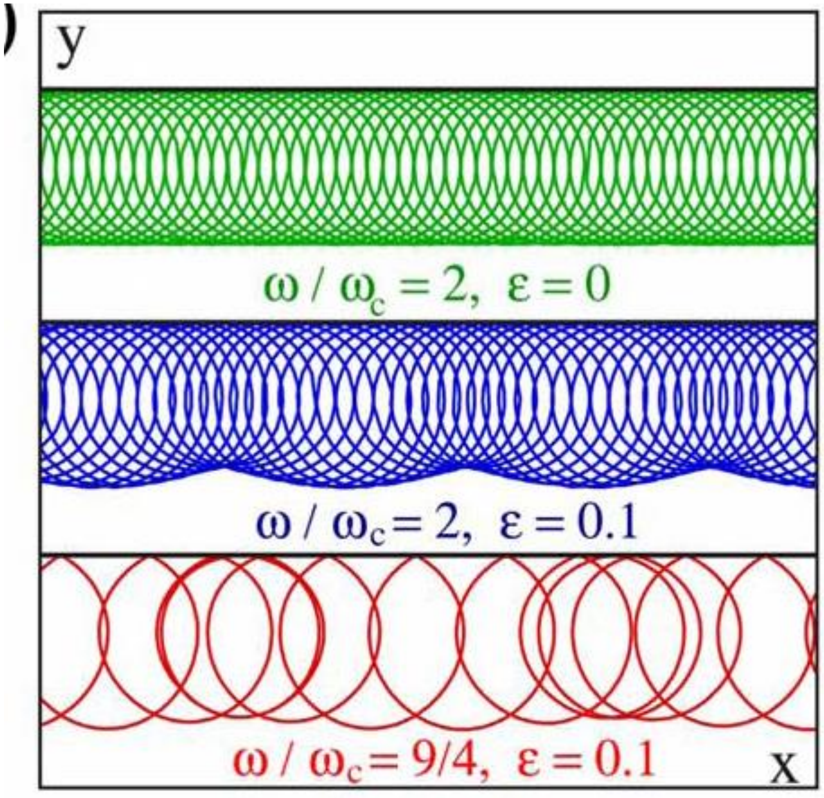


FIG. 10 (color online). (a) Shift of the guiding center of a cyclotron orbit due to quasielastic scattering off disorder. (b) Schematics of the correlations between the direction of the cyclotron-orbit shifts ΔX in the process of photon absorption and the sign of the detuning $\delta_\omega = \omega/\omega_c - 2$ for the second harmonic of the CR. The stripes mark the DOS maxima $\varepsilon_n = (n + 1/2)\omega_c$ in LLs tilted by a dc field.

MIRO as the edge effect

(A.D.Chepelyansky and D.V.Shepelyansky, Phys. Rev. 80, 241308(R) (2009), B 88, 035410 (2013))



- Microwave radiation can stabilize edge trajectories against small angle disorder scattering. For propagating edge channels a microwave field creates a nonlinear resonance well described by the Chirikov standard map. Dissipative processes lead to trapping of particle inside the resonance.

MIRO as a contact effect

(S.A.Mikhailov, PRB, 70 (2004), 74 (2006), 83 (2011))

Microwave irradiation creates near-contact depletion/accumulation regions

$$R_{xx} \simeq R^b_{xx}\mathcal{N}.$$

N is the density factor, defined as the ratio of the electron density in the near-contact region to that in the bulk

