ORIGINS OF TERAHERTZ PHOTORESPONSE IN GRAPHENE TRANSISTORS: THEORY AND EXPERIMENT

Gayduchenko I.A.

2024

Outline:

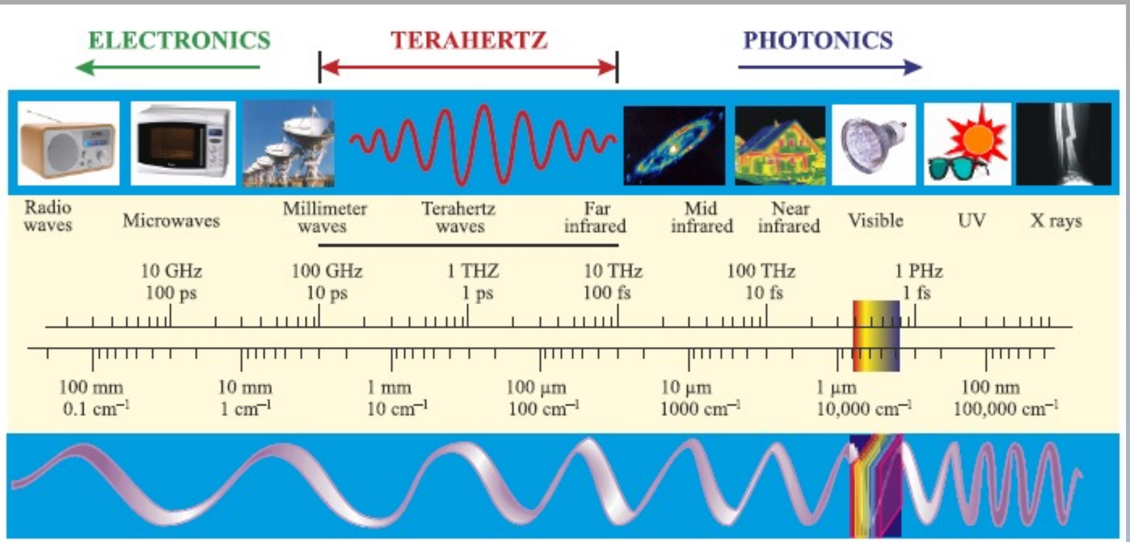
1. Introduction:
- What is THz radiation?
- THz Detectors. Why graphene (CNT) based

2. The main mechanisms of THz radiation detection by graphene-based FET devices

3. Asymmetric devices based on graphene:
- Device fabrication and experimental setup
- Device characterization
- Response of asymmetric devices based on graphene on THz radiation
- Contribution of plasmonic response to the detection of sub-terahertz radiation using graphene based devices

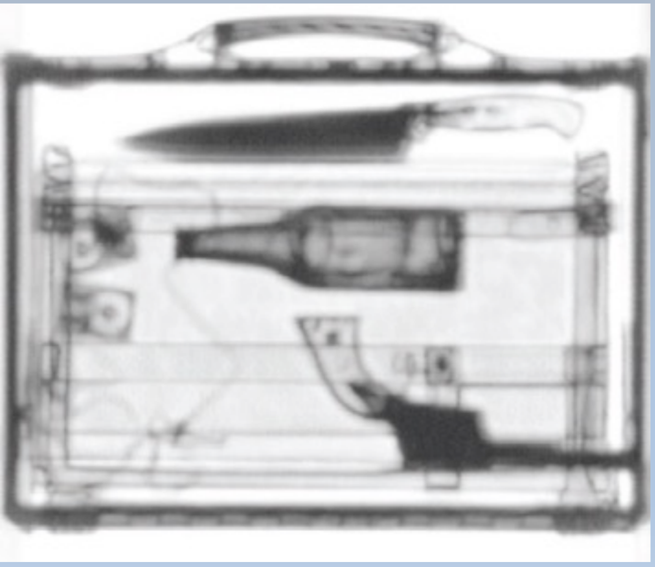
4. Conclusions

MOTIVATION

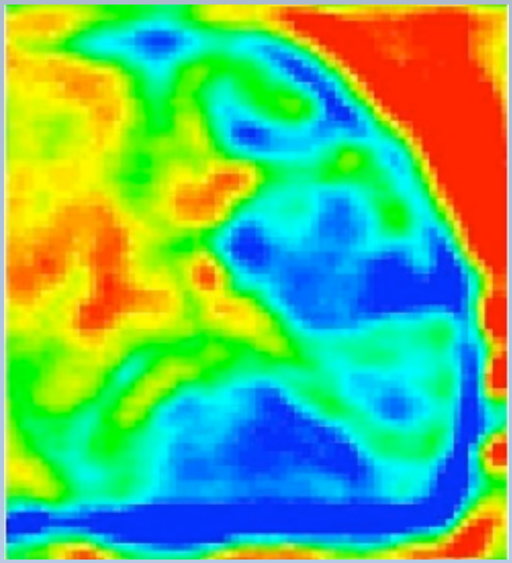


THz range is important for:

- Security
- Medicine
- Astronomy
- Etc.



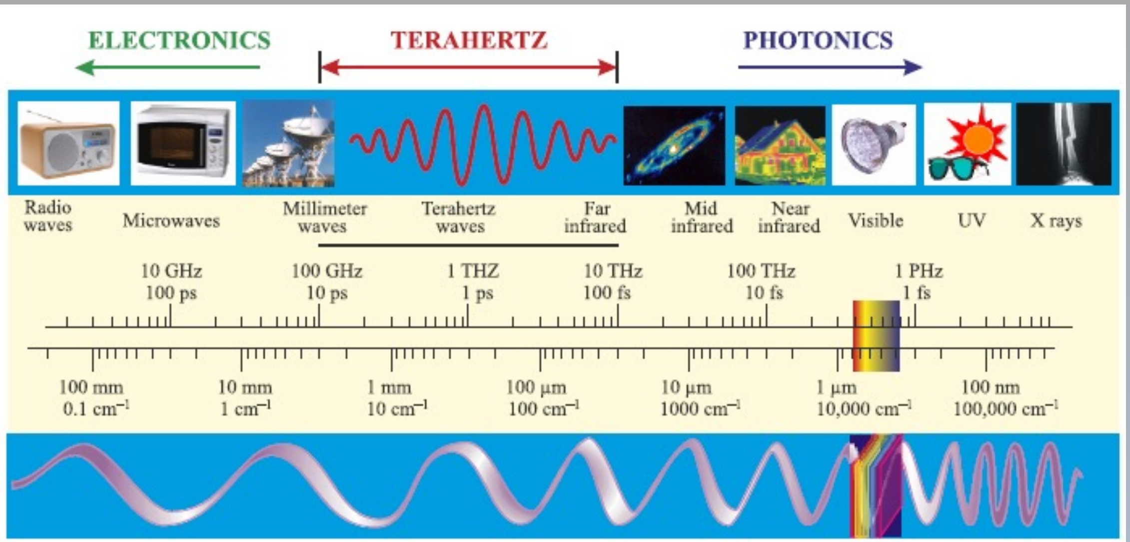
Visualization of the hidden objects



THz image of liver

Astronomy

MOTIVATION



Detectors.

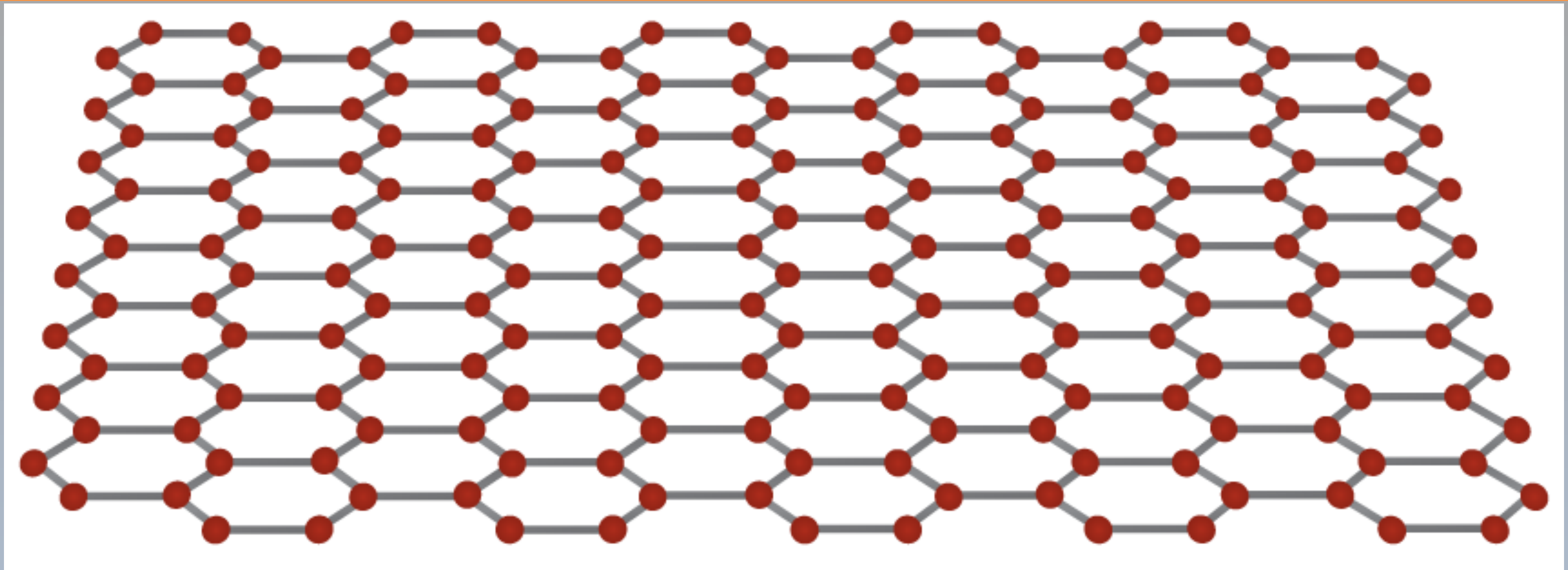
Why nanosturtures:

-Sensitive
- Fast
- Energy efficient
- Etc.

