Фотоэлектрический транспорт в двумерных сверхпроводниках

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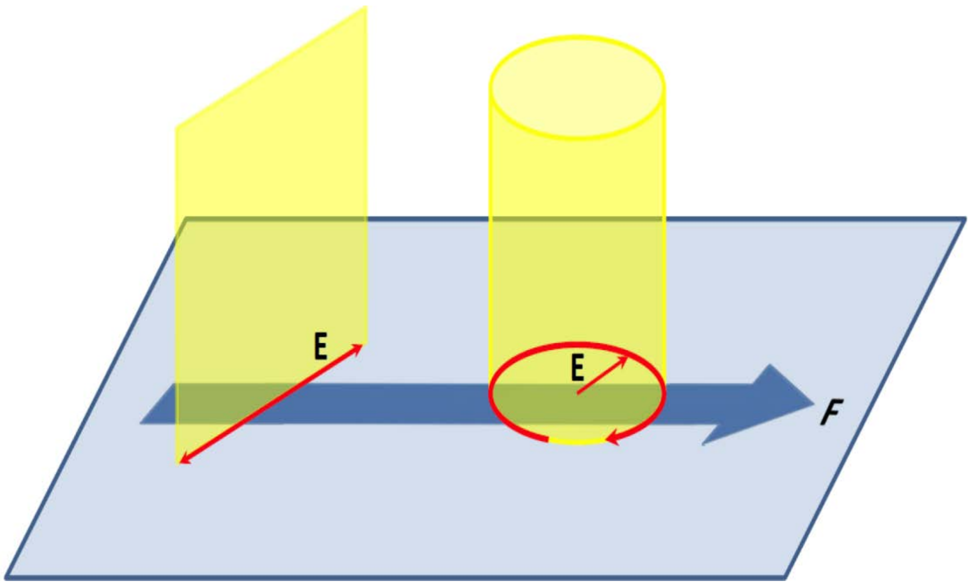
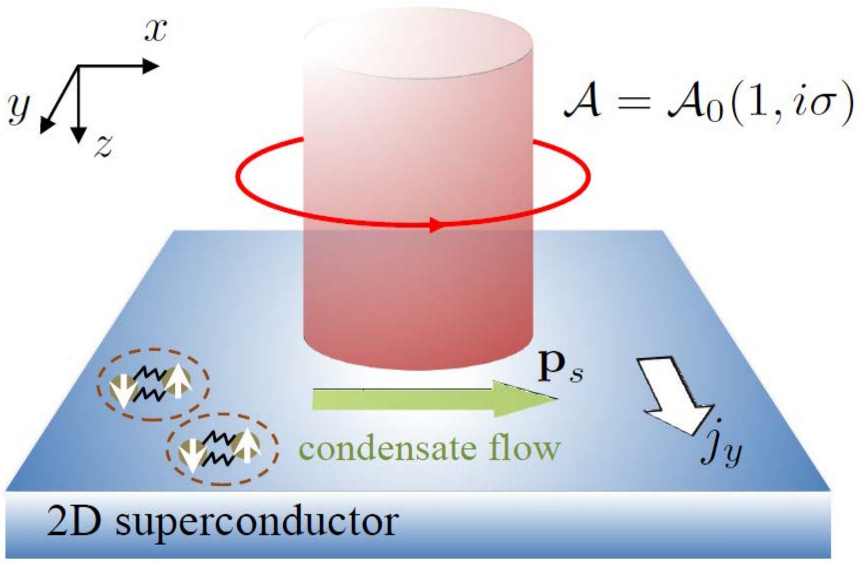
Stationary photocurrent in 2D conducting monolayer

Normal



Superconducting



$$j_\alpha = \sigma_{\alpha\beta} E_\beta + \chi_{\alpha\beta\gamma} E_\beta E_\gamma + \eta_{\alpha\beta\gamma\delta} E_\beta E_\gamma E_\delta + \ldots$$

Stationary photocurrent density with built-in in-plain static field F

$$j_\alpha = \chi_{\alpha\beta\gamma}(\mathbf{F}) E_\beta E_\gamma^*$$

$$\mathbf{j} = a_\omega |\mathbf{E}_\omega|^2 \mathbf{F} + b_\omega [\mathbf{E}_\omega (\mathbf{E}_\omega^* \cdot \mathbf{F}) + \mathbf{E}_\omega^* (\mathbf{E}_\omega \cdot \mathbf{F})] + i c_\omega [\mathbf{F} \times [\mathbf{E}_\omega \times \mathbf{E}_\omega^*]]$$

Photovoltaic Hall effect in semiconducting monolayer

Semiconducting

PHYSICAL REVIEW B **104**, 085306 (2021)

Photovoltaic Hall effect in the two-dimensional electron gas: Kinetic theory

M. V. Durnev

Ioffe Institute, 194021 St. Petersburg, Russia

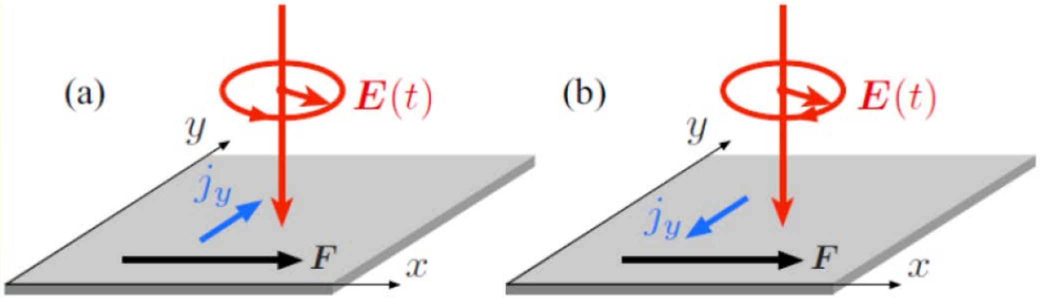
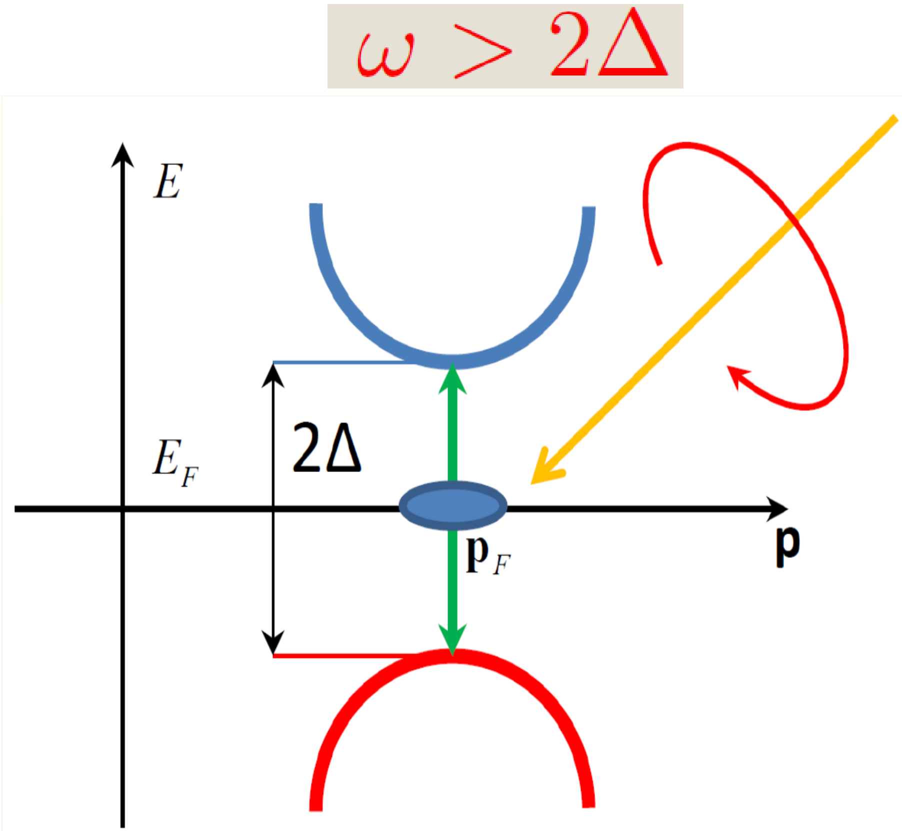
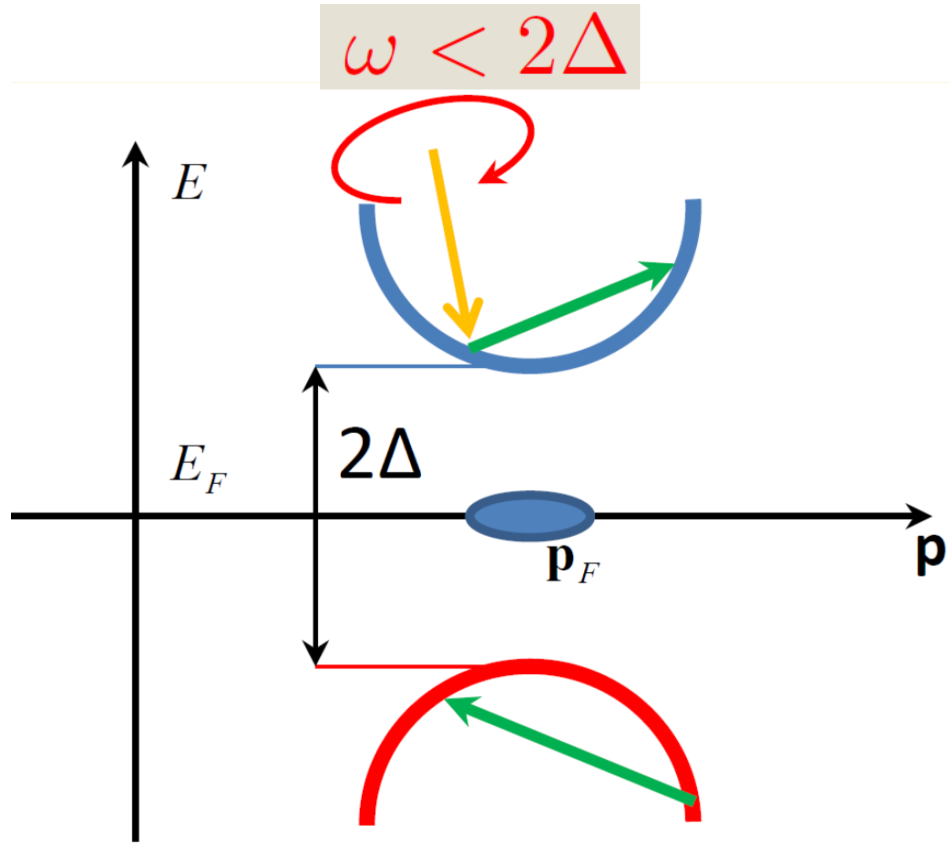


