ФОТОГАЛЬВАНИЧЕСКИЕ ЭФФЕКТЫ В НИЗКОРАЗМЕРНЫХ СИСТЕМАХ – 2 ГЕОМЕТРИЧЕСКИЕ ЭФФЕКТЫ

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PHOTOCURRENTS IN 2D SYSTEMS

Excitation by plane wave $\mathbf{E}(t) = \mathbf{E} \exp(-i\omega t) + \text{c. c.}$ (complex) amplitude **Photocurrents** $j \propto EE^*$, i. e. , $\propto I$ radiation intensity

Mechanisms of dc current (photocurrent) induced by homogeneous radiation

- Macroscopic inhomogeneity (*p*-*n* junction, asymmetry of contacts, ratchets)
- Lack of space inversion symmetry at microscopic level (photogalvanic effects)
- Photon drag (light pressure)

ПЛАН ЛЕКЦИИ

- Краевые фотогальванические эффекты в 2D материалах
	- микроскопические механизмы, кинетическая теория эксперимент на графене
	- генерация второй гармоники
- Фототоки, индуцированные структурированным светом
- Основные результаты

EDGE CURRENTS IN TWO-DIMENSIONAL SYSTEMS

Symmetry is naturally broken at edges ⇒ Second-order effects get allowed

First study of edge photogalvanic effect in 2D systems (graphene)

J. Karch et al., Phys. Rev. Lett. **107**, 276601 (2011)

Surface photogalvanic effects in bulk materials and films

L.I. Magarill, M.V. Entin, Phys. Solid State (1979), JETP (1981)

V.L. Alperovich, A. Minaev, A.S. Terekhov, JETP Lett. (1979)

V.L. Alperovich, V.I& Belinicher, V.N. Novikov, A.S. Terekhov, JETP (1981)

V.L. Gurevich, R. Laiho, Phys. Rev. B (1993)

C.B. Schmidt, S. Priyadarshi, S.A.T., M. Bieler, Phys. Rev. B (2015)

G.M. Mikheev, A.S. Saushin, V.M. Styapshin, Y.P. Svirko, Sci. Rep. (2018)

Edge plasmons

D.B. Mast, A.J. Dahm, and A.L. Fetter, Phys. Rev. Lett. (1985) V.A. Volkov, S.A. Mikhailov, JETP Lett. (1985), JETP (1988) I.V. Kukushkin, M.Yu. Akimov, J.H. Smet, S.A. Mikhailov, K. von Klitzing, I.L. Aleiner, V.I. Falko, PRL (2004) V.M. Muravev, P.A. Gusikhin, A.M. Zarezin, I.V. Andreev, S.I. Gubarev, and I.V. Kukushkin, PRB (2019) A.A. Zabolotnykh, V.A. Volkov, Phys. Rev. B (2019)

Review on edge photogalvanic effects in topological insulators

M.V. Durnev and S.A.T., Ann. Phys. **531**, 1800418 (2019)

EDGE CURRENTS EXCITED BY LINEARLY AND CIRCULARLY POLARIZED RADIATION

E(t)

 E *Jy Jy* c) and c) and c) and c) and c) and c) *E(t) x y E(t) Jy E(t) E(t) Jy Jy* c) de la construcción de la constr *x y E(t)*

 J_{ν}

E(t)

 $J_{\rm \nu}$

$J_y \propto (E_x E_y^* + E_y E_x^*)$ \propto sin2 φ Linearly polarized radiation

Circularly polarized radiation

 $J_y \propto i(E_x E_y^* - E_y E_x^*)$ $\propto P_{\text{circ}}$

QUASI-CLASSICAL APPROACH

Kinetic equation for distribution function

$$
\frac{\partial f}{\partial t} + v_x \frac{\partial f}{\partial x} + e\mathcal{E}(x, t) \cdot \frac{\partial f}{\partial p} = \mathbf{I}\{f\}
$$

Electric field (external field + screening)

$$
\mathcal{E}_{\omega, x}(x) = E_{\omega, x} + \frac{2}{\epsilon} \int_{0}^{\infty} \frac{\rho_{\omega}(x') dx'}{x - x'}, \quad \mathcal{E}_{\omega, y} = E_{\omega, y}
$$