Detectors. Why graphene (CNT) based:

- **Gapless graphene has strong interband absorption at all frequencies**
- **High room-temperature mobility**
- **Geometric control of the band structure**
- **Easy to fabricate**
- **The frequency of graphene plasma waves lies in the terahertz range**

MOTIVATION



Detectors. Why graphene (CNT) based:

-Gapless graphene has strong interband absorption at all frequencies

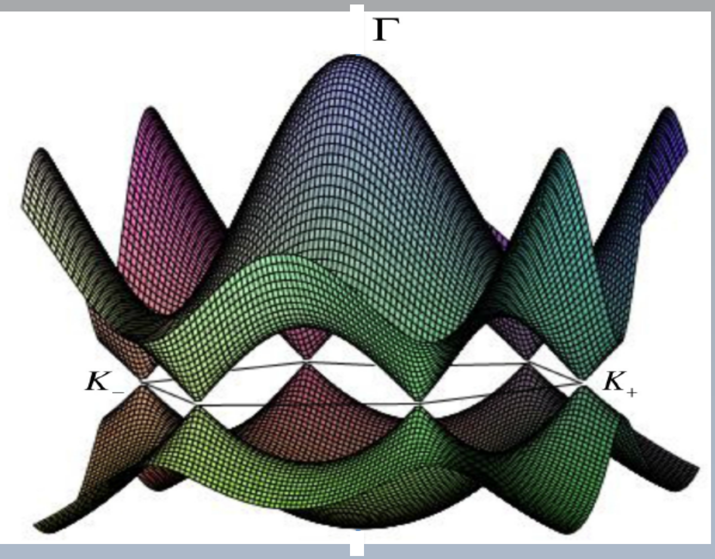
- High room-temperature mobility

-Geometric control of the band structure

- Easy to fabricate

- The frequency of graphene plasma waves lies in the terahertz range

MOTIVATION



$$E(k) = E_0 + 2\gamma_1\left(\cos(\vec{k}\vec{a}_1) + \cos(\vec{k}\vec{a}_2) + \cos(\vec{k}(\vec{a}_1 - \vec{a}_2))\right)$$
$$\pm \gamma_0\sqrt{3 + 2\cos\vec{k}\vec{a}_1 + 2\cos\vec{k}\vec{a}_2 + 2\cos\vec{k}(\vec{a}_1 - \vec{a}_2)}$$

Detectors. Why graphene (CNT) based:

-Gapless graphene has strong interband absorption at all frequencies

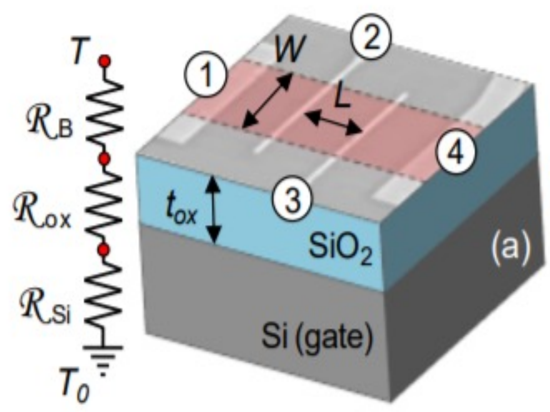
- High room-temperature mobility

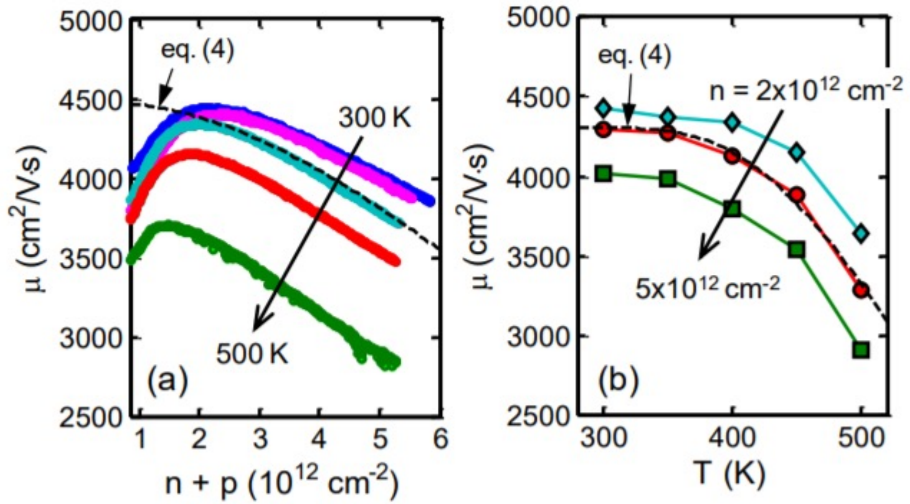
-Geometric control of the band structure

- Easy to fabricate

- The frequency of graphene plasma waves lies in the terahertz range

MOTIVATION

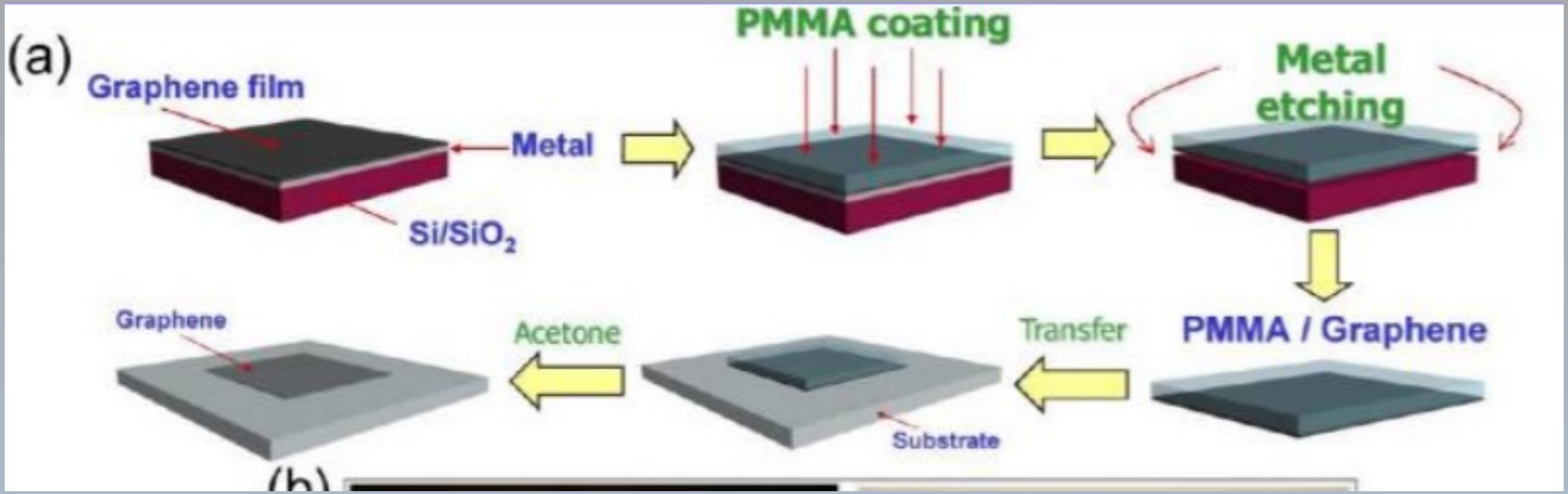




Detectors. Why graphene (CNT) based:

- -Gapless graphene has strong interband absorption at all frequencies
- - High room-temperature mobility
- -Geometric control of the band structure
- - Easy to fabricate
- - The frequency of graphene plasma waves lies in the terahertz range

MOTIVATION



Detectors. Why graphene (CNT) based:

- Gapless graphene has strong interband absorption at all frequencies
- High room-temperature mobility
- Geometric control of the band structure
- Easy to fabricate
- The frequency of graphene plasma waves lies in the terahertz range