FIG. 1. The sketch of the photovoltaic Hall effect. Circularly polarized radiation induces transverse dc current, which direction is opposite for the right- (a) and left- (b) circular polarization.

Key result: normal electron gas with parabolic dispersion yields the photovoltaic Hall transport if the particle momentum relaxation time depends (!) on electron energy

Photovoltaic Hall effect in superconducting monolayer

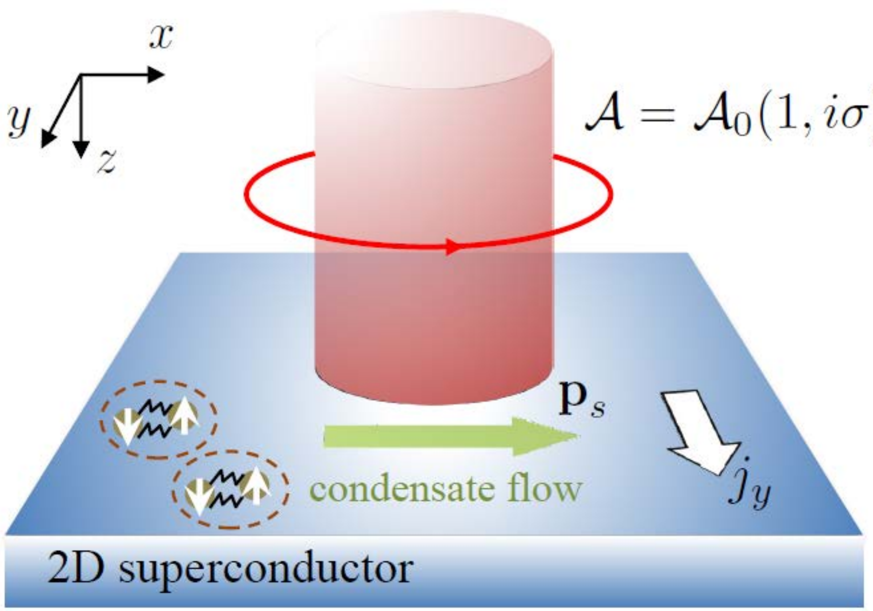




A.V. Parafilo, VMK, I.G. Savenko, Photoinduced anomalous supercurrent Hall effect, PRB (2023)

A V Parafilo, M Sun, K Sonowal, VMK, I G Savenko, Proposal for superconducting photodiode, 2D Materials (2025)

Photovoltaic Hall effect in superconducting monolayer



$$\mathbf{p}_s = (p_s, 0)$$

$\omega > 2\Delta$

$$j_y = \sigma \frac{e^3 p_s A_0^2}{2m} \left(\frac{\Delta}{\omega}\right)^2 \frac{\tau_R}{\tau_i} \Theta(\omega - 2\Delta)$$

$\omega < 2\Delta$

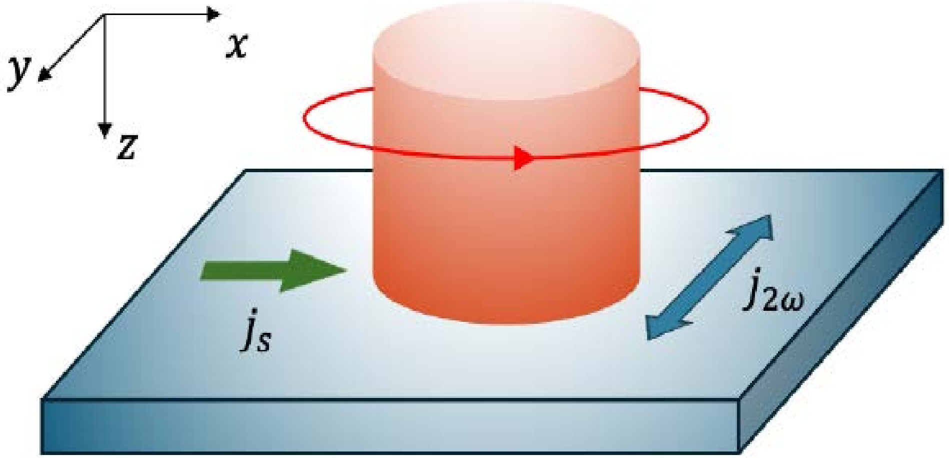
$$j_y = \frac{4 j_0\, \omega\tau_E}{[1 + (\omega\tau_E)^2]^2} \frac{\tau_E}{\tau_i} \left(\frac{\Delta}{2T}\right)^2 \mathcal{I}_1\left(\frac{\Delta}{2T}\right)$$