D = **mean free path**

M ≈ αποπασμοπαν Polarization dependence

 $J_y \propto E_x E_y \propto \sin 2\varphi$

+ Boundary condition at $x = 0$

* 0.000 μ 0.000 μ 0.000 μ 0.000 μ 5 μ 5

SOLUTION OF THE KINETIC EQUATION

Expansion in the Fourier series

$$
f(\mathbf{p}, x, t) = f_0 + [f_1(\mathbf{p}, x)e^{-i\omega t} + c.c.] + f_2(\mathbf{p}, x) + \dots
$$

$$
f_1 \propto E \qquad f_2 \propto EE^*
$$

The density of dc electric current and the total dc current ∞

$$
j_y(x) = ev \sum_{\uparrow} v_y f_2(x, \mathbf{p}) \qquad J_y = \int_0^x j_y(x) dx
$$

the spin and valley degeneracy

The edge current

$$
J_{y} = -ev\tau \sum_{p} v_{x} v_{y} [f_{2}(\boldsymbol{p}, \infty) - f_{2}(\boldsymbol{p}, 0)] + i \frac{e^{2} v \tau}{\omega m^{*}} \sum_{p} v_{x} [E_{y} f_{1}^{*}(\boldsymbol{p}, \infty) - \text{c.c.}]
$$

S. Candussio, M.V. Durnev, J. Yin, J. Keil, Y. Yang, S.-K. Son, A. Mishchenko, H. Plank, V.V. Bel'kov, S. Slizovskiy, S.A.T., V. Fal'ko, and S.D. Ganichev, PRB **102**, 045406 (2020) M.V. Durnev and S.A.T., Phys. Status Solidi B **258**, 2000291 (2021)

CONTRIBUTIONS TO EDGE CURRENT

$$
J_{y} = -ev\tau \sum_{p} v_{x} v_{y} [f_{2}(\mathbf{p}, \infty) - f_{2}(\mathbf{p}, 0)] + i \frac{e^{2} v\tau}{\omega m^{*}} \sum_{p} v_{x} [E_{y} f_{1}^{*}(\mathbf{p}, \infty) - c.c.]
$$

py

Alignment of electron momenta by linearly polarized radiation

Anisotropic part of the distribution function

E

px

$$
f_2(\mathbf{p}, \infty) \propto \sum_{\alpha, \beta} \left(p_\alpha p_\beta - \frac{p^2}{2} \right) E_\alpha E_\beta
$$

j **⁺** *j E* 2nd angular harmonic in *p*-space

D = **mean free path**

CONTRIBUTIONS TO EDGE CURRENT

$$
J_{y} = -ev\tau \sum_{p} v_{x} v_{y} [f_{2}(\boldsymbol{p}, \infty) - f_{2}(\boldsymbol{p}, 0)] + i \frac{e^{2} v\tau}{\omega m^{*}} \sum_{p} v_{x} [E_{y} f_{1}^{*}(\boldsymbol{p}, \infty) - c.c.]
$$

Dynamic accumulation of carriers at the edge

LINEAR VS PARABOLIC ENERGY SPECTRA P. \mathbf{r} *m* ⌘0 *EF mv*² *t*² Re *s*(*w*) 1 + (*wt*2)² **ENERGY SPECTRA**

Edge currents in 2D systems with linear (graphene) and parabolic (bilayer) spectra sum with *f*1(*p*, •) as follows ¹¹¹

Graphene with the carrier density $n = 5*10^{11}$ cm⁻², relaxation time τ_1 = 1 ps, and the intensity I = 1 W/cm² $cm²$

short-range \mathbb{Z} short-range \bigcap Coulomb \mathbb{Z} Coulomb) $\varepsilon = p^2/2m$ bilayer Edge photocurrent, *J_y* (nA) $-15\frac{5}{0}$ −10 −5 0 $\left|5\right|$ Frequency, *ωτ¹* 0 1 2 3 4 5 *E ·* $\overline{1}$ ⇣*t*1*t*² *m*² (*vyE*⇤ *x* + *i* $\frac{1}{\sqrt{1-\frac{1}{n}}}$ **t**
Edg *x* $\frac{1}{2}$ *y* ∠ <u>| i</u> *x v*_E *^y*)*f*1(*p*, •) \mathcal{L}^{max}

Bilayer with the carrier density $n = 5*10^{11}$ cm⁻², relaxation time $\tau_1 = 1$ ps, and the intensity I = 1 W/cm² *m*2*v*² ⇣*t*1*t*² ⌘0 = 1 ps, and the intensity **l**

Edge current (specular reflection from the edge) and contributions of the edge current we obtain

$$
J_y = \frac{e \text{Re}\,\sigma(\omega)}{m} \left\{ \tau_1(\tau_1 - 2\tau_2) + \frac{m^2 v^2}{2} \left[\frac{\tau_1}{2} \left(\frac{\tau_1}{m} \right)' - m \left(\frac{\tau_1 \tau_2}{m^2} \right)' \right] + \frac{m^2 v^2 (\tau_1 + \tau_2)}{4 \left[1 + (\omega \tau_2)^2 \right]} \left(\frac{\tau_1}{m} \right)' \right\} S_2
$$

$$
- \frac{e \text{Re}\,\sigma(\omega)}{m \omega} \left[\tau_1 + \frac{m^2 v^2 [2 + \omega^2 \tau_2 (\tau_2 - \tau_1)]}{4 \left[1 + (\omega \tau_2)^2 \right]} \left(\frac{\tau_1}{m} \right)' \right] S_3.
$$

