DeMeGRaS

Detection mechanisms in graphene radiation sensors

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Partners

Partner	Country	Institution/ Department	Principal Investigators	Co-Investigators	Other participants
1 *Coord.*	Sweden	Chalmers University of Technology/MC2	Prof. August Yurgens		Post Doc
2	Germany	University of Regensburg/Faculty of Physics	Prof. Sergey Ganichev		Post Doc, Visiting researchers
3	France	CNRS/ Laboratoire Charles Coulomb (L2C)	Dr. Frédéric Teppe	Prof. Michel Dyakonov	3 Research Engineers, Post Doc, Visiting researchers

2

The main achivements:

- THz plasmonic interferometer
- Circular Hall effect without magnetic field
- Giant magnetooscillations of ratchet effect
- Temperature-tunable zero-field splitting in graphene
- THz spin-splitting both in rathchet structures and *p-n* junctions
- Current-tunable thermoelectric readout in graphene symmetric structures
- Calculations of the ideal responsivity of thermoelectric graphene detectors

Despite:
Covid-19 pandemic has taken its toll on plans and activities

13 published papers (w. ackn. to DeMeGRaS)
(incl. Phys Rev B, ACS Photonics, Nano Lett, Opt Express)

3 manuscripts submitted/in preparation:
(incl. Nature Photonics)

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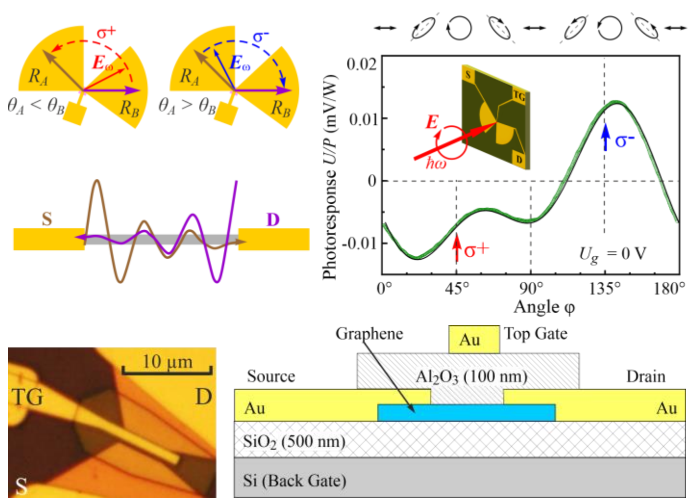
Helicity-Sensitive Plasmonic Terahertz Interferometer

- based on GFET with asymmetric bow-tie antennas.
- helicity- and phase-sensitive conversion of circularly polarized radiation into dc photo-voltage caused by the plasmon-interference mechanism.
- dc signal changes sign with inversion of the helicity.
- our plasmonic interferometer can measure the phase difference between two arbitrary optical signals.



Y. Matyushkin, M. Moskotin, V. Belosevich, M. Rybin, E. Obraztsova, S. Danilov, G. Fedorov, I. Gorbenko, V. Kachorovskii, and S. Ganichev, *Helicity sensitive plasmonic terahertz interferometer*, Nano Lett. **20**, 7296 (2020)

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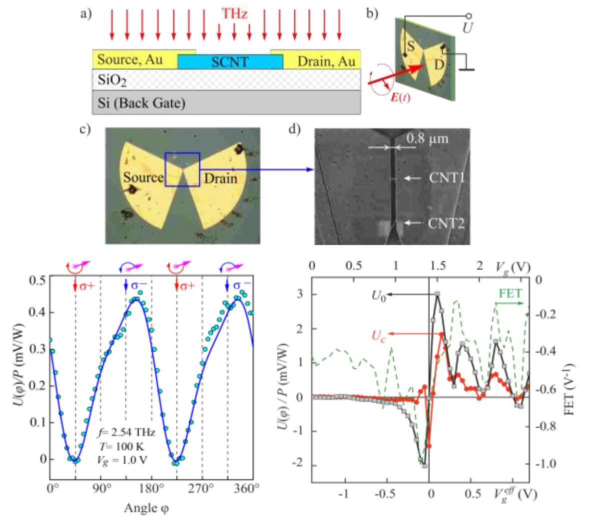
Carbon nanotubes for polarization sensitive terahertz plasmonic interferometry

- CNT lengths 0.8 µm & 2.8 µm
- Diameters of both CNTs 2-4 nm.
- Bow-tie antenna + a field-effect transistor

- Helicity sensitive photovoltaic THz response
- The effect is a fingerprint of the plasma waves interference in the transistor channel.