$$\mathcal{N} = n_s^c / n_s^0$$

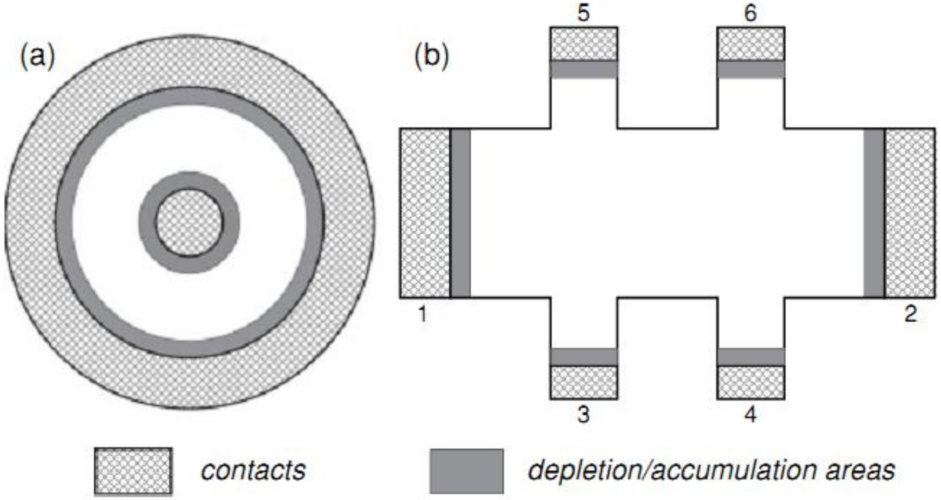


FIG. 4. The geometry of (a) the Corbino disk and (b) the Hall-bar sample under intense microwave irradiation. The gray areas near the contacts show the microwave-induced depletion/accumulation regions.

Эффекты памяти в магнетотранспорте двумерных электронов

(Э.М.Баскин, Л.М.Магарилл, М.В.Энтин, ЖЭТФ, т.75, стр.723 (1978)

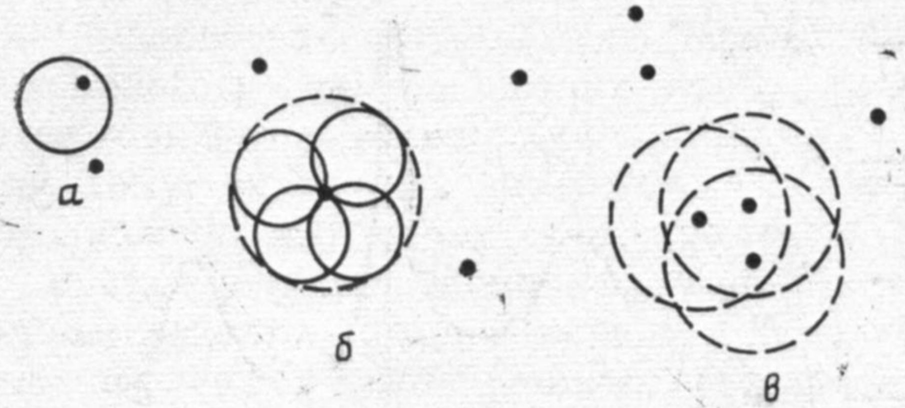
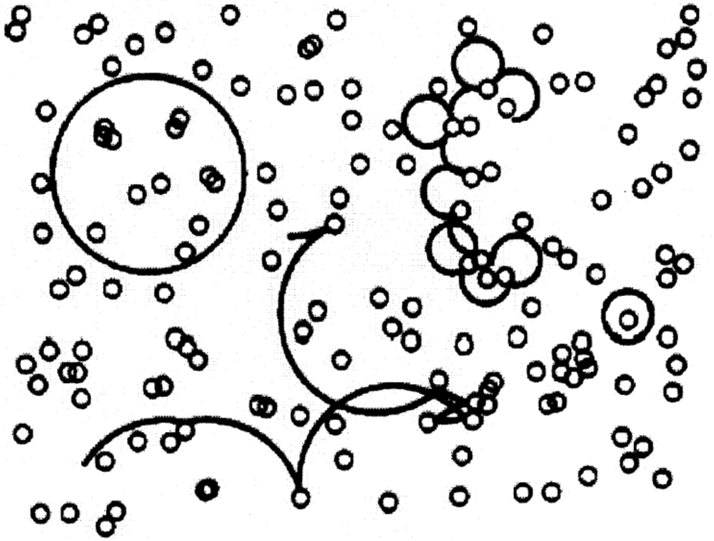
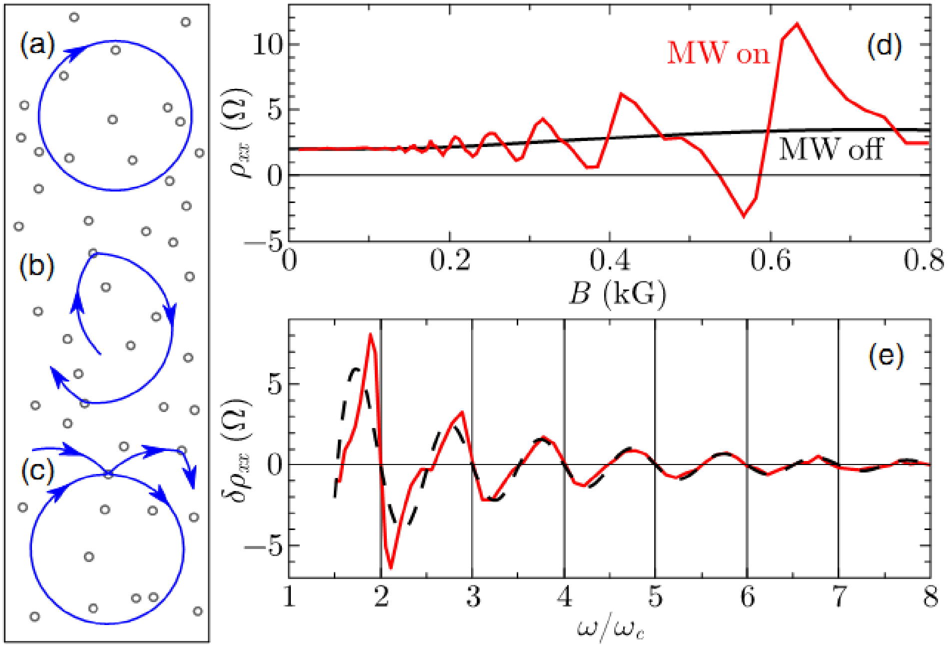