Equation (21) represents the main result of this paper. It describes the edge ac current ¹¹³ M.V. Durnev and S.A.T., Appl. Sci. **13**, 4080 (2023)flowing in 2D electron gas with an arbitrary electron dispersion \mathcal{P}_n and \mathcal{P}_n and arbitrary energy-

SAMPLES: GRAPHENE MONOLAYERS AND BILAYERS

Sketch of samples

- exfoliated mono and bilayers/ h-BN
- epitaxial graphene on SiC
- contacts, Hall bar structure
- back gate to tune the Fermi level

Samples: Regensburg, Goteborg, Manchester

Transport data. Dependence on gate voltage in graphene bilayer

EXPERIMENTAL TECHNIQUE

Photoresponse vs laser spot position

Experimental geometry

pulsed molecular THz laser $f = 0.6, 0.8, 1.1, 2.0,$ and 3.3 THz

Experiment: Regensburg

large-scale epitaxial graphene

PHOTOVOLTAGE IN SQUARE-SHAPE BILAYER SAMPLE

e a strategy \overline{e} Electrostatic potential distribution $div (j_{photo} + j_{drift}) = 0$ $\bm{j}_{\mathrm{drift}} = \sigma \bm{E} = - \sigma$ grad Φ

$$
J_y = -\frac{2e^{3}\tau^3 n_e E_x E_y}{m^{*2}[1 + \omega^2 \tau^2]} \propto \sin 2\alpha
$$

S. Candussio, M.V. Durnev, J. Yin, J. Keil, Y. Yang, S.-K. Son, A. Mishchenko, H. Plank, V.V. Bel'kov, S. Slizovskiy, S.A.T., V. Fal'ko, and S.D. Ganichev, PRB **102**, 045406 (2020)

EFFECT OF MAGNETIC FIELD

y Rotation of momentum alignment

 p_{ν}

E

Dependence of the edge current on magnetic field

Edge photocurrent in classical magnetic field

px

$$
J_y = -\frac{e^3 \tau n_e}{m^{*2} \omega^2} \left[\frac{E_x E_y}{1 + (2\omega_c \tau)^2} - \frac{(E_x^2 - E_y^2)\omega_c \tau}{1 + (2\omega_c \tau)^2} \right] \propto \sin(2\alpha + \alpha_0)
$$

evolution frequency
② ω > ω_c, 1/τ

EDGE PHOTOCURRENT AT INTER-BAND TRANSITIONS

Strong absorption and optical alignment of electron momenta at inter-band transitions in 2D Dirac materials

Optical alignment in bulk zinc-blende crystals and quantum wells: D.N. Mirlin, in *Optical orientation* (North-Holland, 1984) V.I. Zemskii, B.P. Zakharchenya, D.N. Mirlin, JETP Lett. (1976) V.D. Dymnikov, M.I. D'yakonov, and V.I. Perel, JETP (1976) N.A. Merkulov, V.I. Perel, and M.E. Portnoi, JETP (1991)

Optical alignment in graphene:

R.R. Hartmann and M.E. Portnoi, (LAP Lambert Academic, Chisinau, 2011) L.E. Golub, S.A.T., M.V. Entin, L.I. Magarill, Phys. Rev. B 84, 195408 (2011)

EDGE PHOTOCURRENT AT INTER-BAND TRANSITIONS

Edge photocurrents of electrons and holes

electron-hole asymmetry is required for the electric current to emerge

Structure with many narrow strips

projection to 1 μA per W/cm2 in 3×3 mm2 sample

Excitation spectrum of edge photocurrent

at radiation intensity 1 W/cm2 and momentum relaxation time 1 ps

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SECOND HARMONIC GENERATION

p-polarized emission *s*-polarized emission

AC electric field E_{ω} exp $(-i\omega t) + c.c.$

MICROSCOPIC THEORY OF EDGE SHG

Boltzmann equation for distribution function

$$
\frac{\partial f}{\partial t} + v_x \frac{\partial f}{\partial x} + e\mathcal{E}(x, t) \cdot \frac{\partial f}{\partial p} = \mathbf{I}\{f\}
$$