MOTIVATION

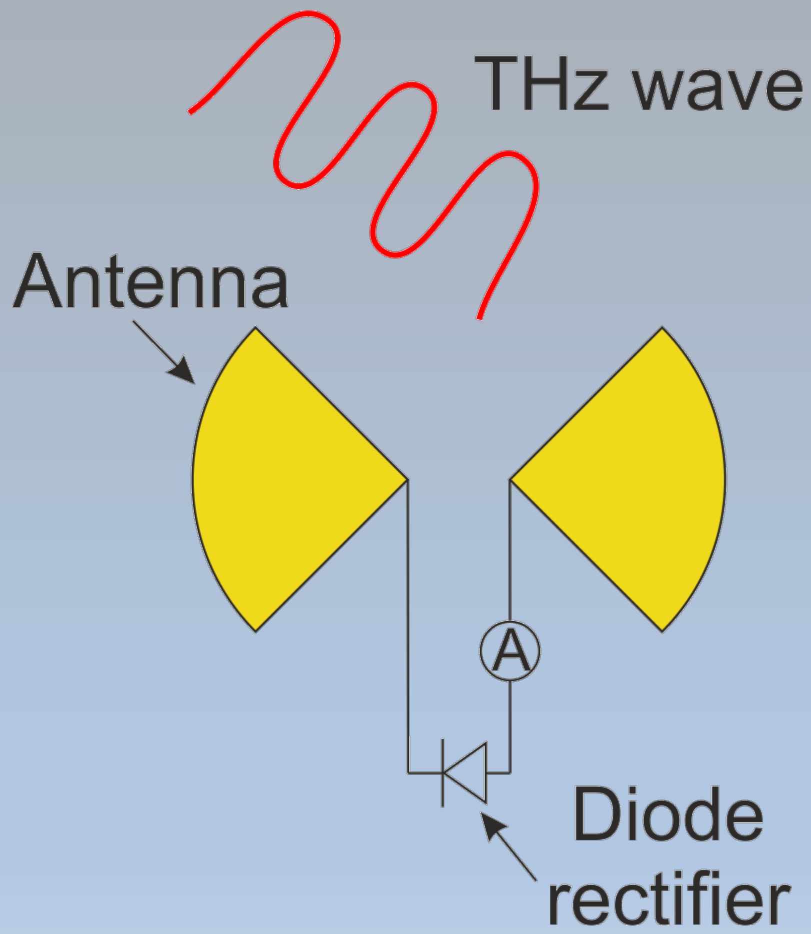
Plasmonics forms a major part of the fascinating field of *nanophotonics*, which explores how electromagnetic fields can be confined over dimensions on the order of or smaller than the wavelength.

Plasmonics: Fundamentals and Applications
Authors: Maier, Stefan Alexander
Springer, 2007

Detectors. Why graphene (CNT) based:

- **Gapless graphene has strong interband absorption at all frequencies**
- **High room-temperature mobility**
- **Geometric control of the band structure**
- **Easy to fabricate**
- **The frequency of graphene plasma waves lies in the terahertz range**

What do we mean by graphene THz detector



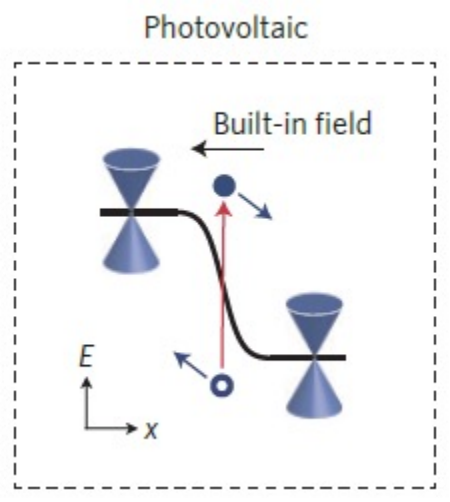
$$\left\langle I\left(\delta V\cos\omega t\right)\right\rangle_T \approx$$

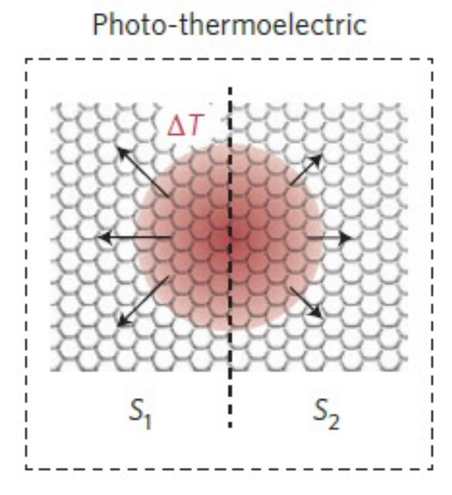
$$\frac{dI}{dV}\delta V\left\langle \cos\omega t\right\rangle_T + \frac{1}{2}\frac{d^2I}{dV^2}\delta V^2\left\langle \cos^2\omega t\right\rangle_T$$

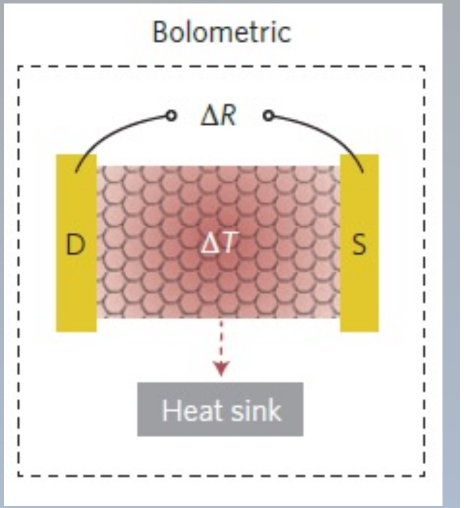
$$= \frac{1}{4}\frac{d^2I}{dV^2}\delta V^2$$

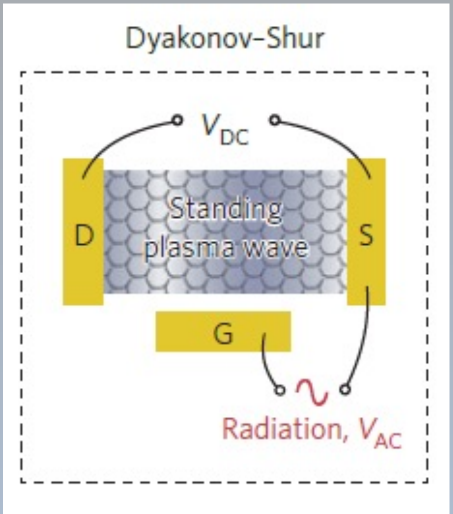
Study of detection mechanisms is the study of nonlinearities

The main mechanisms of THz radiation detection by graphene-based FET devices









Current due to built-in field at the junction OR rectification due to diode nonlinearity

Voltage due to temperature gradients in nonuniformly doped channel

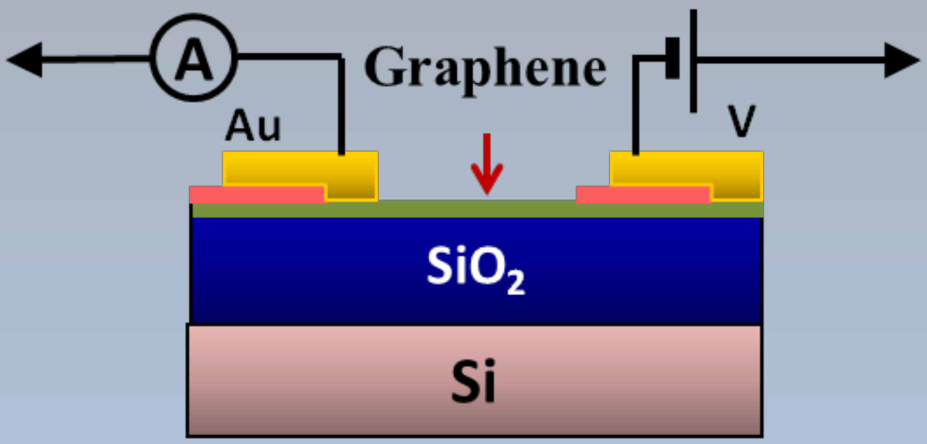
Resistance change due to overall device heating

Formation of standing plasma waves in the device channel

Figure from: F.H.L. Koppens, T. Mueller, P. Avouris, A.C. Ferrari, M.S. Vitiello, M. Polini, "Photodetectors based on graphene, other two-dimensional materials and hybrid systems" Nature nanotechnology, 9, 780-793 (2014)

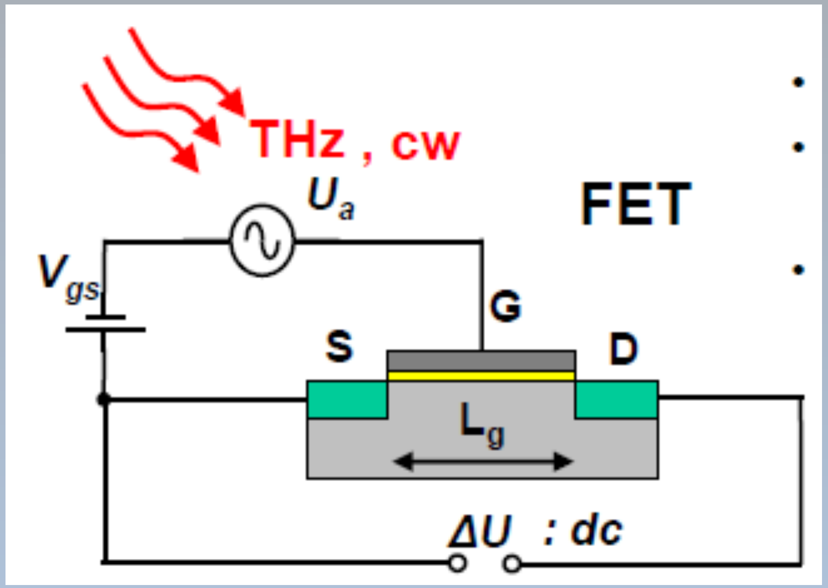
Two types of asymmetric graphene based structures