Рис. 3. Траектории электронов в поле короткодействующих примесей. Черными кружками изображены примеси, сплошными линиями — траектории электронов, пунктирными — границы розеток



MIRO как классический эффект памяти

Beltukov, Y.M. and Dyakonov, M.I. Phys. Rev. Lett., 116, 176801 (2016).



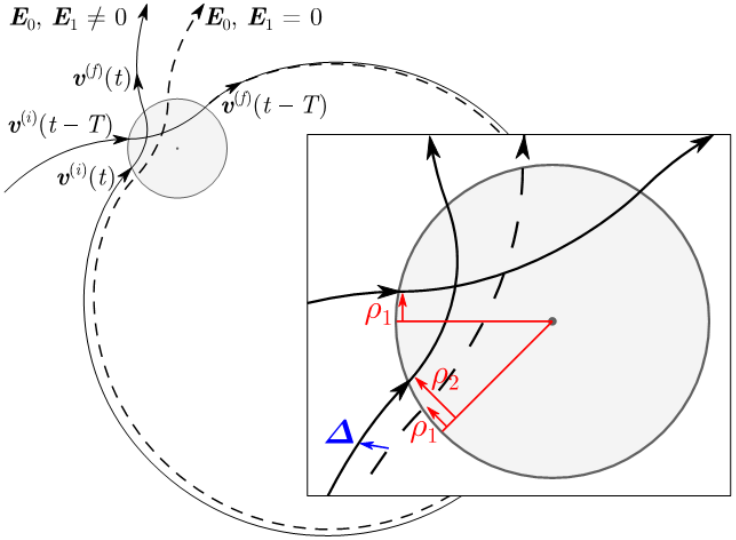


FIG. 2. Extended double collision. At time $t-T$ the electron hits the scattering center with an impact parameter ρ_1 and velocity $\mathbf{v}^{(i)}(t-T)$, which is changed to $\mathbf{v}^{(f)}(t-T)$ after scattering. In the absence of external fields (dashed line), after completing the cyclotron circle the impact parameter remains to be ρ_1, while the velocity becomes $\mathbf{v}^{(i)}(t)$. The action of dc and ac electric fields during the cyclotron period produces a mismatch $\boldsymbol{\Delta}$, which results in changing the new impact parameter to ρ_2. After the second scattering, the velocity becomes $\mathbf{v}^{(f)}(t)$.