+ collision integral + boundary conditions

Electric field (external field + screening) at ω and 2ω

$$
\mathcal{E}_{\omega,x}(x) = E_{\omega,x} + \frac{2}{\epsilon} \int_{0}^{\infty} \frac{\rho_{\omega}(x')dx'}{x - x'}, \quad \mathcal{E}_{2\omega,x}(x) = \frac{2}{\epsilon} \int_{0}^{\infty} \frac{\rho_{2\omega}(x')dx'}{x - x'}
$$

Expansion in the Fourier series

$$
f(\mathbf{p}, x, t) = f_0 + [f_1(\mathbf{p}, x)e^{-i\omega t} + c.c.] + [f_2(\mathbf{p}, x)e^{-2i\omega t} + c.c.] + ...
$$

Currents at double frequency along and normal to edge

$$
j_{2\omega,\parallel} = \frac{-ev\tau_1}{1 - 2i\omega\tau_1} \left[\sum_{p} v_x v_y \frac{\partial f_2}{\partial x} - \frac{eE_{\omega,y}}{m} \sum_{p} f_1 \right]
$$

$$
j_{2\omega,\perp} = \frac{-ev\tau_1}{1 - 2i\omega\tau_1} \left[\sum_{p} v_x^2 \frac{\partial f_2}{\partial x} - \frac{eE_{\omega,x}}{m} \sum_{p} f_1 \right] + \frac{ne^2\tau_1}{1 - 2i\omega\tau_1} \mathcal{E}_{2\omega,x}
$$

2ω CURRENT ALONG THE EDGE

Frequency dependence of the current at 2ω *x y* $\overline{E_{\omega}}$ $E_{2\omega}$ || y *x* E ^{(1)} $z \sim J_{2\omega, y}$ **g**_{ω}^{ω} $\left|y\right\rangle$ $\left|y\right\rangle$ E_2 $\frac{3}{2}$ $k_{2\omega}$ **f** $\begin{bmatrix} 8 & 4 \end{bmatrix}$ (a) $\mathbf{A}^{\mathbf{E}_{\omega}}$ $\tau_2 = 0$ *τ2* = *τ¹* arg (*J2 ω, y*) $-\pi/2$ 0 $\pi/2$ Frequency (*ωτ1*) $0 \qquad \qquad 1 \qquad \qquad 2$ Edge current *J2 ω, y /J0* $0^L₀$ 1 2 3 4 5 Frequency (*ωτ1*) 0 0.5 1.0 1.5 2.0

Current along the edge

$$
J_{2\omega,\parallel} = -i \frac{ne^3 \tau_1 (1 - 4i\omega \tau_2)}{m^{*2} \omega (1 - i\omega \tau_1)(1 - 2i\omega \tau_1)(1 - 2i\omega \tau_2)} E_{\omega,x} E_{\omega,y}
$$

 τ_1 , τ_2 are the relaxation times of first and second angular harmonics

- The total current weakly depends on screening (while the current profile does depend)

M.V. Durnev and S.A.T., Phys Rev. B **106**, 125426 (2022)

2ω CURRENT PERPENDICULAR TO THE EDGE

Frequency dependence of the current and current profile

|*J*²ω*,^x* | and the argument arg(*J*²ω*,^x*) of the complex-value current *J*²ω*,^x* , Numerical calculations for 2D system with parabolic spectrum: —– strong screening (local response approximation)

currents induced by local electric fields prevail over diffusion - - - no screening

m.V. Durnev and S.A.T., Ph B_{0} is a 106 125126 (2022) M.V. Durnev and S.A.T., Phys Rev. B **106**, 125426 (2022)

ПЛАН ЛЕКЦИИ

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STRUCTURED RADIATION

From intensity or polarization gratings to beams carrying orbital angular momentum (twisted radiation) and fields with fully controlled spatiotemporal structure

OPTICAL BEAMS

Superposition of plane waves

$$
E(r,t) = \sum_{q} E_q \exp(iq \cdot r - i\omega t) + c.c.
$$

$$
|q| = \omega/c
$$

Paraxial approximation $|q_x|, |q_y| \ll q_z$

Examples are Gaussian, Hermite-Gaussian, or Laguerre-Gaussian beams

Bessel beams

VECTOR BEAMS

Bessel beams

(a) Radial beam (c) Azimuthal beam

Distribution of electric field *E* in the beam cross-section

Electric field

$$
E(\boldsymbol{\rho}, z) = \sum_{\boldsymbol{q}_{\parallel}} E_{\boldsymbol{q}_{\parallel}} \exp(i q_z z + i \boldsymbol{q}_{\parallel} \cdot \boldsymbol{\rho})
$$

TWISTED LIGHT

K.A. Forbes, D.L. Andrews, J. Phys. Photonics **3**, 022007 (2021)