Y. Matyushkin, S. Danilov, M. Moskotin, G. Fedorov, A. Bochin, I. Gorbenko, V. Kachorovskii, and S. Ganichev, *Carbon nanotubes for polarization sensitive terahertz plasmonic interferometry,* Opt. Express **29**(23), 37189 (2021)

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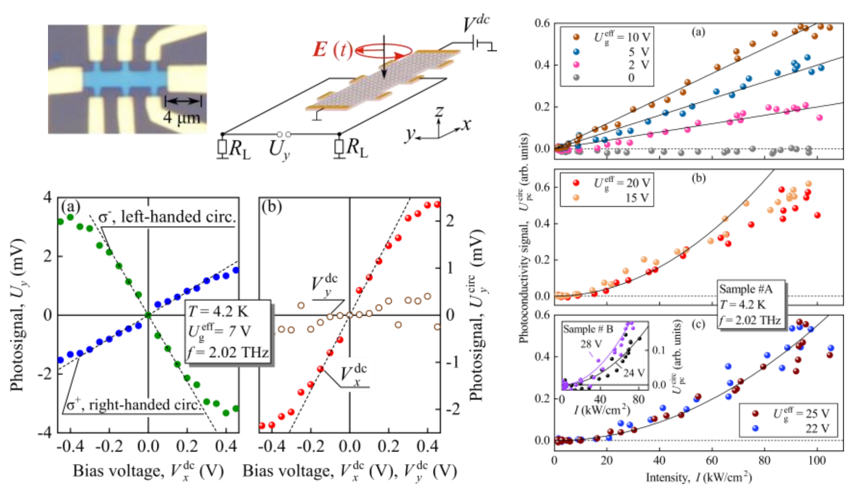
THz radiation induced circular Hall effect in graphene

- **circular transversal** THz photoconductivity
- **dc Hall effect** manifests the time-inversion symmetry breaking by circularly polarized THz radiation in **the zero magnetic field**.
- the interplay of the 2- and 4-order effects in the radiation electric field



$$j_x = \gamma_1 |\boldsymbol{E}|^2 E_x^{\rm dc}\,,$$
$$j_y = \eta \gamma_3 |\boldsymbol{E}|^2 E_x^{\rm dc}$$

$$j_y = \eta \left(\gamma_3^{(2)} |\boldsymbol{E}|^2 + \gamma_3^{(4)} |\boldsymbol{E}|^4 + \cdots \right) E_x^{\rm dc}$$

S. Candussio, S. Bernreuter, T. Rockinger, K. Watanabe, T.Taniguchi, J. Eroms, I.A. Dmitriev, D. Weiss, and S.D. Ganichev, *THz radiation induced circular Hall effect in graphene*, Phys. Rev. B (2022), arXiv:2202.0113v1 [cond-mat.mes-hall]

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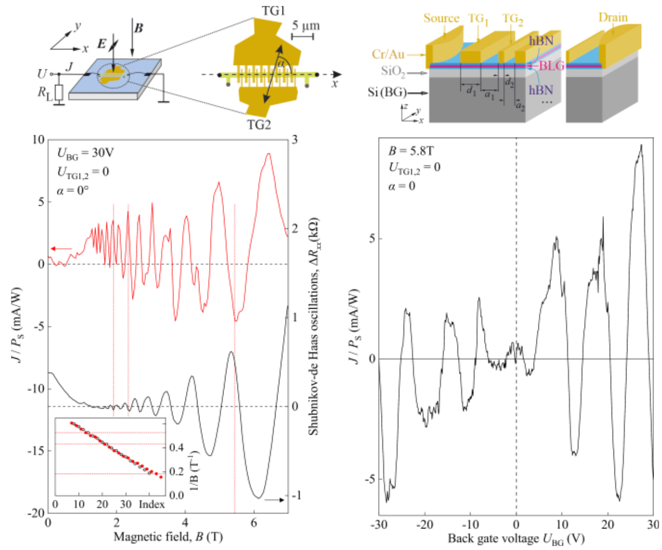
Giant ratchet magneto-photocurrent in graphene lateral superlattices