Зачем терагерцы?

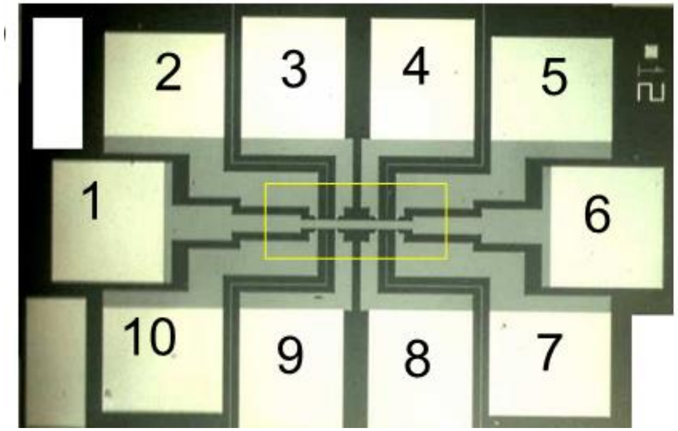
- Во-первых, любопытно: до каких частот эффект все еще существует? Возможен ли переход от MIRO к TIRO?
- Теория и MIRO эксперименты дают пессимистический ответ на второй вопрос: величина эффекта $\Delta\rho_\omega \sim \omega^{-4}$. То есть при 1 THz
- $\Delta\rho_\omega$ будет на 4 порядка меньше, чем при 100 ГГц.

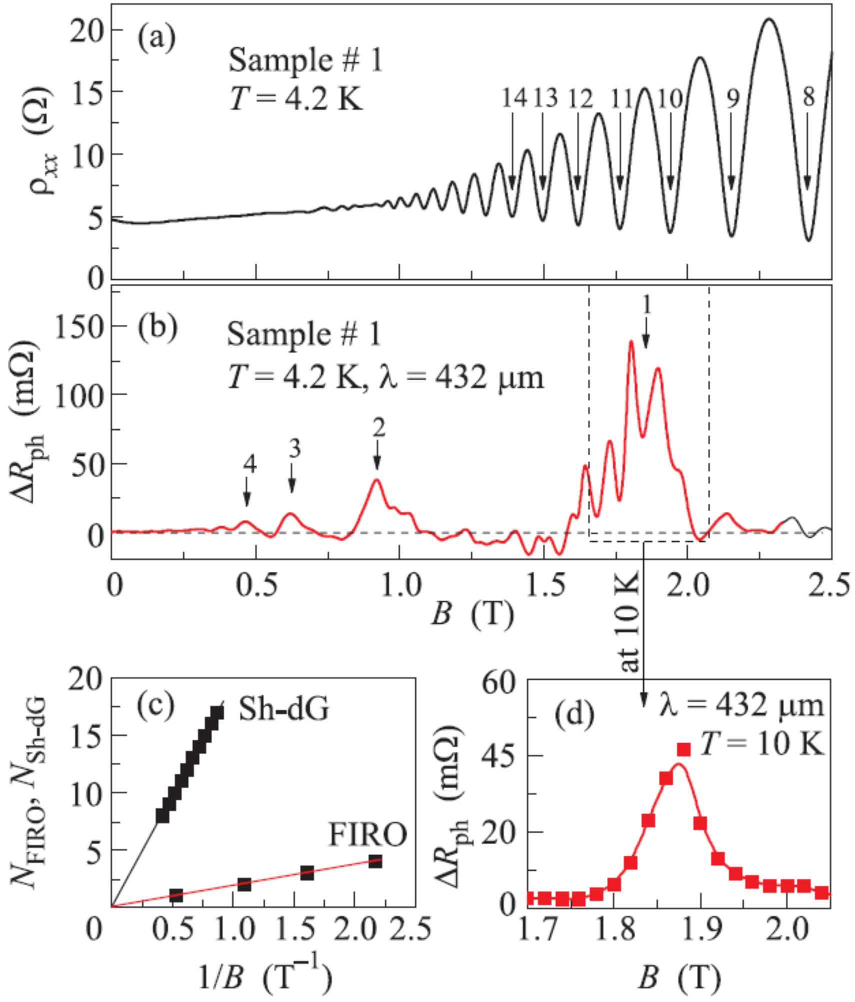
- И все же использование терагерцового излучения имеет два важных преимущества: намного проще проводить поляризационные эксперименты (так как это уже квазиоптика) и локальное зондирование. А постановка этих экспериментов принципиальна для определения теории, наиболее адекватно описывающей эффект.