$$\mathcal{I}_1(y) = \int_y^\infty \frac{dx}{x^2 \cosh^2(x)}$$

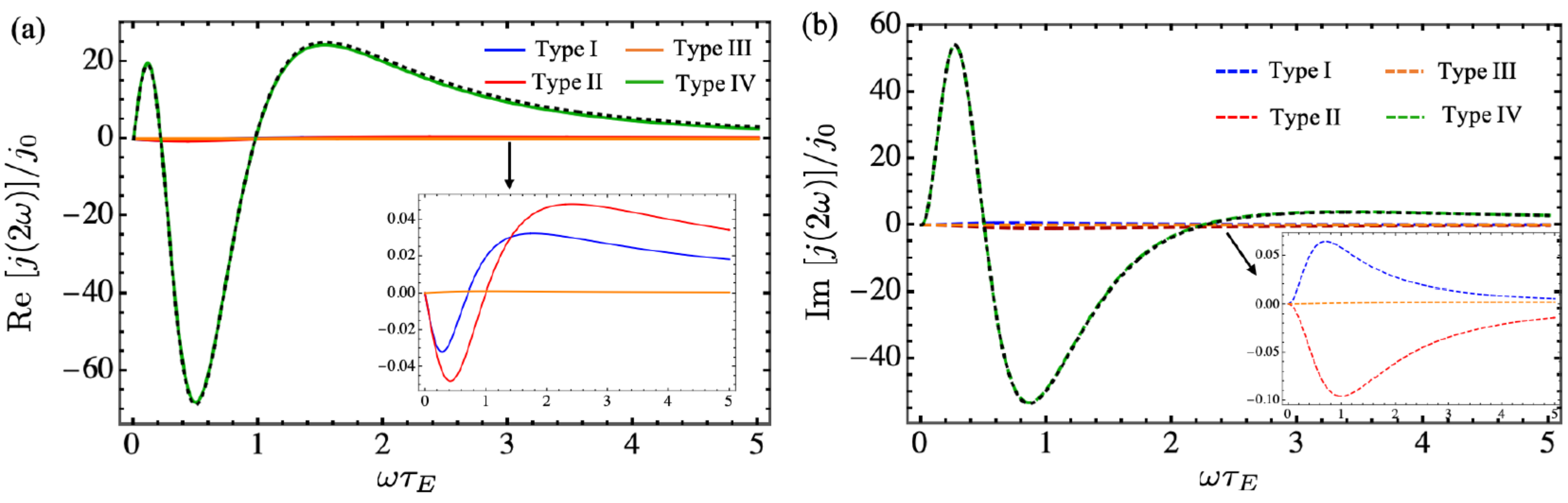
A.V. Parafilo, VMK, I.G. Savenko, Photoinduced anomalous supercurrent Hall effect, PRB (2023)

A V Parafilo, M Sun, K Sonowal, VMK, I G Savenko, Proposal for superconducting photodiode, 2D Materials (2025)

ac Hall effect (SHG) in superconducting monolayer

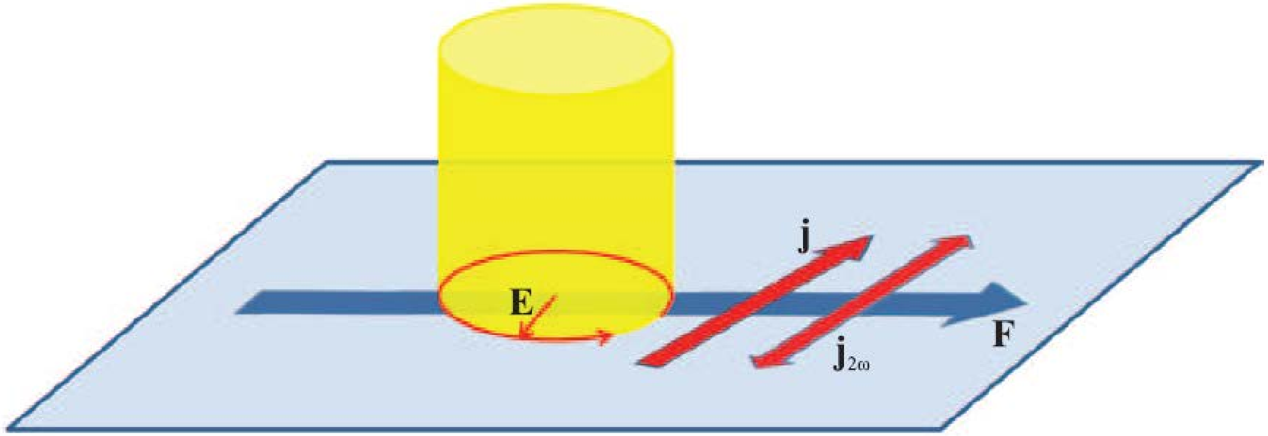


$$j_y^{IV}(2\omega) = 8 j_0 (2\tau_E T)^2 \left(\frac{\Delta}{2T}\right)^2 \frac{\omega\tau_E(2+3i\omega\tau_E)}{(4\omega^2\tau_E^2+1)^2} \times \frac{(2\omega\tau_E - i)^2(\omega\tau_E - i)^2}{(\omega^2\tau_E^2+1)^2} \tilde{\mathcal{I}}_{IV}\left(\frac{\Delta}{2T}\right)$$



K. Sonowal, A.V. Parafilo, VMK, I.G. Savenko, «Nonlinear ac Hall effect in two-dimensional superconductors», PRB (2024)

Photovoltaic Hall effect due to superconducting fluctuations



$$\mathbf{E}(t) = \mathbf{E}\exp(-i\omega t) + \mathbf{E}^*\exp(i\omega t)$$

dc Hall current

$$\mathbf{j} = i\gamma[\mathbf{F} \times [\mathbf{E} \times \mathbf{E}^*]]$$

ac (SHG) current

$$\mathbf{j}(t) = \{\alpha\mathbf{F}(\mathbf{E}\cdot\mathbf{E}) + \beta\mathbf{E}(\mathbf{F}\cdot\mathbf{E})\}e^{-2i\omega t} + \mathrm{c.c.}$$

М.В. Боев, ВМК, «Фотовольтаический эффект Холла в двумерных флуктуирующих сверхпроводниках», Письма в ЖЭТФ, (2024)

Kinetic equation approach

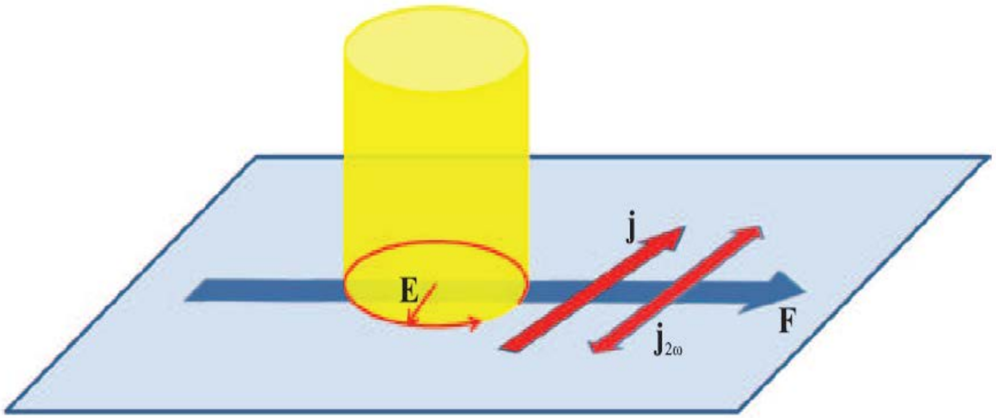
$$\frac{\partial f}{\partial t} + \frac{f - f_0}{\tau_{\mathbf{p}}} + 2e(\mathbf{F} + \mathbf{E}(t)) \cdot \nabla_{\mathbf{p}} f = 0$$

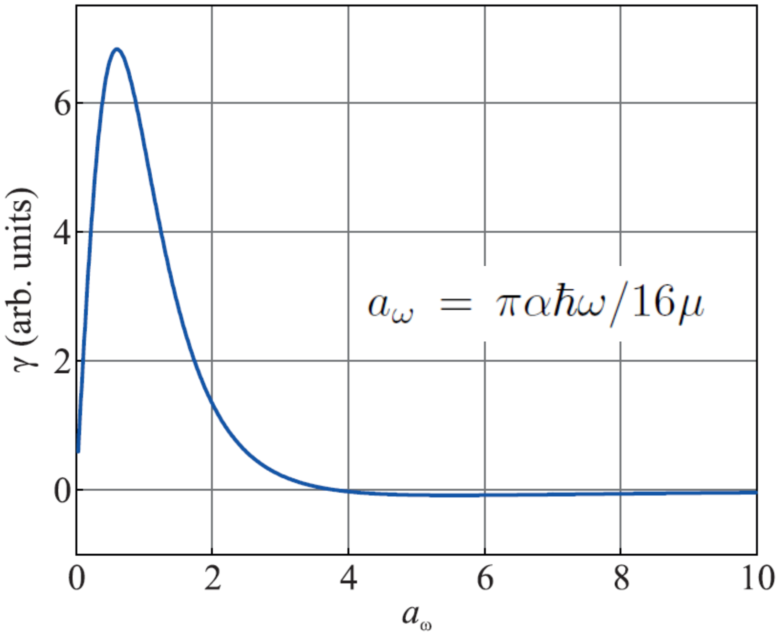
$$f_0 = T/(\varepsilon_{\mathbf{p}} + \mu)$$