Asymmetric metallization



Difference in workfunction results in formation of a p-n junction along the channel. Schottky diode

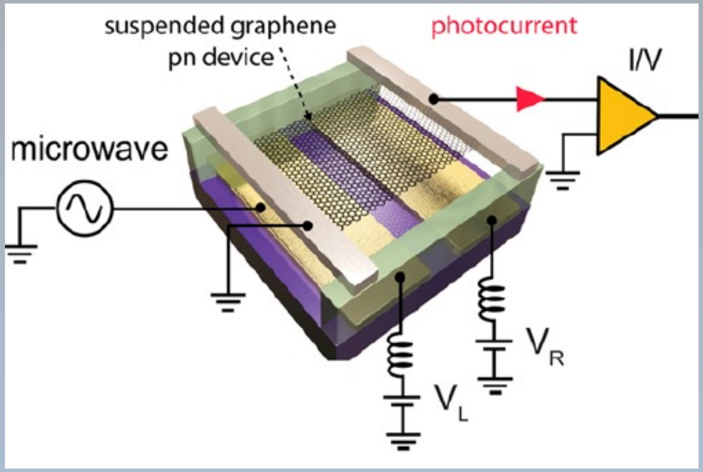
Dyakonov – Shur configuration

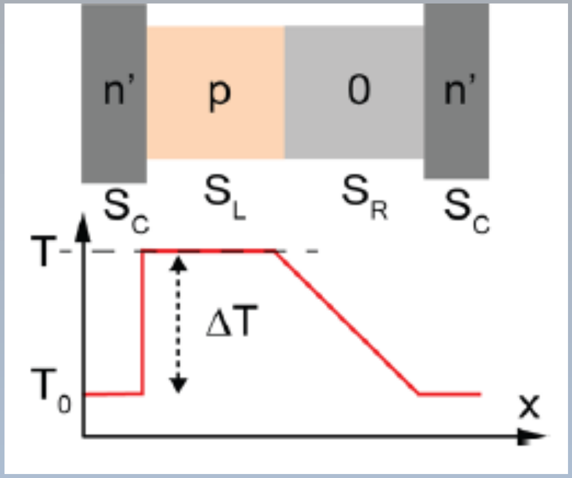


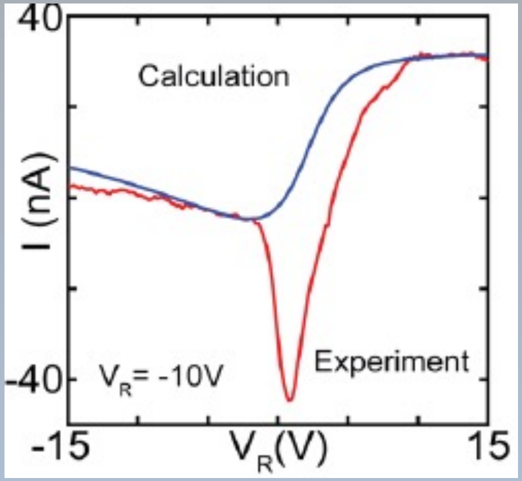
Asymmetric boundary conditions:
$V_S = V_0 \cos(\omega t); I_D = 0$
Result in a DC voltage signal as the device is exposed to radiation

Photo-thermoelectric effect in graphene

In case of a **photothermoelectric effect** an non-uniform doping of the channel and non-uniform heating of the channel results in onset of a DC voltage proportional to increase of the electron temperature







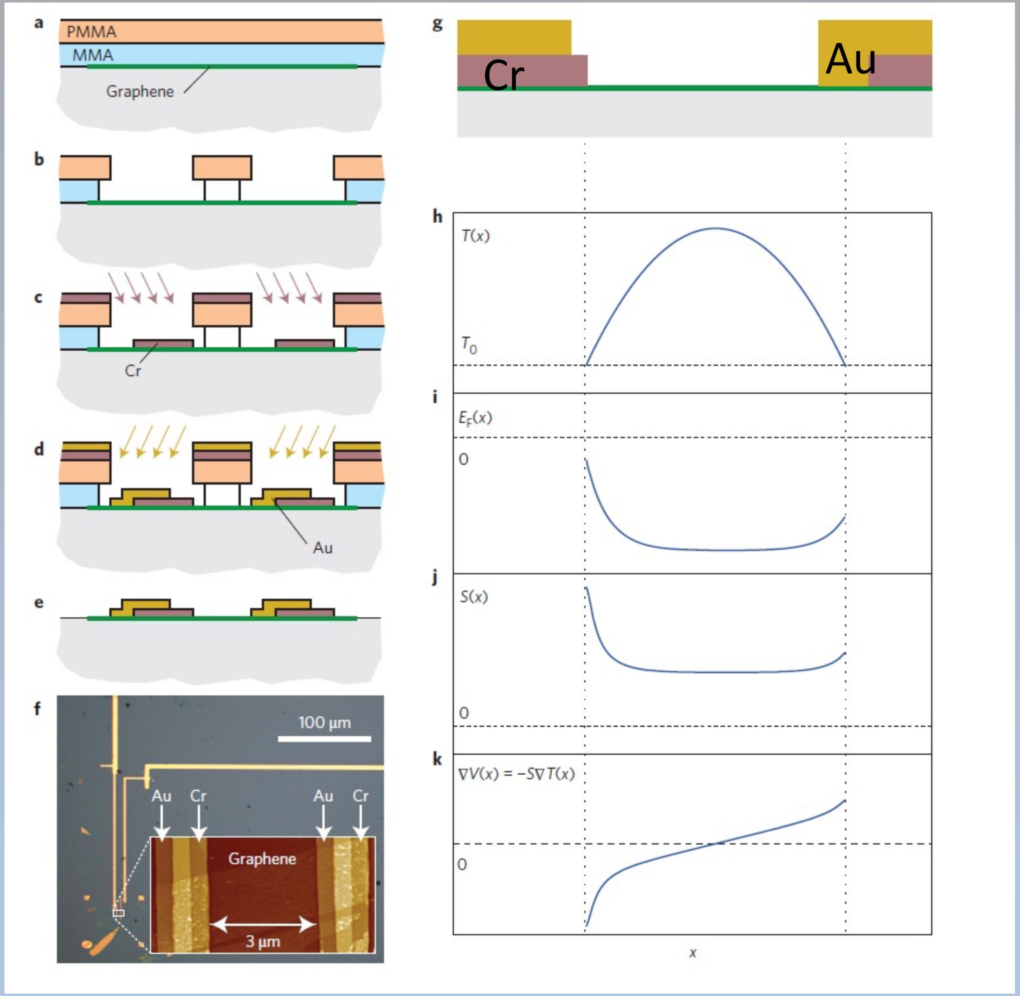
Graphene advantages for hot-electron photothermoelectric detection:

o-Gapless graphene has strong interband absorption at all frequencies.
o-The electronic heat capacity of single-layer graphene is much lower than in bulk materials, resulting in a larger change in temperature for the same absorbed energy
o- The photothermoelectric effect has a picosecond response time, set by the electron– phonon relaxation rate