Experimental setup

- The terahertz response was studied at wavelengths of 432 and 184 μm in magnetic fields of up to 7 T and at temperatures T = 1.9 K – 15 K. A molecular laser with an optical pumping by a CO_2 laser was used as a terahertz source. The active medium used to generate radiation at a frequency of 0.7 and 1.63 THz (the wavelength λ = 432 and 184 μm) was formic acid and difluoromethane, respectively. The terahertz radiation power was about 80 mW at the 184 and 5 mW at 432μm lines.

Осцилляции, индуцированные терагерцовым излучением (TIRO). Первое наблюдение.

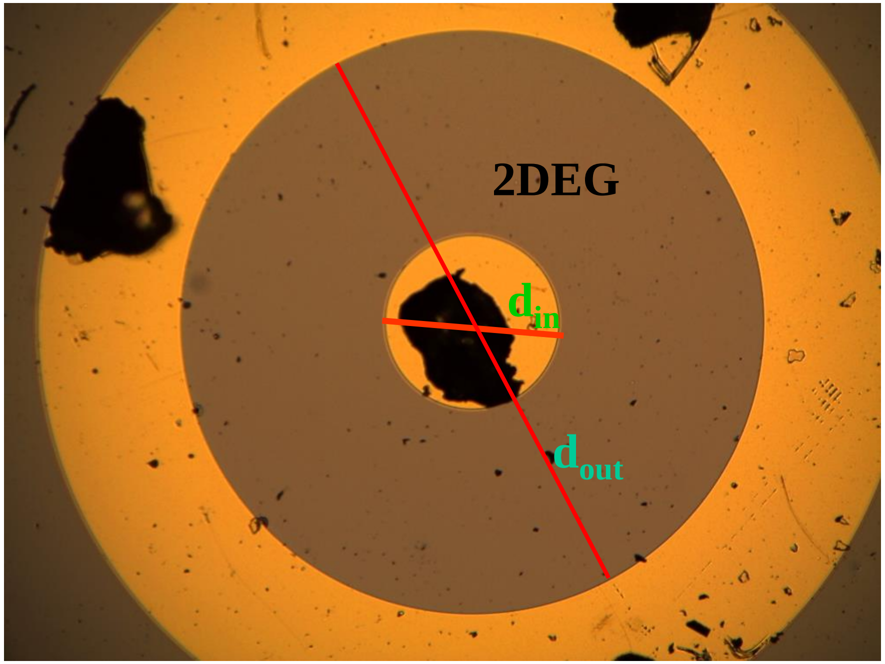




Corbino disc on the basis of a 2DEG

d_{in} = 0.65 mm

d_{out} = (2-10) mm



2DEG in AlGaAs/GaAs

$N_s = (5\text{-}24)\cdot 10^{11}\ \mathrm{cm}^{-2}$

$\mu = (0.5\text{-}10)\cdot 10^{5}\ \mathrm{cm}^2/\mathrm{Vs}$

$$(I/V) = G_{Co} = \sigma_{xx} 2\pi / \ln(dout/din)$$