$$\varepsilon_{\mathbf{p}} = p^2/4m \qquad \mu = \alpha T_c \epsilon, \; \epsilon = (T - T_c)/T_c$$

$$\tau_{\mathbf{p}} = \pi\alpha/(16(\varepsilon_{\mathbf{p}} + \mu))$$

dc Hall effect



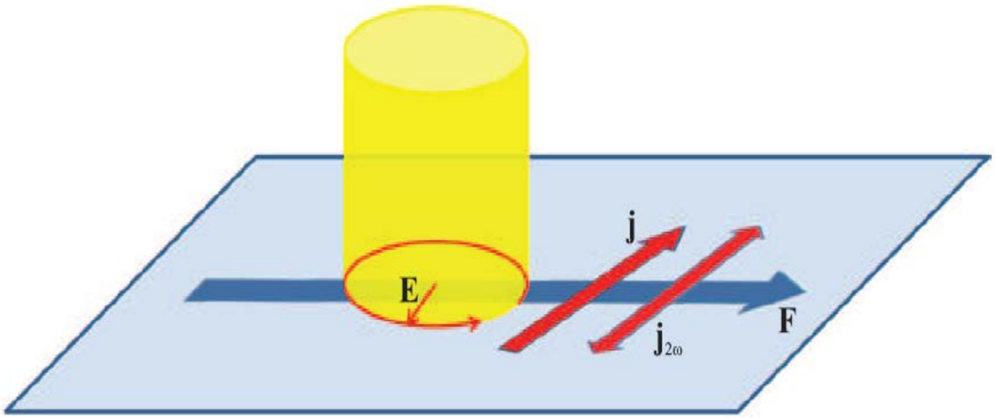


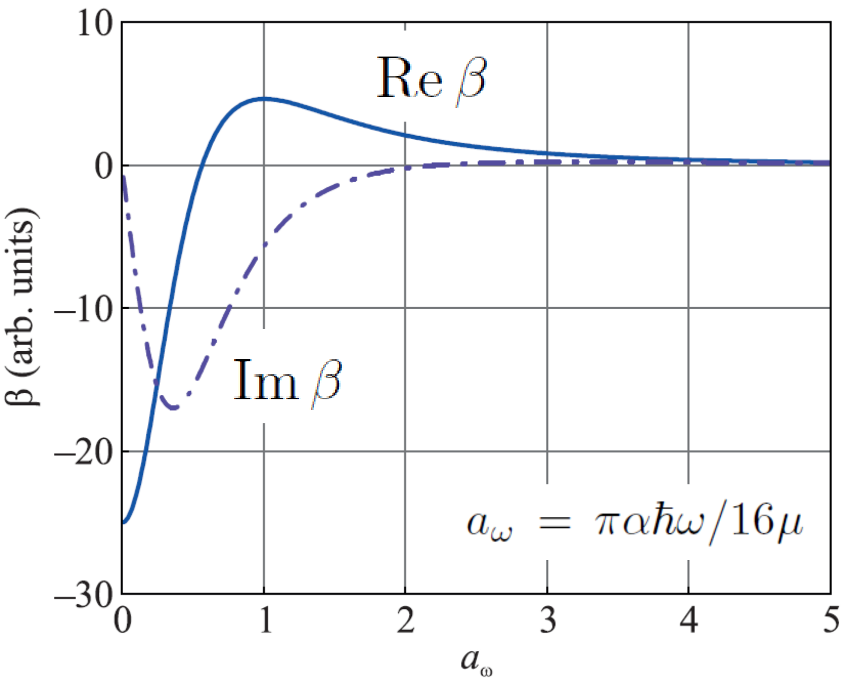
$$\mathbf{j} = i\gamma[\mathbf{F} \times [\mathbf{E} \times \mathbf{E}^*]]$$

$$\gamma = \frac{2(2e)^4}{(2m)^2} \int \frac{d^2\mathbf{p}}{(2\pi\hbar)^2} \left(\frac{\omega\tau_{\mathbf{p}}^3}{(1+\omega^2\tau_{\mathbf{p}}^2)^2} \right)' \varepsilon_{\mathbf{p}}\tau_{\mathbf{p}} f_0'$$

$$\gamma = \frac{(2e)^4}{20\pi} \left(\frac{\pi\alpha}{16}\right)^3 \left(\frac{T_c\hbar}{m\mu^4}\right) a_\omega \sim \frac{\omega}{(T-T_c)^5}$$

ac Hall effect



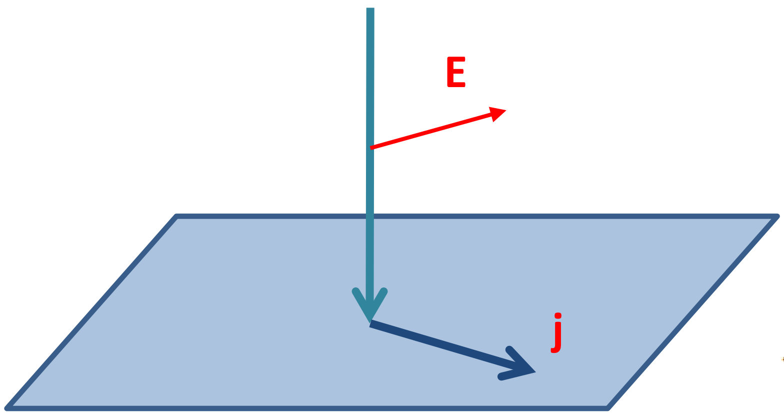


$$\mathbf{j}(t) = \{\alpha\mathbf{F}(\mathbf{E}\cdot\mathbf{E}) + \beta\mathbf{E}(\mathbf{F}\cdot\mathbf{E})\}e^{-2i\omega t} + \text{c.c.}$$

$$\beta = -\frac{(2e)^4}{2\pi 2m}\int_0^\infty d\varepsilon\, f_0'\Big\{\varepsilon(\tau_\varepsilon + \tau_\omega)[\tau_\omega(\varepsilon\tau_{2\omega})']' + \frac{\tau_\omega}{2}[\varepsilon^2(\tau_{2\omega}^2)']'\Big\}$$

Fluctuating photogalvanic transport in noncentrosymmetric 2D Ising superconductors

Photogalvanic effect (PGE)



General expression

$$j_\alpha = \frac{L_{\alpha\beta\gamma}}{2}\left(E_\beta E_\gamma^* + E_\beta^* E_\gamma\right) + iC_{\alpha\beta}[\mathbf{E}\times\mathbf{E}^*]_\beta$$

Microscopics

Asymmetry of

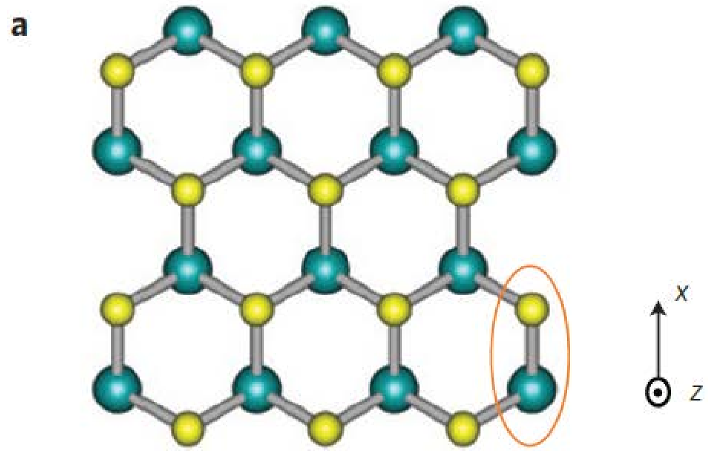
1) Electron scattering processes,
2) Generation/Recombination processes,
3) Spin-related phenomena,
4) Coulomb interaction,
5) Anisotropy and nonparabolicity,
6) …