- Magnetic quantum ratchet effect in graphene with an *asymmetric* lateral dual-grating top gate.
- Photoresponses sensitive to the orientation of radiation **electric field** (linear ratchet), **radiation helicity** (circular ratchet) and the **polarization independent** one (Seebeck ratchet)
- The THz ratchet shows 1/*B* magneto-oscillations in phase with the Shubnikov–de Haas effect
- The amplitude of the oscillations is greatly enhanced by magnetic field. Giant oscillations are also observed as functions of V_{tg}.



$$\Xi = \overline{|\boldsymbol{E}(x)|^2 \frac{dV(x)}{dx}}.$$

S. Hubmann, V. V. Bel'kov, L. E. Golub, V. Y. Kachorovskii, M. Drienovsky, J. Eroms, D. Weiss, and S. D. Ganichev, *Giant ratchet magneto-photocurrent in graphene lateral superlattices*, Phys. Rev. Res. **2**, 033186 (2020)

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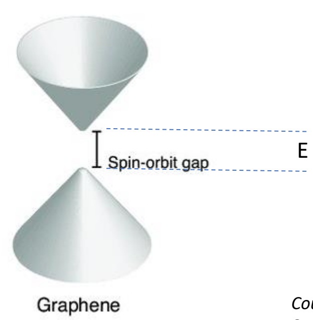
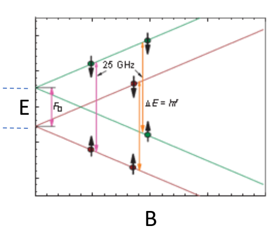
Temperature Tunable Zero-Field Splittings in Graphene-based THz detectors

- The spin orbit interaction in graphene is weak and the zero-field splitting (ZFS) or spin-orbit gap is small.
- However, probing it is of great interest as this gap is topologicaly non trivial.
- Recent Electron Spin Resonance (EPR) experiments have shown that this gap is on the order of 45 μeV
- THz detectors may serve as complemetary tools to probe the fine structure of EPR



Courtesy of J. Kim et al
Phys. Rev. Lett. 119, 226801 (2017)



Courtesy of R. G. Mani et al., **Nature Commun.** 10.1038/ncomms1986 (2012)
J. Sichau et al., **Phys. Rev. Lett. 122**, 046403 (2019)
U.R. Singh et al., **Phys. Rev. B** 102, 245134 (2020)

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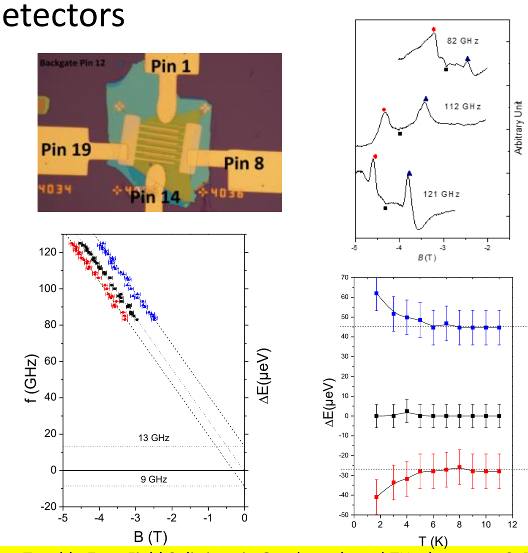
Temperature Tunable Zero-Field Splittings in Graphene-based THz detectors

- THz detectors allow to detect spin resonances (i.e. spin-flip transitions) by photoconductivity technique
- The fourfold degeneracy of graphene in K and K' points is lifted by the SO coupling to produce a pair of spin degenarate levels.
- The spin degeneracy is lifted by the Zeeman effect in the magnetic field *B*
- Extrapolation of the results as a function of *B* allow to extract the ZFS of 13 GHz (~50 μeV)
- Morevover, unexpectedly, this spin-orbit gap changes with temperature. This may be due to the temperature induced strain effect on the graphene layer.