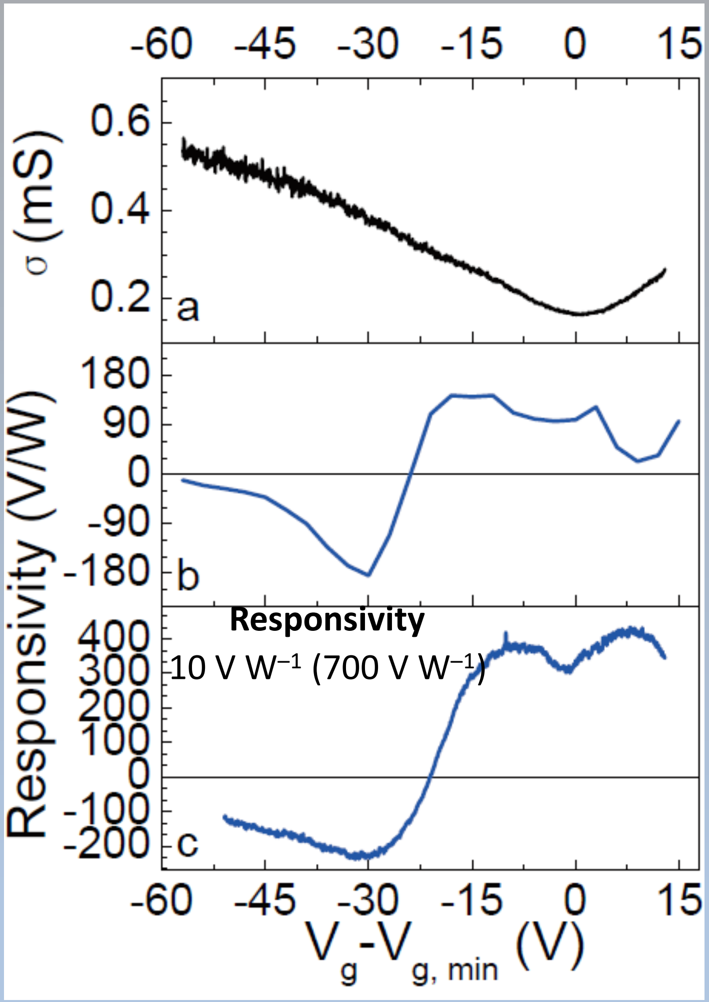
Nano Lett. ***16****, 6988 (2016)*

Photo-thermoelectric effect in graphene

Graphene photothermoelectric detector.
Principle of operation



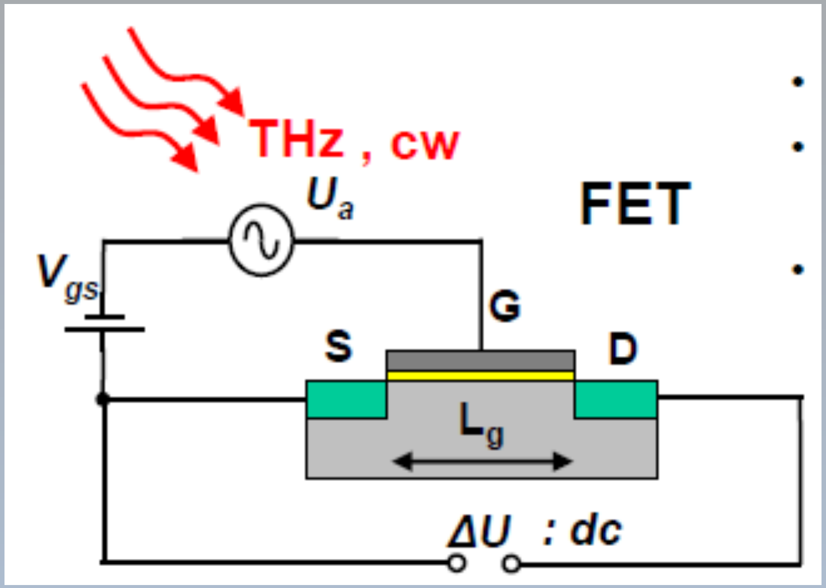
Graphene photothermoelectric detector device fabrication and principle of operation. (a-e) Lithographic sequence used to produce the graphene terahertz detector.(f) Optical micrograph showing electrical contacts and (inset) atomic force micrograph showing bimetallic contacts connected to an exfoliated graphene layer. (g-k) Schematic of the principle components during device operation. (g) Cross-sectional view of the device. (h-j) Profiles across the device of (h) electron temperature T(x), (i) Fermi level EF(x), (j) Seebeck coefficient S(x) and (k) potential gradient



Broadband thermoelectric responsivity of graphene photothermoelectric detector. (a,d) Electrical conductance, (b,e) responsivity to Joule heating, and (c,f) responsivity to radiation as a function of gate voltage for the device shown in Fig. 1f at room temperature and in ambient environment.

*Nature Nanotechnology **9**, 814–819 (2014)

Detection, mixing, and frequency multiplication of terahertz radiation by two-dimensional electronic fluid*



The basic equations describing the two dimensional electronic fluid are the relationship between the surface carrier concentration and gate voltage swing, the equation of motion, and the continuity equation

$$n_s = CU/e$$

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + \frac{e}{m}\frac{\partial U}{\partial x} + \frac{v}{\tau} = 0$$

$$\frac{\partial U}{\partial t} + \frac{\partial (Uv)}{\partial x} = 0.$$

The boundary conditions

$$U(0,t) = U_o + U_a \cos \omega t \quad \text{for} \quad x = 0$$

$$j(L,t) = 0 \quad \text{for} \quad x = L$$

$$\frac{\Delta U}{U_o} = \frac{1}{4}\left(\frac{U_a}{U_o}\right)^2 f(\omega)$$

where

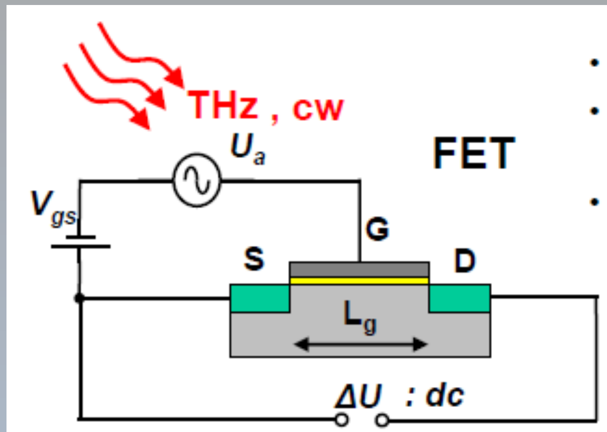
$$f(\omega) = 1 + \beta - \frac{1 + \beta \cos(2k_o' L)}{\sinh^2(k_o'' L) + \cos^2(k_o' L)}.$$

Here

$$\beta = \frac{2\omega\tau}{\sqrt{1 + (\omega\tau)^2}}$$

*IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 43, NO. 3, MARCH 1996

Detection, mixing, and frequency multiplication of terahertz radiation by two-dimensional electronic fluid



$$\frac{\Delta U}{U_o} = \frac{1}{4}\left(\frac{U_a}{U_o}\right)^2 f(\omega)$$

where

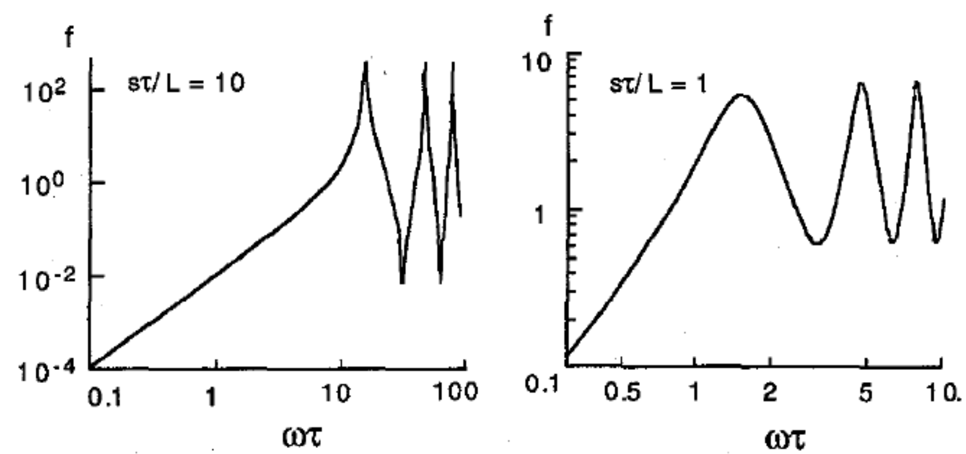
$$f(\omega) = 1 + \beta - \frac{1 + \beta\cos(2k_o' L)}{\sinh^2(k_o'' L) + \cos^2(k_o' L)}.$$

Here

$$\beta = \frac{2\omega\tau}{\sqrt{1 + (\omega\tau)^2}}$$

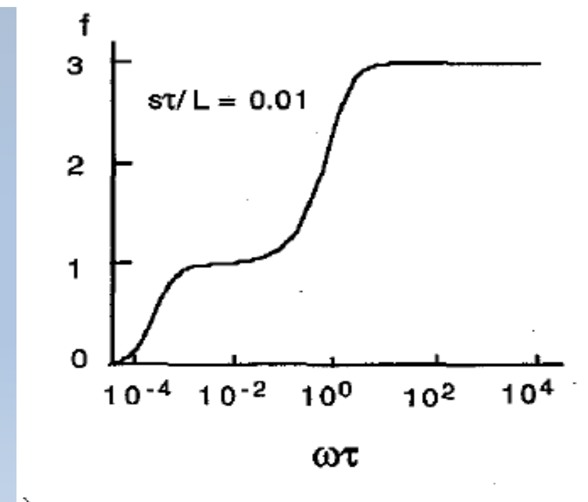
Resonant Detector $\omega\tau >> 1$

$$f(\omega) = \frac{3\sinh^2\left(\frac{L}{2s\tau}\right) + \sin^2\left(\frac{\omega L}{s}\right)}{\sinh^2\left(\frac{L}{2s\tau}\right) + \cos^2\left(\frac{\omega L}{s}\right)}.$$



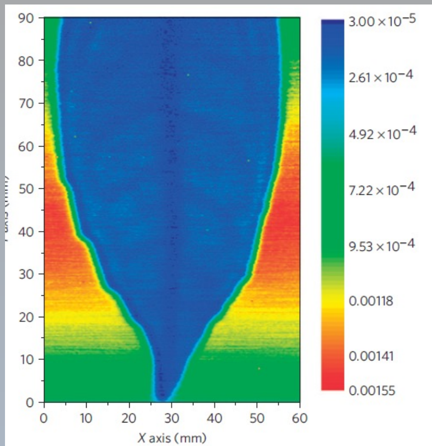
Broadband Detector $\omega\tau << 1$

$$f(\omega) = 1 + \frac{2\omega\tau}{\sqrt{1 + \omega^2\tau^2}}.$$



*IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 43, NO. 3, MARCH 1996

Graphene field-effect transistors as room-temperature terahertz detectors*



Due to high room-temperature mobility (up to **10 000 cm²/(V s)** on SiO_2 graphene is promising for THz FET photodetectors.