Эксперимент с циркулярно поляризованным излучением

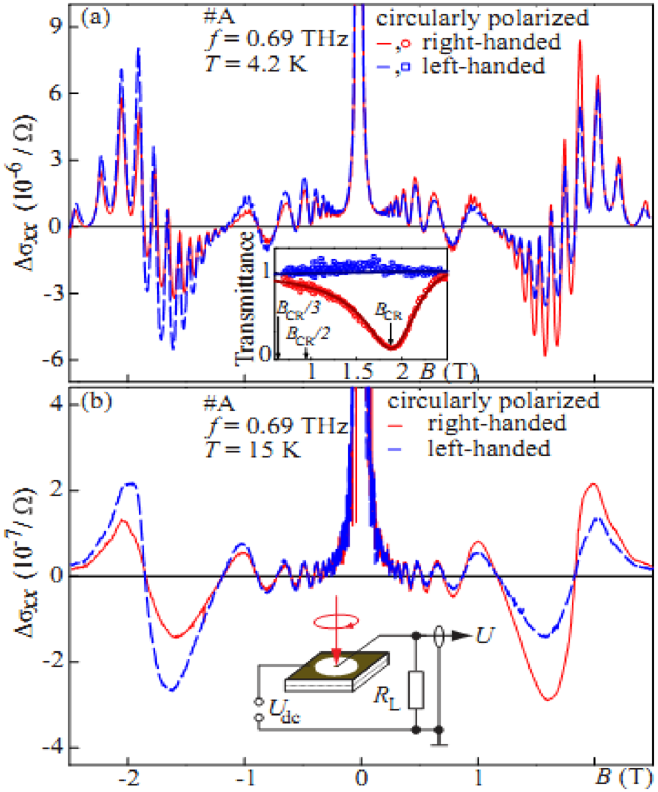


FIG. 1. Magnetic field dependence of $\Delta\sigma_{xx}$ induced by modulated cw radiation with power $P \approx 10$ mW. The inset in panel (a) shows the transmission data. Lines show the transmission calculated after [47] by taking multiple reflections within the substrate and the superradiant decay into account [47–50].

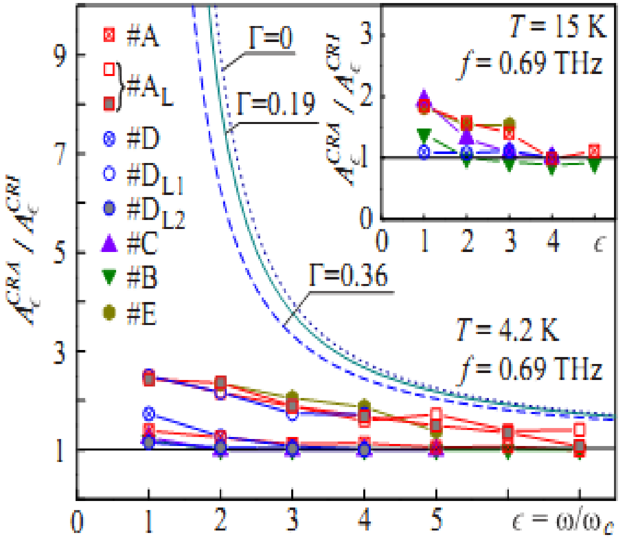


FIG. 4. $A_\epsilon^{CRA}/A_\epsilon^{CRI}$ vs ϵ for all samples. For sample A_L it is shown for the laser focused in between the contacts (open squares) and onto the edge of the outer Corbino contact (solid squares). D_{L1} and D_{L2} are large samples made from the same wafer. Lines are calculated using Eq. (3) for $\Gamma = 0.19$ and 0.36 corresponding to samples A and D, respectively.