Temperature Tunable Zero-Field Splittings in Graphene-based THz detectors, C. Bray, C. Consejo, K. Maussang, J. A. Delgado Notario, I. Yahniuk, S. Krishtopenko, S. Ruffenach, S. Gebert, J. Torres, E. Moench, A. Yurgens, S. Ganichev, F. Teppe – in preparation (2022)

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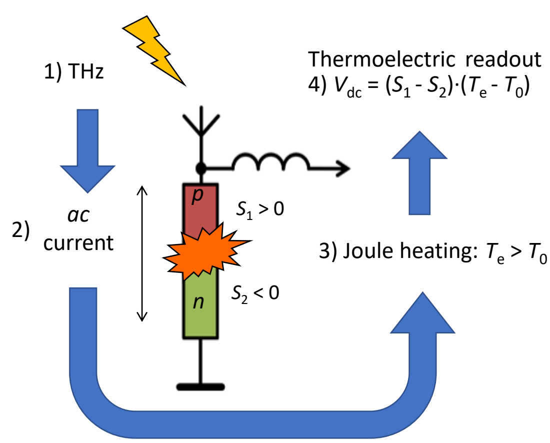
Thermoelectric readout in graphene radiation sensors

- Graphene parts with different doping (*p*-*n* junction).
- Weak *e*-*ph* coupling + Joule heating: $T_e > T_0$ is easy.
- The Seebeck coefficient *S* of graphene is large ~ 100 μV/K → large signal
- No bias → no 1/f noise
- Contrary to anti-heating prejudice, the *e*-heating is fast



F.H.L. Koppens, *et al.*, Nat. Nanotechnol. **2014**, 9, 780.
X. Cai, *et al.*, Nat. Nanotechnol. **2014**, 9, 814.

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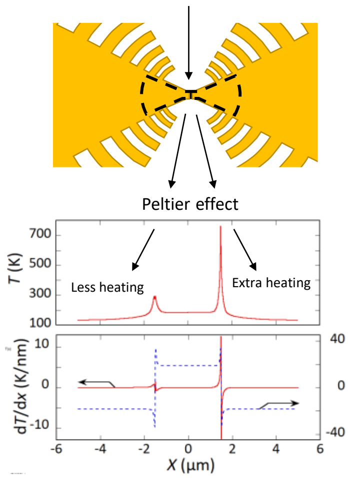
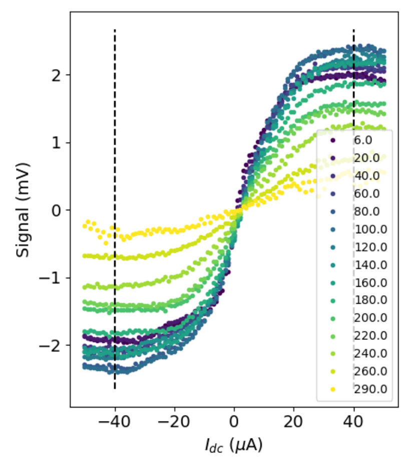
Current induced asymmetry in graphene detector turns thermoelectric readout on

P5

- Two identical *p-n* junctions near each electrode = initial symmetry
- DC current induces additional heating in one- and cooling in another *p-n* junction = asymmetry
- AC current gets rectified because of the asymmetry
- Variable sensitivity

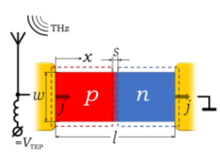




K. Indykiewicz, …, F. Teppe, S.D. Ganichev, and A. Yurgens, in preparation (2022)

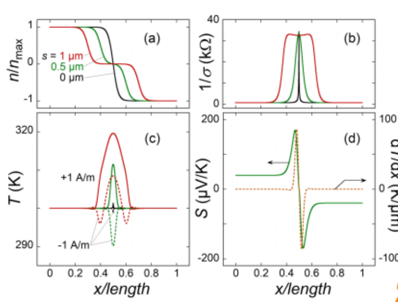
Thermoelectric readout: responsivity in the ideal case

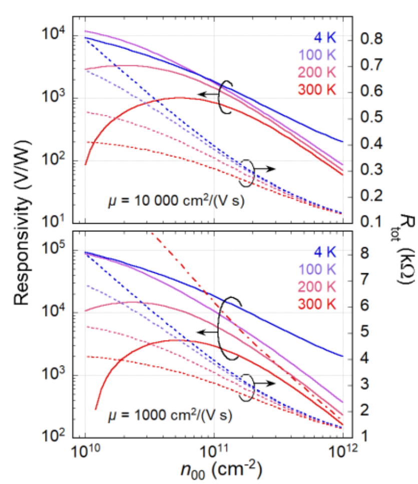
- Large responsivity ~$10^3 - 10^5$ V/W
- Mobility is only important to keep the overall resistance low.
- Peltier effect is significant
- Graphene uniformity (n_{00}) is the key parameter



$$-\frac{\partial}{\partial x}\left(\kappa_e \frac{\partial T}{\partial x}\right) = \frac{j^2}{\sigma} - jT\frac{\partial S}{\partial x} - \alpha_i (T^i - T_0^i)$$