Diffusive transport model

$\omega\tau_{ee} << 1$

$\omega\tau_{tr} << 1$

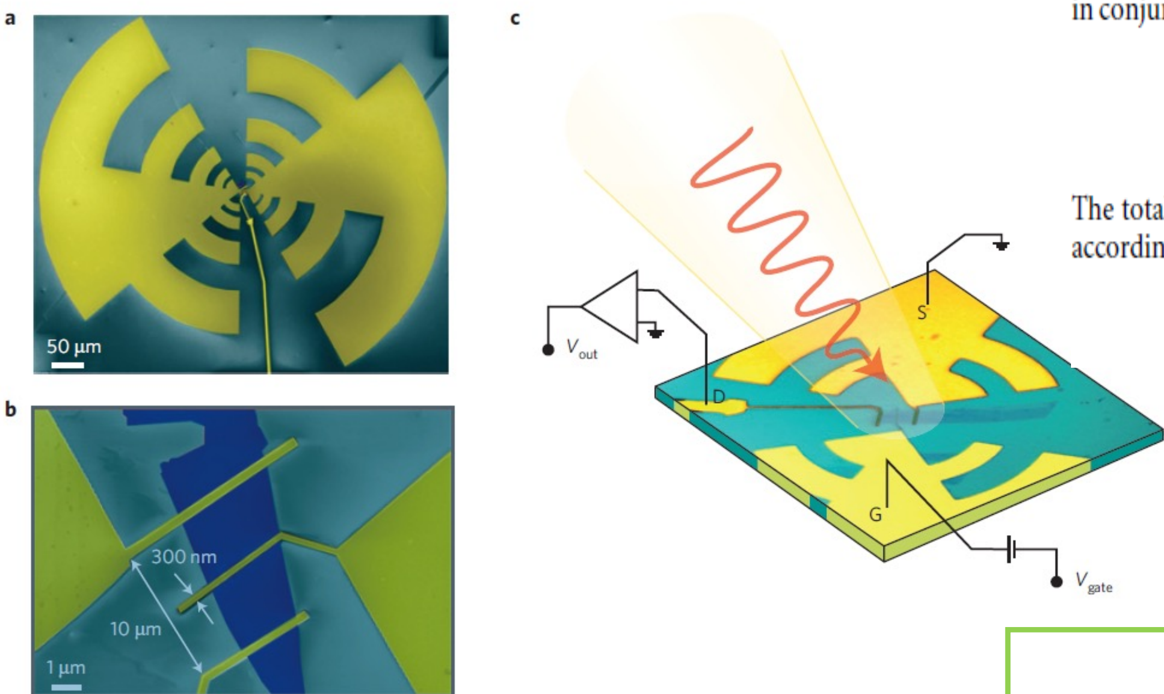
$$j(x,t) = \sigma E(x,t) = -\sigma \frac{\partial V_G(x,t)}{\partial x}$$

in conjunction with the continuity equation:

$$\frac{\partial[-en(x,t)]}{\partial t} + \frac{\partial j(x,t)}{\partial x} = 0$$

The total carrier density $-en(x,t)$ is modulated by the gate voltage $V_G(x,t$ according to

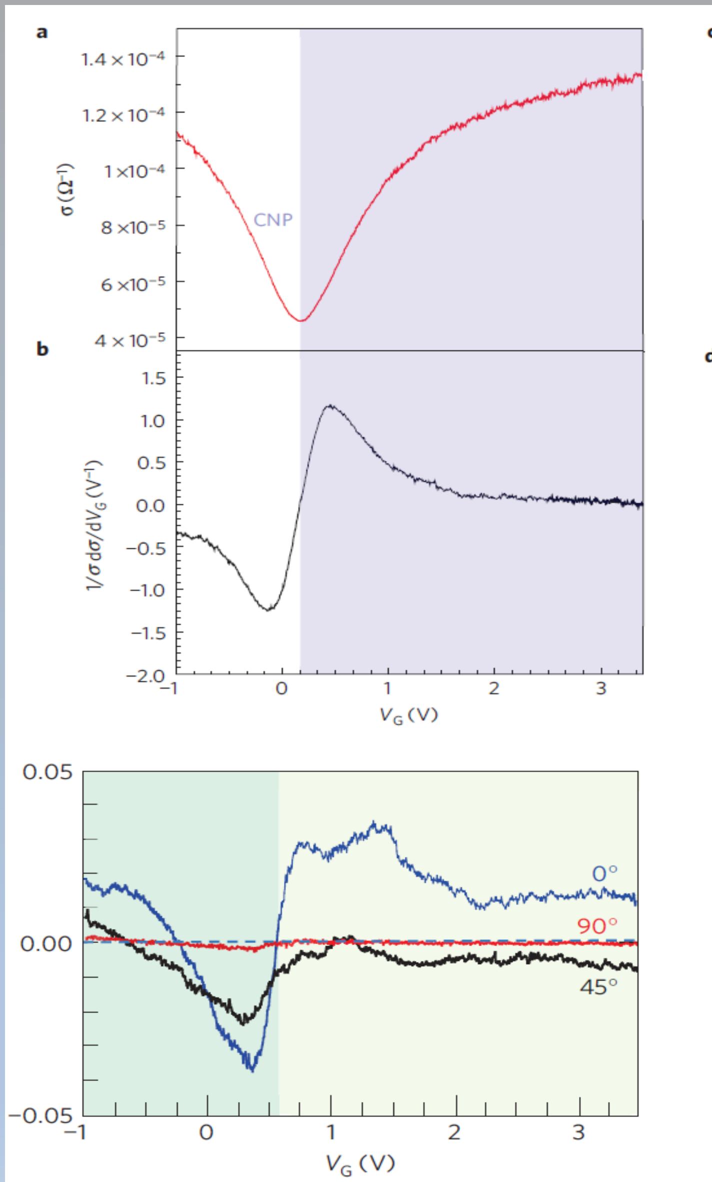
$$-en(x,t) = CV_G(x,t)$$



$$\Delta u = \frac{U_a^2}{4} \frac{1}{\sigma(U_0)} \left. \frac{d\sigma(V_G)}{dV_G} \right|_{V_G=U_0}$$