Локальное зондирование

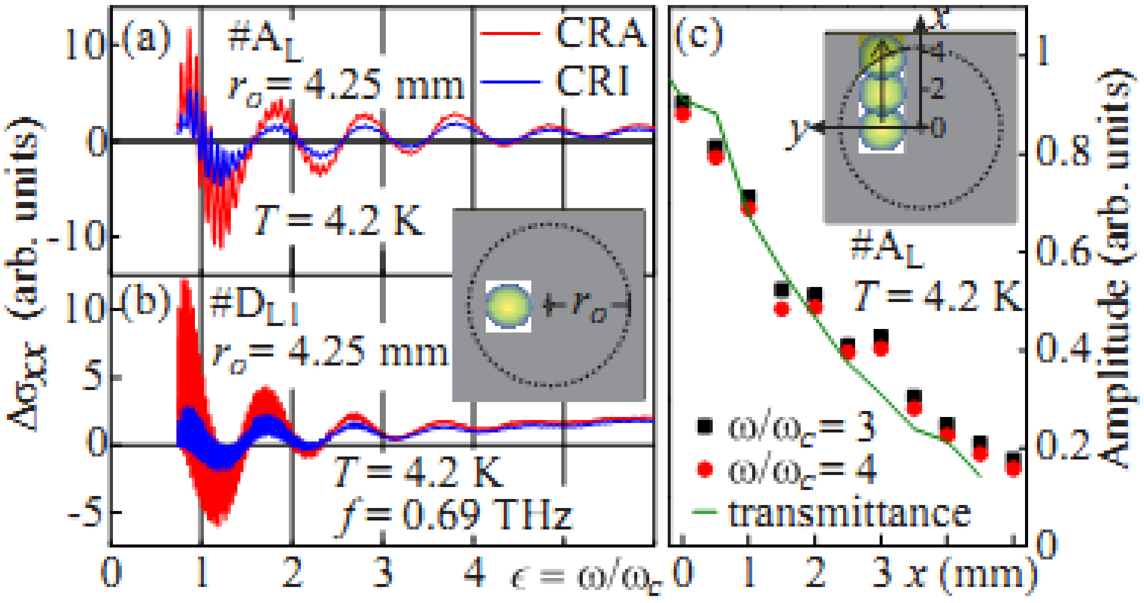
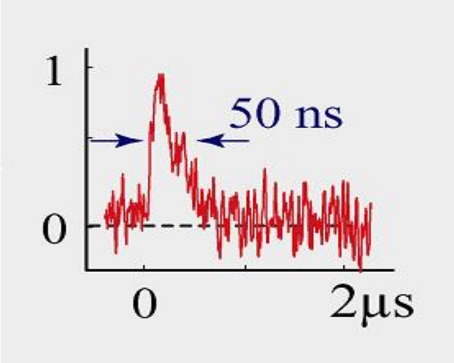


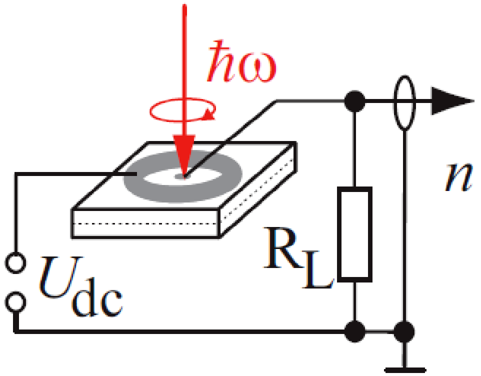
FIG. 3. $\Delta\sigma_{xx}$ as a function of ω/ω_c for large size samples A_L (a) and D_{L1} (b) with a metal mask (gray square) preventing irradiation of contacts. (c) Oscillation amplitude as a function of the laser spot position for sample covered by a metal mask with a slit (see inset). The beam is scanned along the slit from bulk regions of the Corbino disk onto the outer contact area. The solid line shows the transmission signal measured simultaneously with the oscillations.

Осцилляции МС, индуцированные мощным терагерцовым излучением.