Reviews: A. Forbes, M. de Oliveira, and M. R. Dennis, Structured light, Nat. Photonics **15**, 253 (2021) B.A. Knyazev and V.G. Serbo, Phys. Usp. **61**, 449 (2018)

THz range: X. Wei, C. Liu, L. Niu et al., Appl. Opt. **54**, 10641 (2015) Y.Y. Choporova, B.A. Knyazev, G.N. Kulipanov et al., Phys. Rev. A **96**, 023846 (2017)

PHOTORESPONSE TO STRUCTURED RADIATION

Observation: Photoresponse sensitive to photon orbital angular momentum (OAM)

Z. Ji, W. Liu, S. Krylyuk et al., Science **368**, 763 (2020)

Open questions: Microscopic mechanisms, Theory

Photoresponse: Z. Ji, W. Liu, S. Krylyuk et al., Science **368**, 763 (2020) S. Sederberg, F. Kong, F. Hufnagel et al., Nat. Photon. **14**, 680 (2020)

PHOTOCURRENTS BY STRUCTURED THZ RADIATION

Electric field of incident radiation in the 2D electron gas plane

$$
E(r,t) = E(r) \exp(-i\omega t) + c.c.
$$

(complex) amplitude varying in 2D plane

Emergent dc photocurrent $j(r)$ due to ac field structure

$$
j_{\alpha}(\boldsymbol{r}) \propto \frac{\partial}{\partial r_{\beta}} E_{\gamma} E_{\delta}^*
$$

QUASI-CLASSICAL APPROACH

Boltzmann equation for electron distribution function $f(\boldsymbol{p}, \boldsymbol{r}, t)$

$$
\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \frac{\partial f}{\partial r} + e \left[\boldsymbol{E}_{\parallel}(\boldsymbol{r}, t) + \frac{1}{c} \boldsymbol{v} \times \boldsymbol{B}_{z}(\boldsymbol{r}, t) \right] \cdot \frac{\partial f}{\partial \boldsymbol{p}} = \mathbf{I} \left\{ f \right\}
$$

Electric $\mathbf{E}(\mathbf{r},t)$ and magnetic $\mathbf{B}(\mathbf{r},t)$ fields of radiation

$$
B_z = -i\frac{c}{\omega} \left(\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} \right)
$$

Collision integral (relaxation time approximation)

$$
I\{f\} = \frac{f - \langle f \rangle}{\tau} + I_{e-e}\{f\} + I_{\varepsilon}\{f\}
$$

Solution to second order in the electric field, i.e., the radiation intensity

Assumptions: length of field variation $L(\sim \lambda) \gg l$ mean free path, spatial dispersion of screening is negligible at $L \gg (2\pi\sigma/c)$

SOLUTION OF THE KINETIC EQUATION

Expansion in the field amplitude

$$
f(\boldsymbol{p}, \boldsymbol{r}, t) = f_0(\boldsymbol{p}) + [f_1(\boldsymbol{p}, \boldsymbol{r})e^{-i\omega t} + \text{c.c.}] + f_2(\boldsymbol{p}, \boldsymbol{r})
$$

$$
f_1 \propto E \qquad f_2 \propto EE^*, EB^*
$$

Set of differential equations

$$
-i\omega f_1 + \mathbf{v} \cdot \frac{\partial f_1}{\partial r} + eE_{\parallel}(r, t) \cdot \frac{\partial f_0}{\partial p} = \mathbf{I} \{f_1\}
$$

$$
\mathbf{v} \cdot \frac{\partial f_2}{\partial r} + e \{ \left[E_{\parallel}(r, t) + \frac{1}{c} \mathbf{v} \times B_z(r, t) \right] \cdot \frac{\partial f_1^*}{\partial p} + c.c. \} = \mathbf{I} \{f_2\}
$$

The density of dc electric current

$$
\boldsymbol{j}(\boldsymbol{r}) = \boldsymbol{e}\boldsymbol{v} \sum_{\boldsymbol{p}} \boldsymbol{v} f_2(\boldsymbol{p}, \boldsymbol{r})
$$

 ν is the spin and/or valley degeneracy

CONTRIBUTIONS TO PHOTOCURRENT Finally, combining all the contributions to the photocur-**RENT CONTINUE** Finally, contributions to PHOTOCURR drag effect to the electromagnetic field with a *<u>CONTRIBUTIONS TO PHOTOCURRENT</u>* ²)*.* (15) *<u>CONTRIBUTIONS</u>* **TO PHOT** ²)*.* (15)