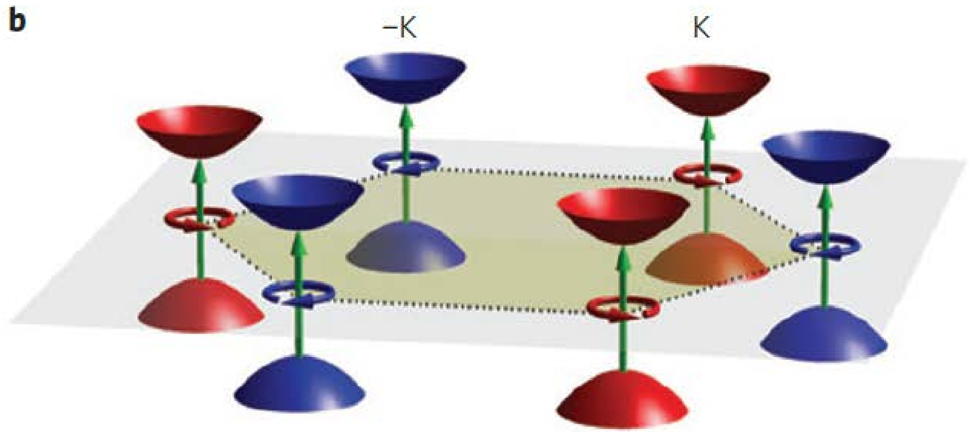
Photogalvanic effect:

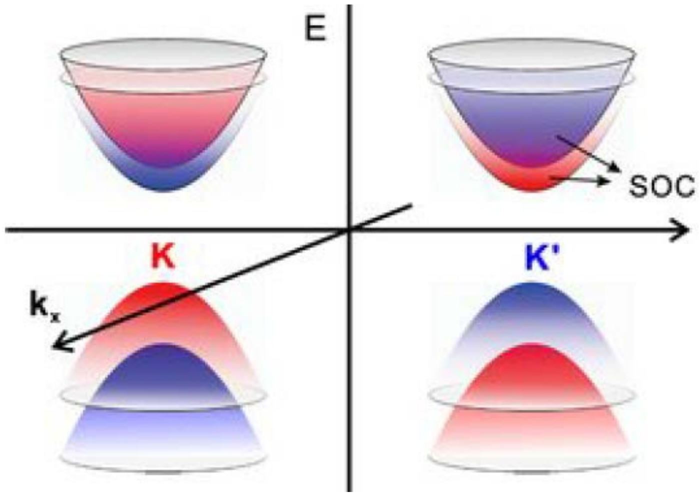
The emergence of a stationary electric current in a homogeneous medium under the action of uniform stationary illumination in the absence of (stationary) dragging fields. This effect is not connected with the transfer of a momentum from photons to electrons.

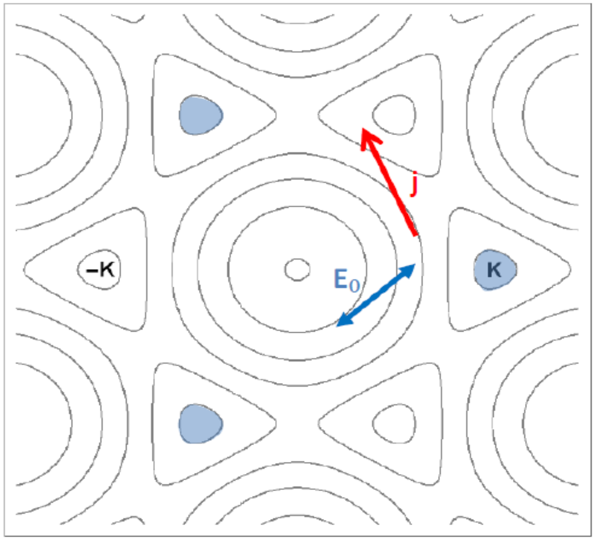
Belinicher, Sturman, *Sov. Phys. Usp.* (1980); Ivchenko, «*Optical spectroscopy…*» (2007)

MoS2 monolayer: Band structure







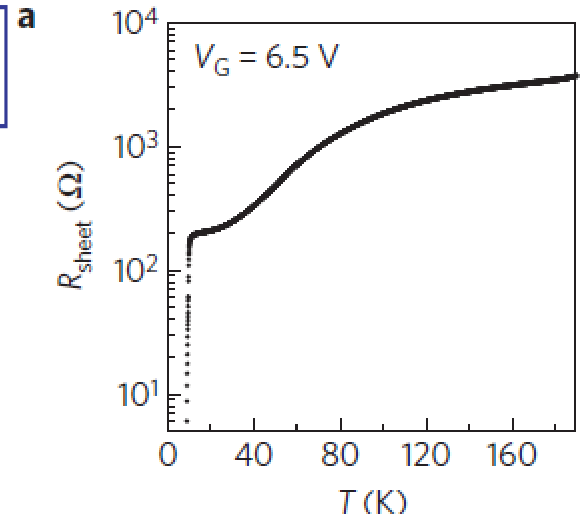


Superconductivity in MoS2

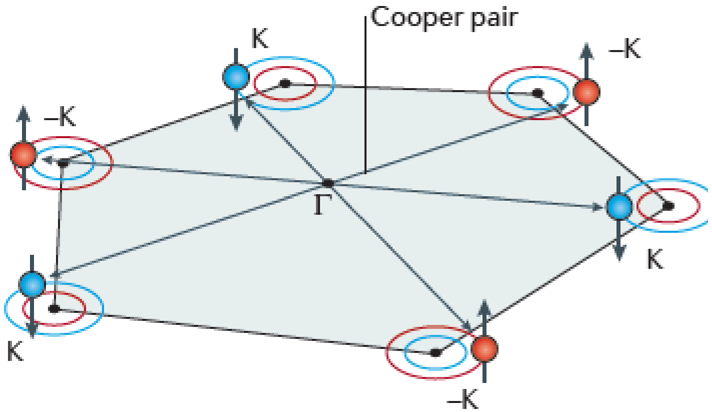
LETTERS
PUBLISHED ONLINE: 7 DECEMBER 2015 | DOI: 10.1038/NPHYS3580
nature physics

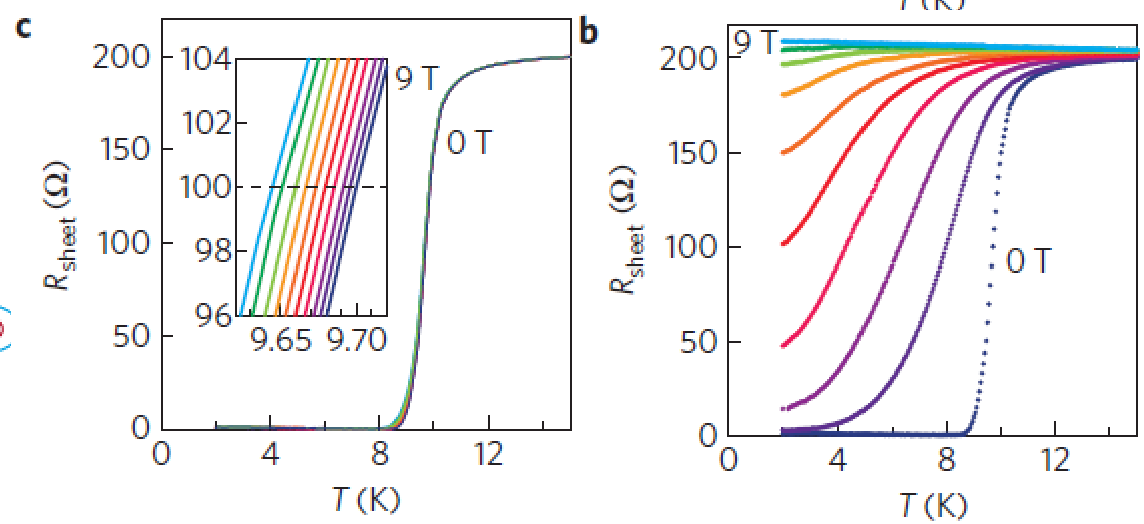
Superconductivity protected by spin–valley locking in ion-gated MoS_2

Yu Saito[1*], Yasuharu Nakamura[2,3], Mohammad Saeed Bahramy[1,4], Yoshimitsu Kohama[5], Jianting Ye[1,4], Yuichi Kasahara[3], Yuji Nakagawa[1], Masaru Onga[1], Masashi Tokunaga[5], Tsutomu Nojima[6], Youichi Yanase[3,7] and Yoshihiro Iwasa[1,4*]