Joule heating | Peltier effect | Energy losses





$NEP = 0.01 - 100$ pW Hz$^{-0.5}$

A. Yurgens, *Sensors* **20**(7), 1930 (2020)

Summary

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- Circular Hall effect without magnetic field
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- Temperature-tunable zero-field splitting in graphene
- THz spin-splitting both in rathchet structures and *p-n* junctions
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- Calculations of the ideal responsivity of thermoelectric graphene detectors

Overall outcome: 13 papers published and 3 in preparation

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The project output

- Temperature Tunable Zero-Field Splittings in Graphene-based THz detectors, C. Bray, C. Consejo, K. Maussang, J. A. Delgado Notario, I. Yahniuk, S. Krishtopenko, S. Ruffenach, S. Gebert, J. Torres, E. Moench, A. Yurgens, S. Ganichev, F. Teppe – in preparation (2022)
- Terahertz Cyclotron Emission of Dirac Fermions in HgTe Quantum Wells S. Gebert, C. Consejo, S.S. Krishtopenko, S. Ruffenach, M. Szola, J. Torres, B. Jouault, M. Orlita, P. Ballet, S.V. Morozov, V.I. Gavrilenko, N.N. Mikhailov, S.A. Dvoretskii, and F. Teppe - Submitted to **Nature Photonics** (2022)
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- Many-particle effects in optical transitions from zero-mode Landau levels in HgTe quantum wells, SS Krishtopenko, AM Kadykov, S Gebert, S Ruffenach, C Consejo, J. Torres, C. Avogadri, B. Jouault, W. Knap, NN Mikhailov, SA Dvoretskii, and F. Teppe - **Physical Review B** 102 (4), 041404 (2020)
- Quantum Hall states in inverted HgTe quantum wells probed by transconductance fluctuations S Mantion, C Avogadri, SS Krishtopenko, S Gebert, S Ruffenach, C Consejo, SV Morozov, NN Mikhailov, SA Dvoretskii, W Knap, S Nanot, F Teppe, B Jouault - **Physical Review B** 102 (7), 075302 (2020)
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- Y. Matyushkin, M. Moskotin, V. Belosevich, M. Rybin, E. Obraztsova, S. Danilov, G. Fedorov, I. Gorbenko, V. Kachorovskii, and S. Ganichev, Helicity sensitive plasmonic terahertz interferometer, **Nano Lett.** 20, 7296 (2020).
- K. A. Baryshnikov, Yu. B. Vasilyev, S. Novikov and S.N. Danilov, and S. D. Ganichev, Terahertz photoconductivity enhancement in graphene in magnetic fields, **J. Phys.** Conf. Series 1482, 012039 (2020).
- Yu. B. Vasiliev, S. N. Novikov, S. N. Danilov, and S. D. Ganichev, Terahertz Photoconductivity in Graphene in a Magnetic Field, **Semiconductors** 54, 465 (2020).
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- S. Hubmann, V. V. Bel'kov, L. E. Golub, V. Y. Kachorovskii, M. Drienovsky, J. Eroms, D. Weiss, and S. D. Ganichev, Giant ratchet magneto-photocurrent in graphene lateral superlattices, **Phys. Rev. Res.** 2, 033186 (2020); DOI: 10.1103/PhysRevResearch.2.033186.
- A. Yurgens, Large Responsivity of Graphene Radiation Detectors with Thermoelectric Readout: Results of Simulations, **Sensors** 20(7), 1930 (2020)
- Munis Khan, Kornelia Indykiewicz, Pui Lam Tam and August Yurgens, High Mobility Graphene on EVA/PET, Nanomaterials **2022**, *12*(3), 331; https://doi.org/10.3390/nano12030331
- K. Indykiewicz, …, F. Teppe, S.D. Ganichev, A. Yurgens, in preparation (2022)

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