Photocurrent density $\boldsymbol{j} = \boldsymbol{j}^{(\mathrm{th})} + \boldsymbol{j}^{(\mathrm{pol})} + \boldsymbol{j}^{(\mathrm{ph})}$ rent, we obtain *j* = *j* $\int f(x) dx + \int f(x) dx + \int f(x) dx$ current density $\boldsymbol{i} = \boldsymbol{i}^{(\text{th})} + \boldsymbol{i}^{(\text{pol})} + \boldsymbol{i}^{(\text{ph})}$

 $\mathsf{term}\Omega$ (i) Photothermoelectric current

$$
\begin{aligned}\n\text{catrix current} \\
\mathbf{j}^{(\text{th})} &= -2 \frac{e \tau \tau_{\varepsilon} \operatorname{Re} \sigma}{m^*} \nabla S_0\n\end{aligned}
$$

pola *x*
bolarization grad #∂*S*¹ *fents by polarization gradients a* by polarization g *S*
∂ Pec (as −2 *S j* (th) ⁼ [−]² *m*[∗] (ii) Currents by polarization gradients

(ii) Currents by polarization gradients
\n
$$
j_x^{(\text{pol})} = -\frac{e\tau^2 \text{Re}\,\sigma}{m^*} \left(\frac{\partial S_1}{\partial x} + \frac{\partial S_2}{\partial y} - \frac{1}{\omega \tau} \frac{\partial S_3}{\partial y} \right)
$$
\n
$$
j_y^{(\text{pol})} = -\frac{e\tau^2 \text{Re}\,\sigma}{m^*} \left(\frac{\partial S_2}{\partial x} - \frac{\partial S_1}{\partial y} + \frac{1}{\omega \tau} \frac{\partial S_3}{\partial x} \right)
$$

$$
S_0
$$
 "Stokes" parameters
\n
$$
S_0 = |E_{\parallel}|^2
$$
 intensity
\n
$$
-\frac{1}{\omega \tau} \frac{\partial S_3}{\partial y}
$$
\n
$$
S_2 = (E_x E_y^* + E_y E_x^*)
$$
\n
$$
+\frac{1}{\omega \tau} \frac{\partial S_3}{\partial x}
$$
\n
$$
S_3 = i(E_x E_y^* - E_y E_x^*)
$$
\n
$$
\propto P_{circ}
$$

(ii) Currents by phase gradient

 $j^{(\text{ph})} = -2$ *e*τ Re σ *m*∗ω $\text{Im}(E_{x}\boldsymbol{\nabla}E_{x}^{*}+E_{y}\boldsymbol{\nabla}E_{y}^{*})$ generalized photon drag σ the high-frequency conductivity

A.A. Gunyaga, M.V. Durnev, and S.A.T., Phys. Rev. B 108, 115402 (2023) *^x Ey*, and *S*³ = *i*(*ExE*[∗] *^y* − *E*[∗]

(I) PHOTOTHERMOELECTRIC CURRENT *UTOTHERMOELECTRIC CURR* portional to the cube of the electric charge *e*. It means that

Photothermoelectric current Stokes parameter

$$
\boldsymbol{j}^{(\text{th})} = -2 \frac{e \tau \tau_{\varepsilon} \operatorname{Re} \sigma}{m^*} \nabla S_0
$$

 ∇S_0 $S_0 = |E_{\parallel}|^2$ intensity the photocurrents excited in *n*-type and *p*-type structures are $\overline{\text{det}}$ Equation (16) with the contributions (18) and (19) is) **intensity**

, High-frequency conductivity $\frac{d}{dz}$ defined in Fig.

$$
\operatorname{Re}\sigma = \frac{ne^2\tau/m^*}{1+(\omega\tau)^2}
$$

by beams of twisted light. $\overline{011}$ and $\overline{0}$ Momentum and energy relaxation times

 τ and τ_{ε}

(II) CURRENTS DRIVEN BY POLARIZATION GRADIENTS the photocurrents excited in *n*-type and *p*-type structures are directed oppositely while the flows of carriers, electrons or the photocurrents excited in *n*-type and *p*-type structures are

Currents by polarization gradients

$$
j_x^{(\text{pol})} = -\frac{e\tau^2 \operatorname{Re} \sigma}{m^*} \left(\frac{\partial S_1}{\partial x} + \frac{\partial S_2}{\partial y} - \frac{1}{\omega \tau} \frac{\partial S_3}{\partial y} \right)
$$

$$
j_y^{(\text{pol})} = -\frac{e\tau^2 \operatorname{Re} \sigma}{m^*} \left(\frac{\partial S_2}{\partial x} - \frac{\partial S_1}{\partial y} + \frac{1}{\omega \tau} \frac{\partial S_3}{\partial x} \right)
$$