Intervalley Cooper pairing

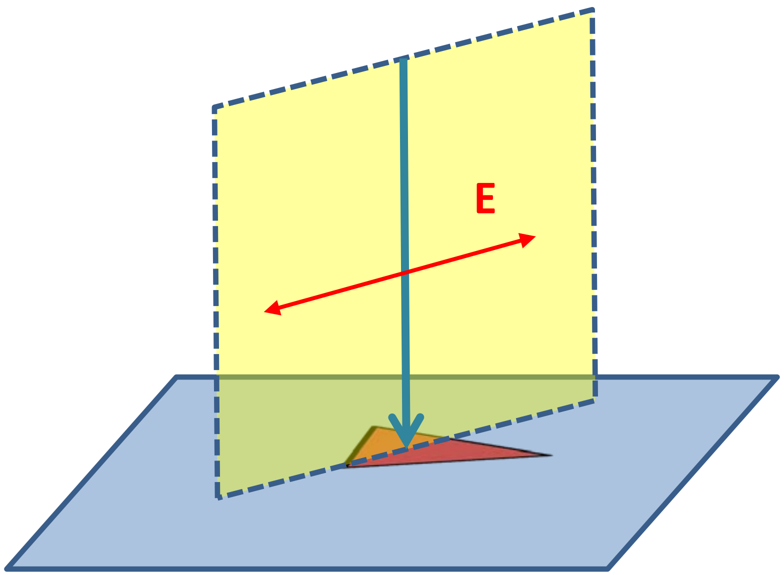


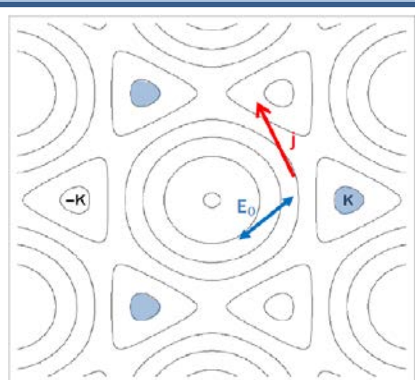


«Почти» s-wave

Ising superconductivity

PGE in MoS2 monolayer





1) Phenomenological expression for D3h group

$$j_x = \lambda(|E_x|^2 - |E_y|^2),$$
$$j_y = -\lambda(E_x E_y^* + E_x^* E_y)$$

2) Microscopic mechanism:

Trigonal warping of valley dispersion

$$\varepsilon_{\mathbf{p}} = \frac{\mathbf{p}^2}{2m} + \eta W (p_x^3 - 3p_x p_y^2)$$

3) Violating of valley degeneracy:

a) Optical valley-selective population

b) External (weak) magnetic field

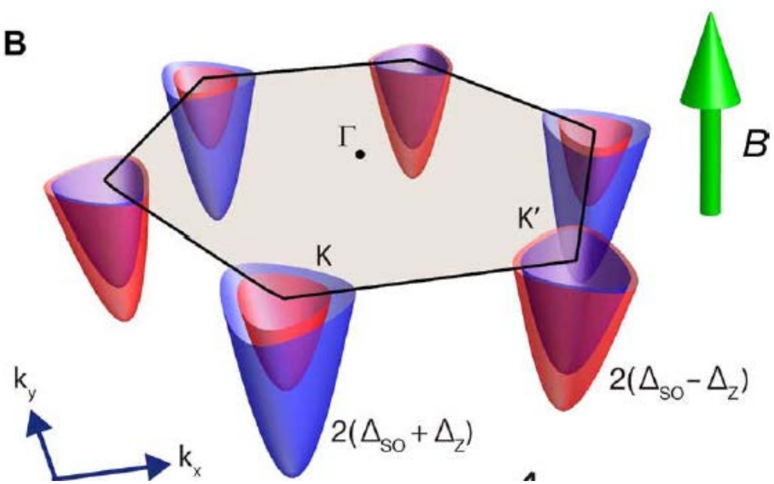
Entin, Magarill, Kovalev, J. Phys.: Condens. Matter (2019)

PGE in Superconducting MoS2

PGE in D3h group

$$j_x = \lambda(|E_x|^2 - |E_y|^2),$$
$$j_y = -\lambda(E_x E_y^* + E_x^* E_y)$$

TDGL with warping has been derived in **Wakatsuki et.al., Sci. Adv. (2017)**



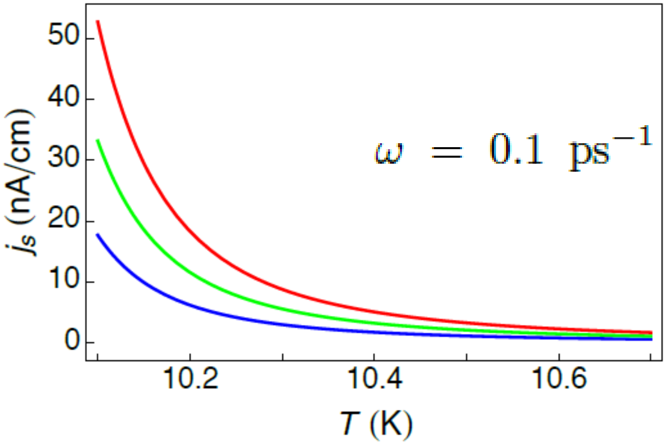
TDGL

$$\gamma\left(\frac{\partial}{\partial t} + 2ie\varphi\right)\Psi +$$
$$\left[\alpha T_c(\epsilon + \xi^2 p^2) + \Lambda(p_x^3 - 3p_x p_y^2)\right]\Psi = \eta$$
$$\Lambda \propto \Delta_z \Delta_{SO} w$$

PGE in Superconducting MoS2

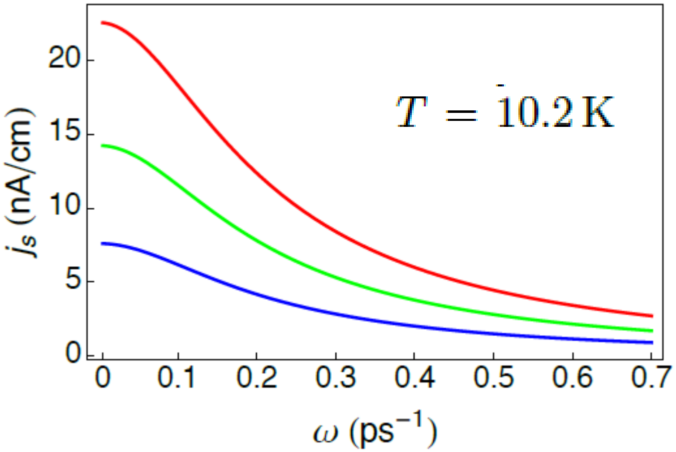
PGE in D3h group

$$j_x = \lambda(|E_x|^2 - |E_y|^2),$$
$$j_y = -\lambda(E_x E_y^* + E_x^* E_y)$$



$$\lambda = \frac{3e^3\Lambda m\pi}{16\hbar^3 k_B T_c \epsilon^2}\frac{1}{\tilde{\omega}^2}\left[1 + \frac{\log\left(1+\tilde{\omega}^2\right)}{\tilde{\omega}^2} + \frac{\pi}{2}\left(\frac{1}{\tilde{\omega}^3} - \frac{1}{\tilde{\omega}}\right) - \frac{1}{\tilde{\omega}}\left(1 + \frac{1}{\tilde{\omega}^2}\right)\arctan\tilde{\omega} + \frac{1}{\tilde{\omega}}\left(1 - \frac{1}{\tilde{\omega}^2}\right)\arctan\frac{1}{\tilde{\omega}}\right]$$

$$\tilde{\omega} = \frac{\pi\hbar\omega}{16k_B(T - T_c)}$$



$\tau = 5\,\mathrm{ps}$ (red)
$\tau = 0.3\,\mathrm{ps}$ (green)
$\tau = 0.1\,\mathrm{ps}$ (blue).
$T_c = 10\,\mathrm{K}$
$B = 1\,\mathrm{T}$