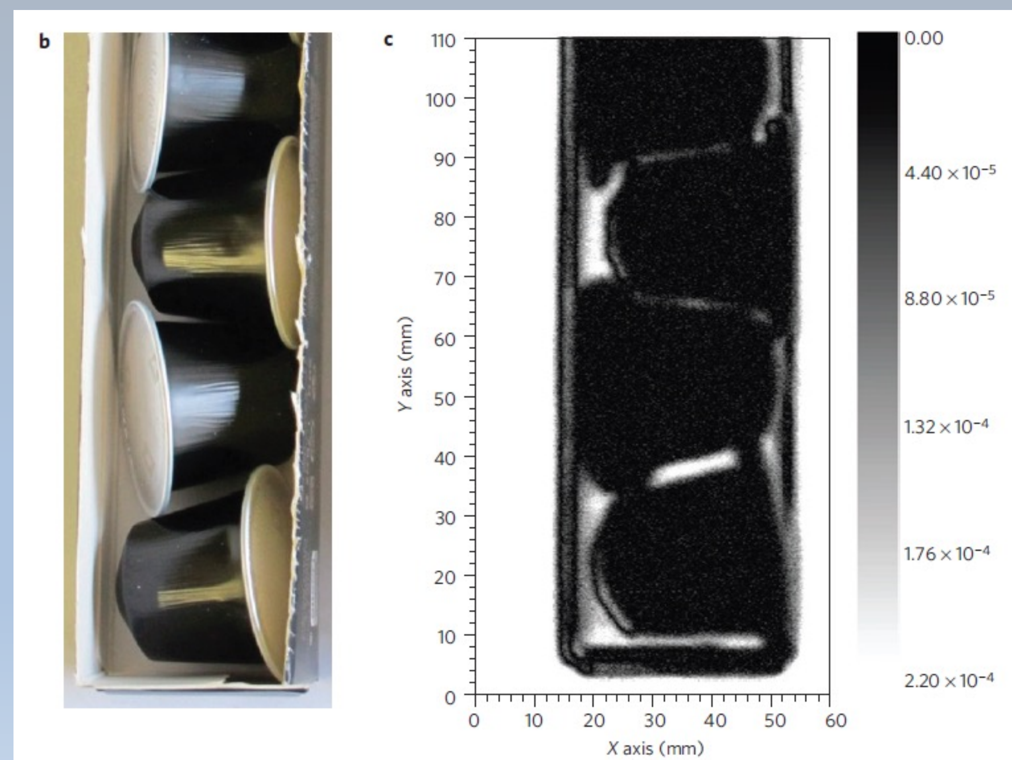
NATURE MATERIALS; VOL 11 ;OCTOBER 2012

Graphene field-effect transistors as room-temperature terahertz detectors*



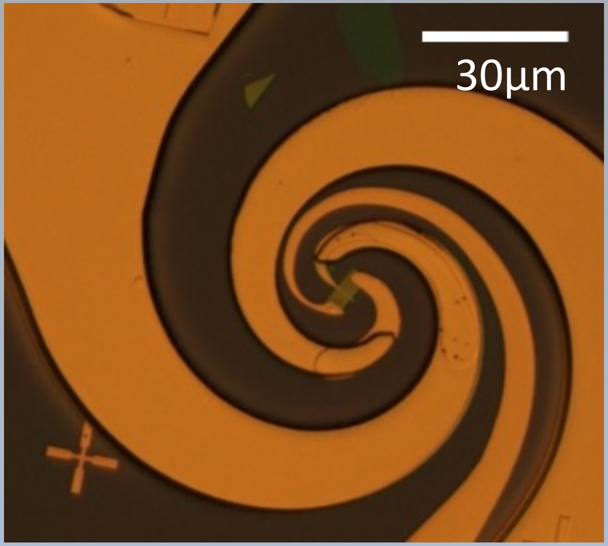
$$\Delta u = \frac{U_a^2}{4}\frac{1}{\sigma(U_0)}\left.\frac{d\sigma(V_G)}{dV_G}\right|_{V_G=U_0}$$

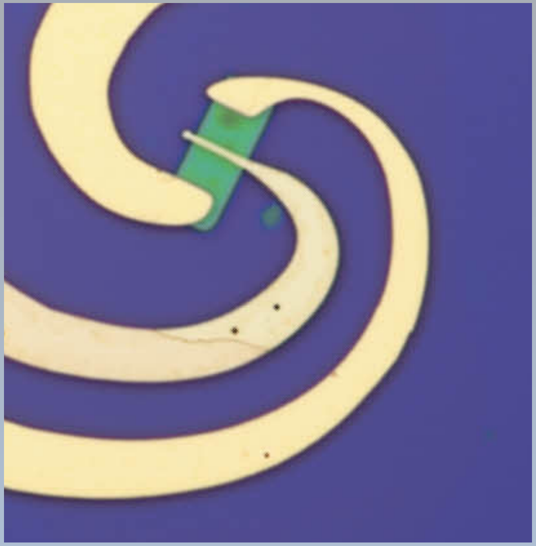
The minimum RT **NEP** is 200nW$Hz^{-1/2}$ for SLG and almost one order of magnitude lower (30nW$Hz^{-1/2}$) for BLG.



NATURE MATERIALS; VOL 11 ;OCTOBER 2012 j

2D FETs for THz detection: Graphene. Further research

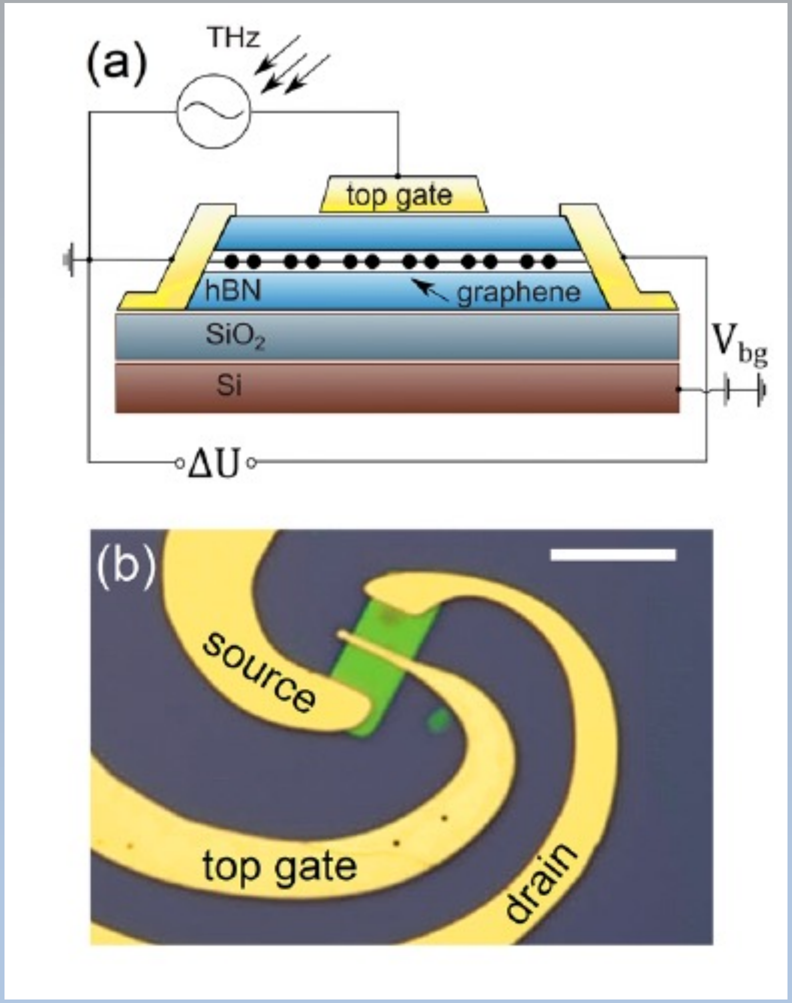




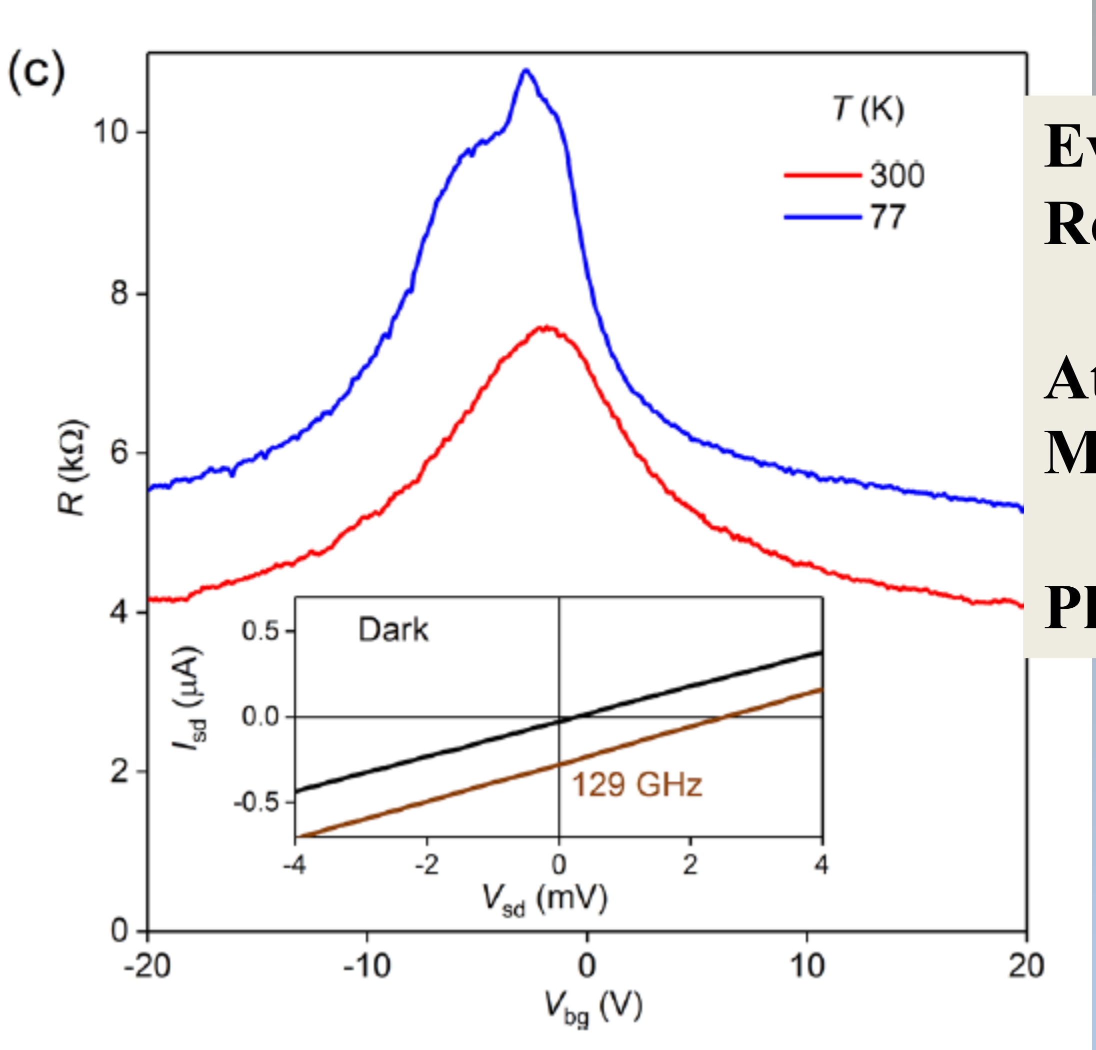
Highest mobility devices probed in DS configuration