) Polarization Stokes parameters

$$
S_1 = |E_x|^2 - |E_y|^2 \propto P_{lin}
$$

$$
S_2 = (E_x E_y^* + E_y E_x^*) \propto P_{diag}
$$

$$
S_3 = i(E_x E_y^* - E_y E_x^*) \propto P_{circ}
$$

PHOTOCURRENTS BY POLARIZATION GRADIENTS – I

A.A. Gunyaga, M.V. Durnev, and S.A.T., Phys. Rev. B **108**, 115402 (2023) [−]³ [−]² [−]10 1 2 3 [−]² nyaga, м.⊽. Durnev, and S.A.T., Priys. Rev. B 1**0o**, T15402 (2023)
Edge currents: M.V. Durnev and S.A.T., Appl. Sci. **13**, 4080 (2023) Coordinate *x L*

PHOTOCURRENTS BY POLARIZATION GRADIENTS – II

left-handed and right-handed circular polarizations flows Total current along the boundary between the domains excited by σ^+ and σ^- radiation

$$
J_{y} = \int j_{y}(x)dx = -\frac{ne^{3}\tau^{2}[S_{3}(+\infty) - S_{3}(-\infty)]}{m^{*2}\omega(1+\omega^{2}\tau^{2})}
$$

Estimation
$$
J_y \sim 20 \,\mu\text{A}
$$

for $n = 5 \cdot 10^{11} \text{cm}^{-2}$, $\text{m}^* = 0.3 \text{m}_0$
 $\tau = 1 \text{ ps}, \omega\tau = 1, \text{ and } I = 1 \text{ kW/cm}^2$

A.A. Gunyaga, M.V. Durnev, and S.A.T., Phys. Rev. B 108, 115402 (2023) The protocurrents: M.V. Durney and S.A.T., Appl. Sci. 13, 4080 (2023) [−]³ [−]² [−]10 1 2 3 [−]² the carrier matrix banner and entity *n* ppt. Soit **to**, tool (2020)

(II) CURRENTS DRIVEN BY PHASE GRADIENT

Currents by the gradient of the phase

 $j^{(\text{ph})} = -2$ *e*τ Re σ *m*∗ω $\text{Im}(E_x \nabla E_x^* + E_y \nabla E_y^*)$ $\propto \nabla \varphi(r)$ for the field $E(r) = E_0 \exp[i\varphi(r)]$

E xample: oblique incidence of plane way **Example: oplique incluence of plane wave** Example: oblique incidence of plane wave

Besides the photothermoelectric current *j* ü Here,

generalized photon drag effect and proportional to the grand generalized photon drag effect

 $j \propto q_{\parallel} |E|^2$ photon drag

Photon drag:

field amplitude, i.e., the radiation intensity, and, therefore, A.M. Danishevskii et al., JETP (1970) V.I. Perel', Ya.M. Pinskii, Phys. Solid State (1973) dient of the radiation intensity, the radiation intensity, the photocurrent contains α A.F. Gibson et al., Appl. Phys. Lett. (1970) J. Karch et al., Phys. Rev. Lett. (2010) M.V. Entin, L.I. Magarill, D.L. Shepelyansky, Phys. Rev. B (2010)

TWISTED RADIATION BEAMS of the projection of the total angular momentum on the total angular momentum on the beam Bessel beams which are characterized by the integer index *m* kV*/*cm corresponding to the terahertz radiation intensity *I* = and β = ±i*/* **POSED RADIATION BEAMS. THE CIRCULAR POST OF THE CIRCULAR POLARIZE**

Bessel beams **IV. PHOTOCURRENT**

Interestingly, the photocurrent between the domains with

BY TWISTED RADIATION

photoresponse of \mathbb{W} \mathbb{W} \mathbb{W}

electromagnetic waves carrying orbital angular momentum,

Fig. 1. Such calculations can be conveniently done in the convenient of $q = (q$

polar coordinate frame with the radial \mathcal{M}

 $\mathbb{N}\mathbb{N}$ the developed theory to calculate the developed theory to calculate the developed theory to calculate the developed to calculate the developed to calculate the developed to calculate the set of \mathbb{N}

left-handed and right-handed circular polarizations flows

along the boundary of the domains, as sketched in \mathcal{A}

 $\sqrt{11}$

Electric field decomposed over plane waves termined by the dependence of *a*(*q*') on the polar angle **EIECINC TIEID DECOMPOSED OVER PIANE WAVES**

$$
E(r, z) = E_0 e^{iq_z z} \sum_{\mathbf{q}_{\parallel}} a(\mathbf{q}_{\parallel}) \exp(i\mathbf{q}_{\parallel} \cdot \mathbf{r}) e_{\mathbf{q}}
$$

 q_{\parallel}, q_z) and the amplitude with the amplitude vector with the vector with q_{\parallel}, q_z) and the projection with q_{\parallel} and q the integral of the integral is the projection
integral of total and integral momentum index of the medium, and the unit polarization vector was the unit polarization vector was the unit polarizatio
The unit polarization vector was the unit polarization vector was the unit polarization vector was the unit p of total angular momentum α cap(*and*) with α and α and α and α and α) are α (α ^o) as α by Eqs. (27) and (27) and (28), respectively, respectively, respectively, \mathcal{L} components of the electric field in the polar coordinate framewhere ϵ