Disorder

$\Lambda_\tau = \Lambda \cdot f_\tau(2\pi T_c \tau)$

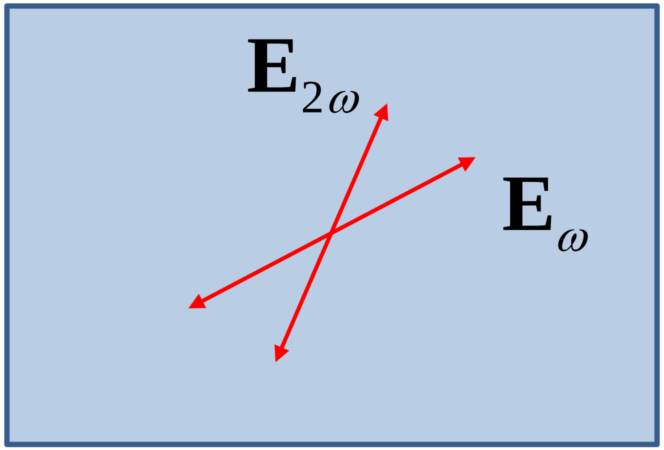
$f_\tau(2\pi T_c \tau \gg 1) \to 1$

$f_\tau(2\pi T_c \tau \ll 1) \to 0.$

Model applicability: $\omega\tau << 1$

Parafilo, Boev, Kovalev, Savenko, submitted to PRB (2022)

Fluctuating Coherent PGE transport in isotropic 2D superconductors: Symmetry consideration



$$\mathbf{E}(t) = \mathbf{E}_{\omega} e^{-i\omega t} + \mathbf{E}_{2\omega} e^{-2i\omega t}$$

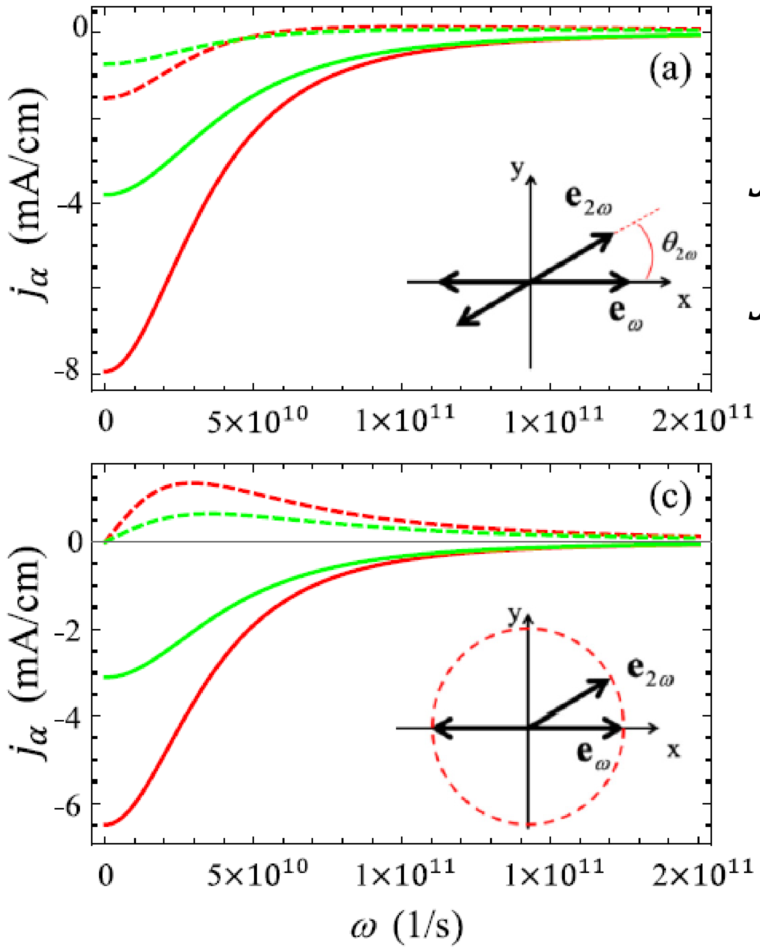
$$\mathbf{j} = A\,\mathbf{E}_{2\omega} E_{\omega}^{2} + B\Big(\mathbf{E}_{\omega}(\mathbf{E}_{2\omega}^{*}\cdot\mathbf{E}_{\omega}) + c.c.\Big) + \\ + iC[\mathbf{E}_{\omega}^{*}\times[\mathbf{E}_{2\omega}\times\mathbf{E}_{\omega}^{*}]] + c.c.$$

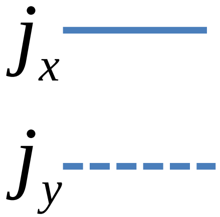
1989 ФИЗИКА И ТЕХНИКА ПОЛУПРОВОДНИКОВ том 23, вып. 6
1989 PHYSICS AND TECHNICS OF SEMICONDUCTORS vol. 23, N 6

ТЕОРИЯ КОГЕРЕНТНОГО ФОТОГАЛЬВАНИЧЕСКОГО ЭФФЕКТА

Энтин М. В.

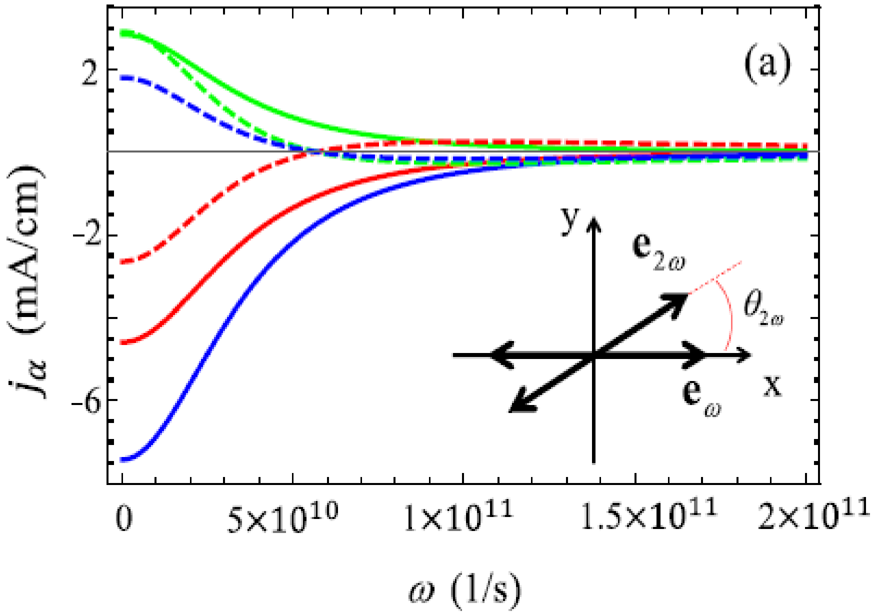
Fluctuating Coherent PGE transport in isotropic 2D superconductors





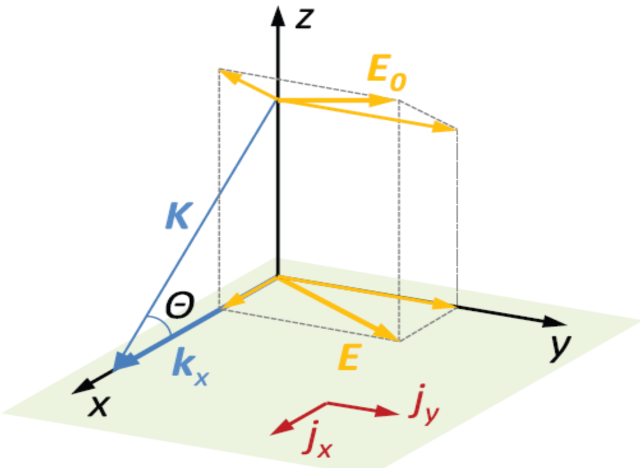
$\mathbf{j} \propto (T - T_c)^{-3}$

Currents may change the sign



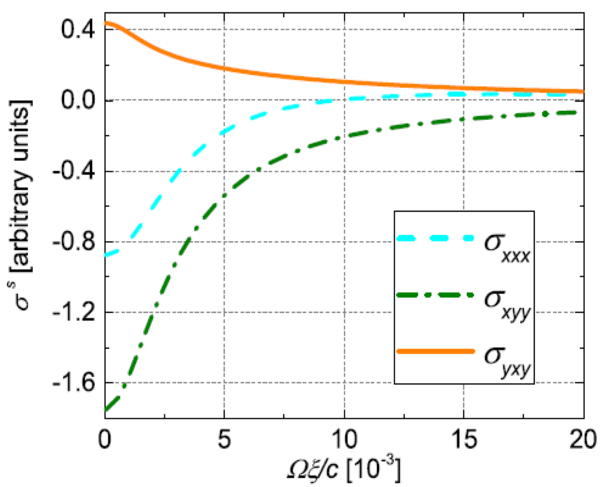
Kovalev, Sonoval, Savenko, PRB (2021)