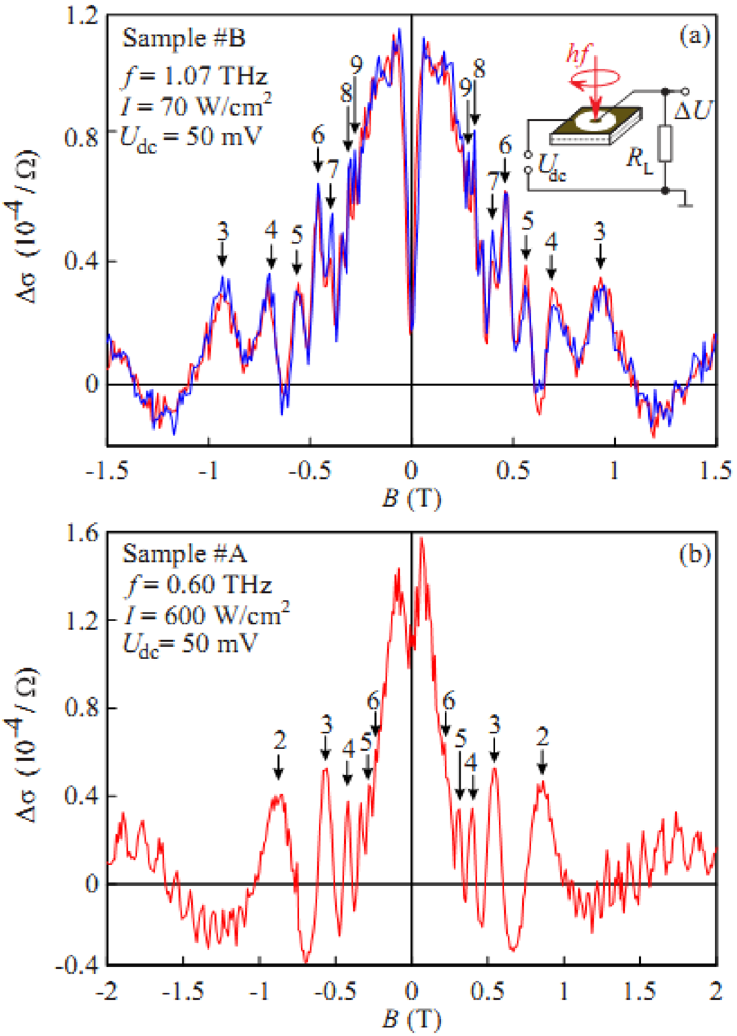
Excitation:

- pulsed molecular THz laser
- λ = 76, 90, 148, 280, 385, 496 μm
- pulse duration ~ 50 ns, power *P* ~ 10 kW

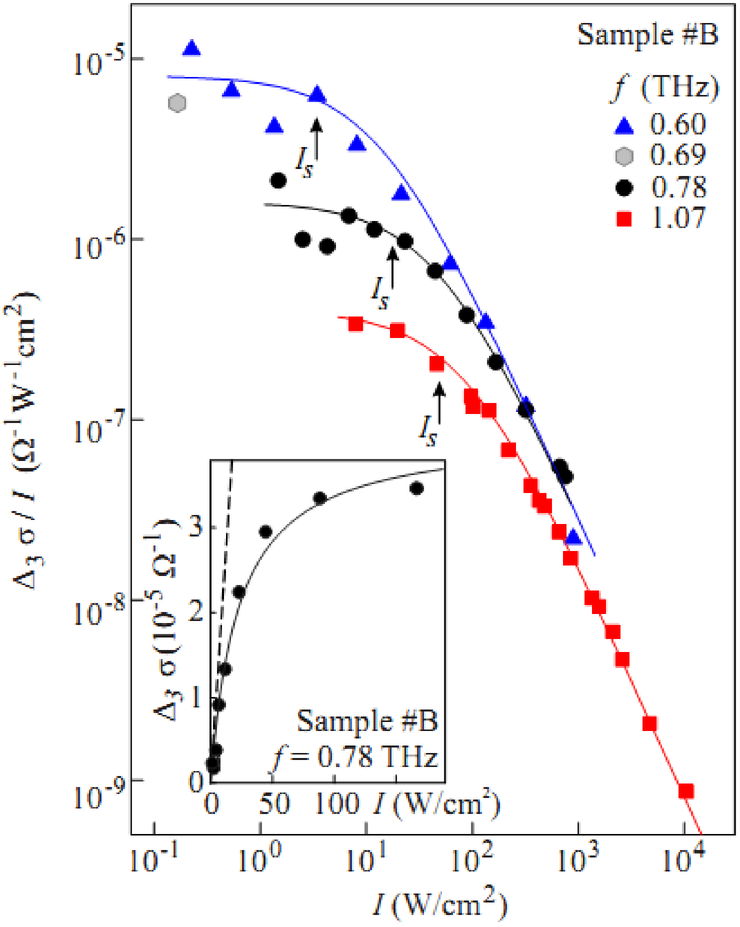




$$U_L = Gph \cdot Udc \cdot R_L$$



Зависимость от мощности



$$\Delta_N \sigma / I = (1 + I / I_s)^{-\beta}$$

While at low power (linear regime) TIRO exhibit a strong frequency dependence, comparison of the traces for different frequencies at high intensities shows that the TIRO amplitude becomes almost frequency independent in the saturation regime of the photoresponse.