 \propto exp(*im* φ) polarization vector

∂*P*²

 $q = (q_{\parallel}, q_{z})$

 e_{q}

 \mathbf{r} for the theory of the theory o

 $E_r(\bar{r},\bar{\varphi})=$

*E*0

2

2*i*

of the plane wave, and α ⁽q') is the plane wave, and α ⁽) is the Fourier coefficient. The Fourier coefficient. The α

G. Molina-Terriza, J. P. Torres, and L. Torner, Nat. Phys. 3, 305 (2007) *<i>see B.A.Kn***^{** \circ **}** see B. A. Kn^{ot} ind V. G. Serbo, Phys. Usp. 61, 449 (2018) $\,$ C. Serbo, Phys. Usp. $\,$ 61, 449 (2018) the beam, the superstripute of the current mag-
Torres, and L. Torner, Nat. Phys. 3, 305 (2007)

index *m*. In particular, *o*[±] = 1 for the "radial" Bessel beam

constructed from *p*-polarized plane waves (α = 1, β = 0) and

RADIAL AND AZIMUTHAL BESSEL BEAMS

Distribution of *E*-field in the cross-sections of the Bessel beams

Radial (composed of *p*-polarized waves) and azimuthal (of s-polarized waves) beams with $m = 0$ (a)

 $\bm{E}(\bm{r})$ (c)

Radial beams with $m = \pm 2$

PHOTOCURRENTS BY BE $\{r, r(\tau)\}$ + 2*P*¹ + ∂∂
∂
P ,

E-fields and Photocurrents for radial Bessel bearing with $\frac{1}{2}$ *,* (24)

Radial and azimuthal components Radial and azimuthal components **DearFid. 3. Photocurrent are controlled** by the photocurrent are controlled by the beam polarization and **community** $\frac{1}{2}$ with the electric field given by Eq. (20) with the electric field given by Eq. (29) **vields angular momentum** by the beam polarization and

eim^ϕ[*o*+*Jm*+1(*q*'*r*) [−] *^o*−*Jm*−1(*q*'*r*)]*,*

where *o*^t and *Jm* is the Bessel function with the Bessel function with the Bessel function with the Bessel function with the Bessel function of the Bessel function with the Bessel function of the Bessel function with t index *m*. In particular, *o*[±] = 1 for the "radial" Bessel beam constructed from *p*-polarized plane waves (α = 1, β = 0) and *o*[±] = ±*i* for the "azimuthal" Bessel beam constructed from

eim^ϕ[*o*+*Jm*+1(*q*'*r*) ⁺ *^o*−*Jm*−1(*q*'*r*)]*,* (29)

Er(*r,* ^ϕ) ⁼ *^E*⁰

^E^ϕ (*r,* ^ϕ) ⁼ *^E*⁰

 $\overline{}$

2*i*

$$
j_r^{(\text{th})} = j_0 \frac{\tau_{\varepsilon}}{\tau} \{J_{m+1}(J_m - J_{m+2}) - J_{m-1}(J_m - J_{m-2})
$$

$$
- [J_{m+1}(J_m - J_{m+2}) + J_{m-1}(J_m - J_{m-2})] p_3 \}
$$

$$
j_r^{(\text{pol})} + j_r^{(\text{ph})} = j_0 J_m (J_{m+1} - J_{m-1}) p_1,
$$

\n
$$
j_{\varphi}^{(\text{pol})} + j_{\varphi}^{(\text{ph})} = j_0 J_m (J_{m+1} - J_{m-1}) \left(p_2 + \frac{p_3}{\omega \tau} \right)
$$

\n
$$
- \frac{j_0}{\omega \tau} J_m (J_{m+1} + J_{m-1}),
$$

araday effect **Inverse Faraday effect of twisted light**

ФОТОГАЛЬВАНИЧЕСКИЕ ЭФФЕКТЫ - 2. ГЕОМЕТРИЧЕСКИЕ ЭФФЕКТЫ

ü Краевой фотогальванический эффект и краевой эффект генерации второй гармоники

ü Фототоки, индуцированные структурированным излучением. Вклады, связанные с градиентами интенсивности, поляризации, фазы э/м волны