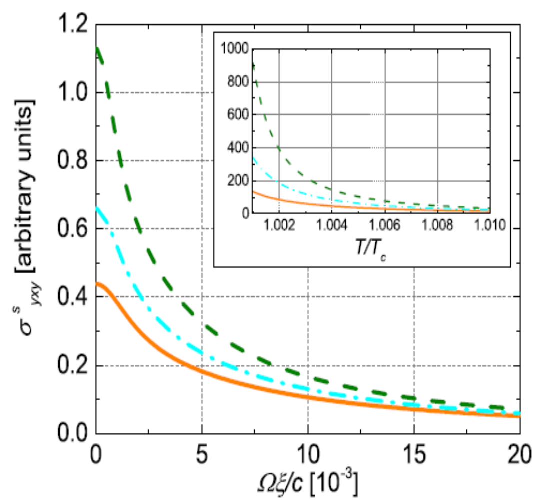
Photon drag effect in 2D isotropic superconductors

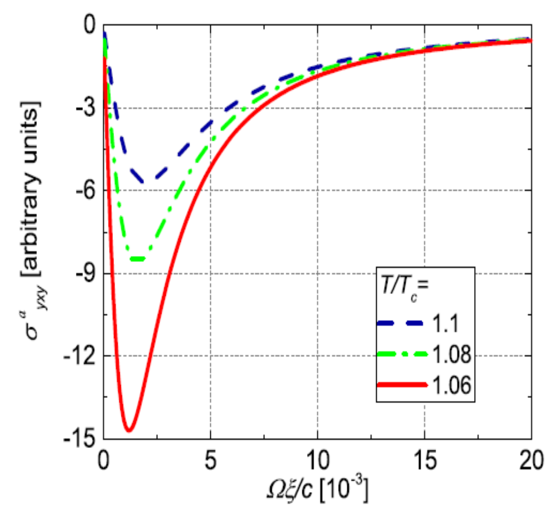


$$\begin{pmatrix} j_x \\ j_y \end{pmatrix} = \begin{bmatrix} \sigma^s_{xxx}|E_x|^2 + \sigma^s_{xyy}|E_y|^2 \\ \sigma^s_{yxy}(E_xE_y^* + E_x^*E_y) - i\sigma^a_{yxy}(E_xE_y^* - E_x^*E_y) \end{bmatrix}$$

$$\frac{j^s}{j_n} = \frac{8}{3}\frac{\gamma''}{\gamma'}\frac{Tn\xi^2}{T_c}\left(\frac{\sigma_{\mathrm{AL}}}{\sigma_n}\right)^2 \qquad \mathbf{j}_n = \frac{2e^3 n}{\Omega m^2}\frac{\tau^2}{1+(\Omega\tau)^2}|E|^2\mathbf{k}.$$

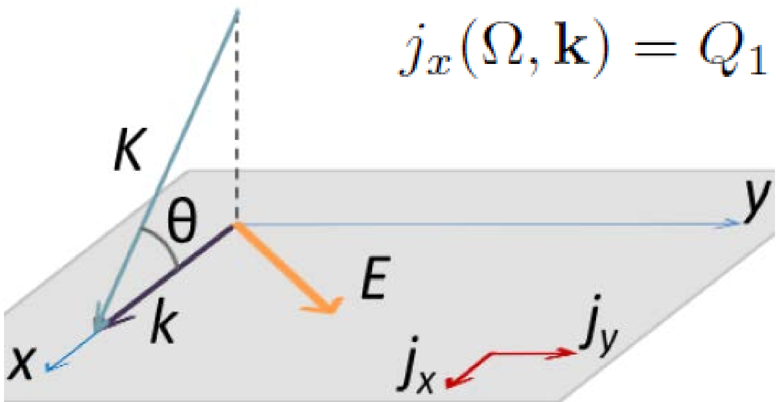






Boev, PRB (2021)

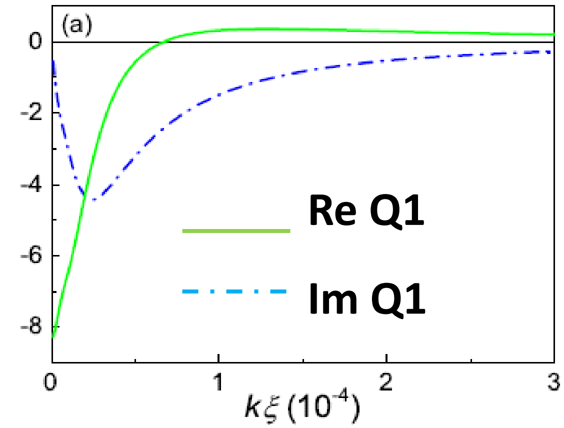
Second Harmonic Generation in 2D isotropic superconductors



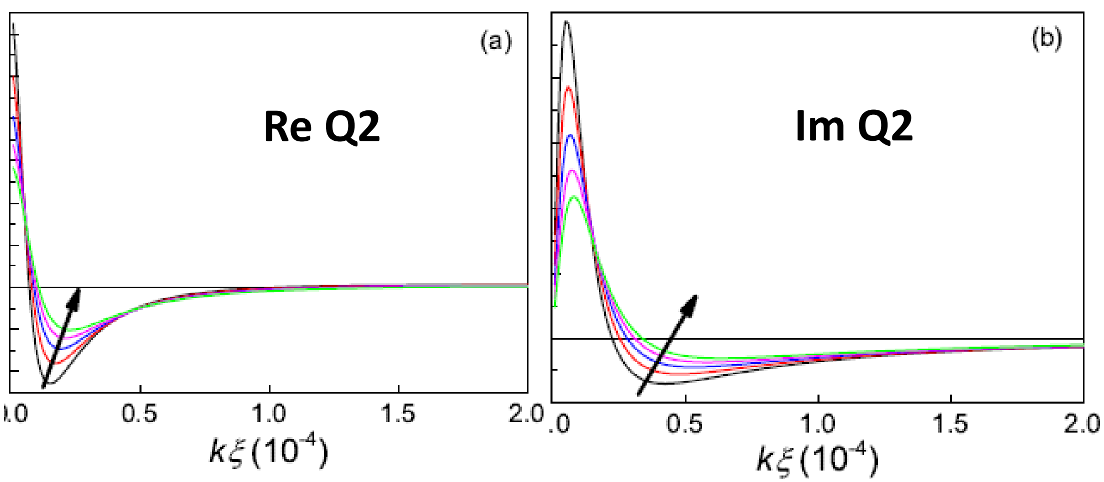
$$j_x(\Omega, \mathbf{k}) = Q_1(\Omega, \mathbf{k})(E_x^2 + E_y^2) + Q_2(\Omega, \mathbf{k})(E_x^2 - E_y^2)$$

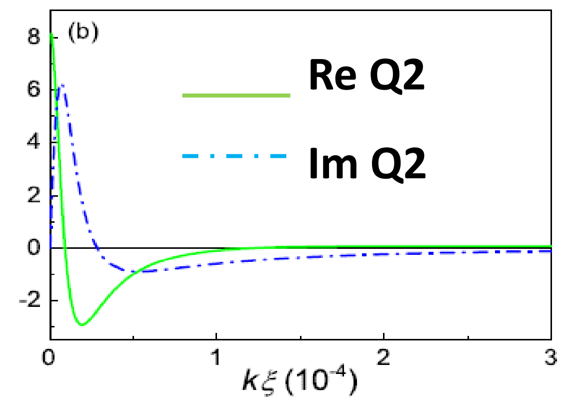
$$j_y(\Omega, \mathbf{k}) = 2Q_2(\Omega, \mathbf{k})E_x E_y$$

$$Q_{1,2} \propto (T - T_c)^{-2}$$



Temperature dependence





Boev, Kovalev, JETP Lett. (2022)

Фотоэлектрический транспорт в двумерных сверхпроводниках

Ковалёв В.М.

Институт физики полупроводников им. А.В. Ржанова СО РАН