D. A. Bandurin, I. Gayduchenko, et al., 112, 141101, (2018)

2D FETs for THz detection: Graphene. Further research



2D FETs for THz detection: Graphene. Further research



Evident contact resistance Rc

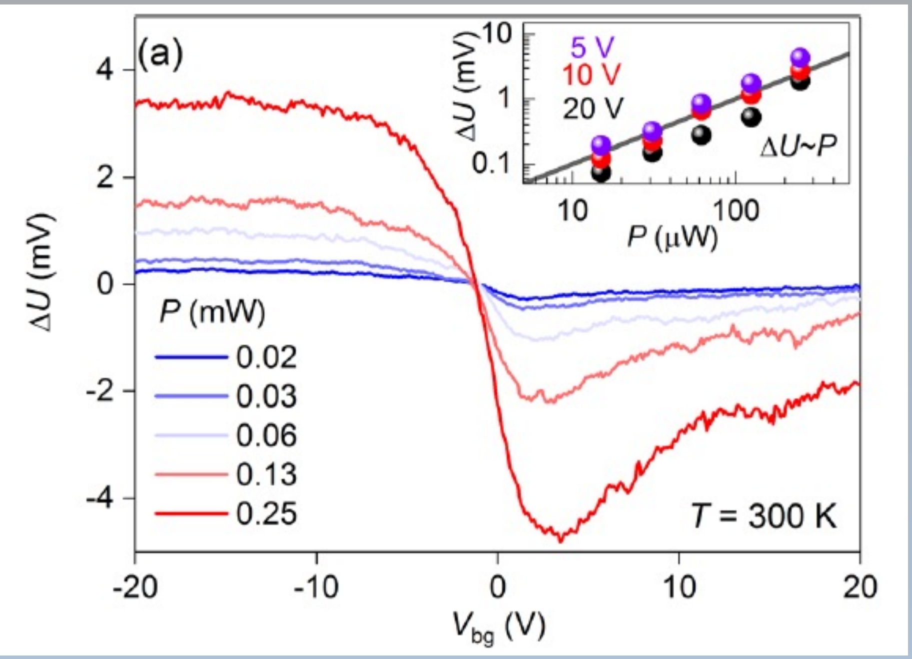
At least two-fold increase of Mobility upon cooling

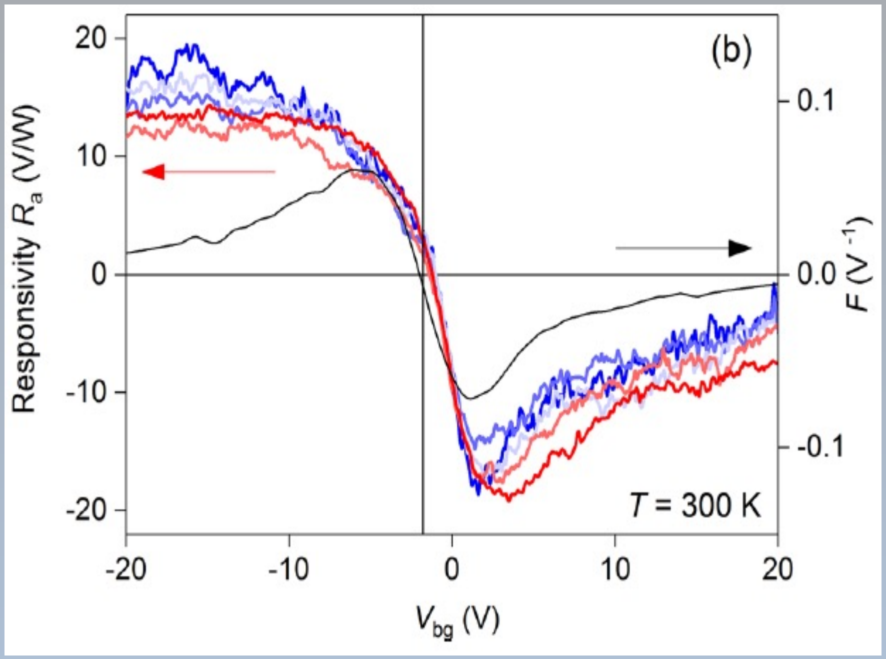
Photo induced voltage

RT mobility

$$\mu = 3200\ cm^2 V^{-1} s^{-1}$$

2D FETs for THz detection: Graphene. Further research

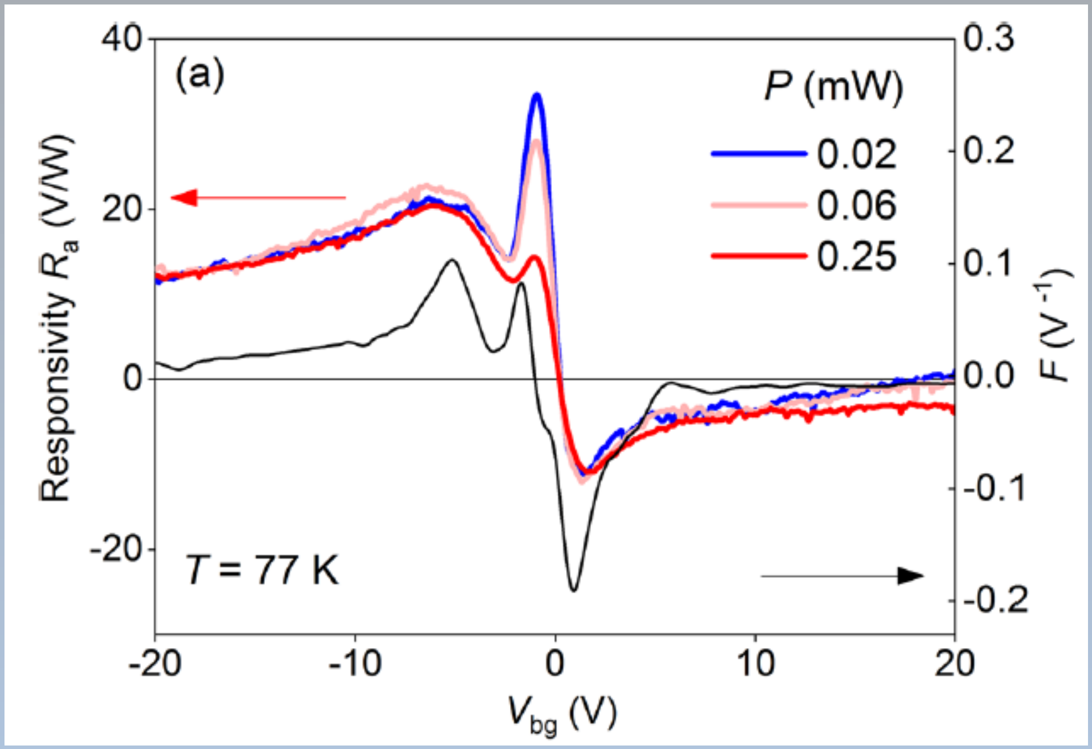


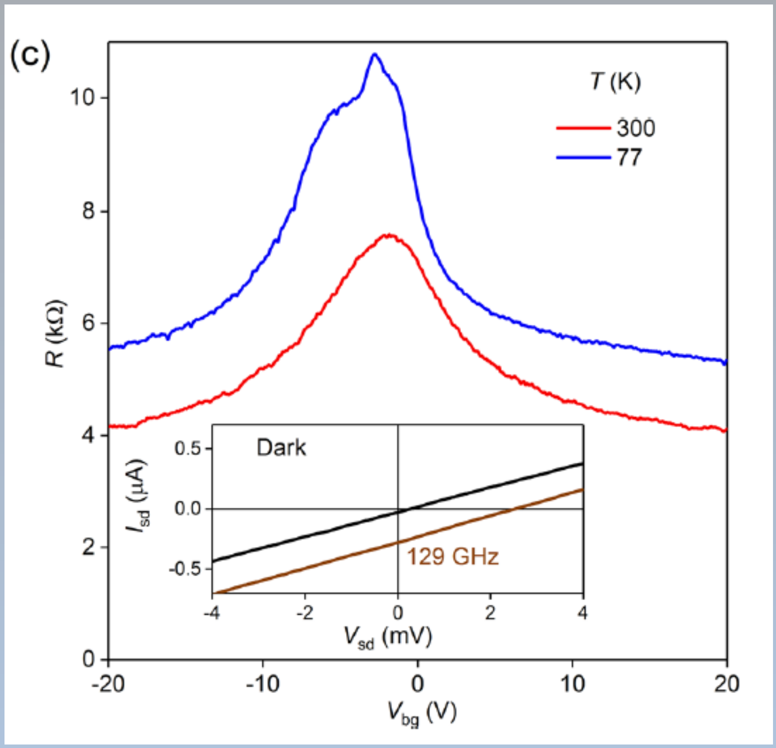


@ Room temperature the response voltage is a linear function of the radiation power

More importantly, R(Vg) follows the F(Vg) with F = dG/dVg * R

2D FETs for THz detection: Graphene. Further research

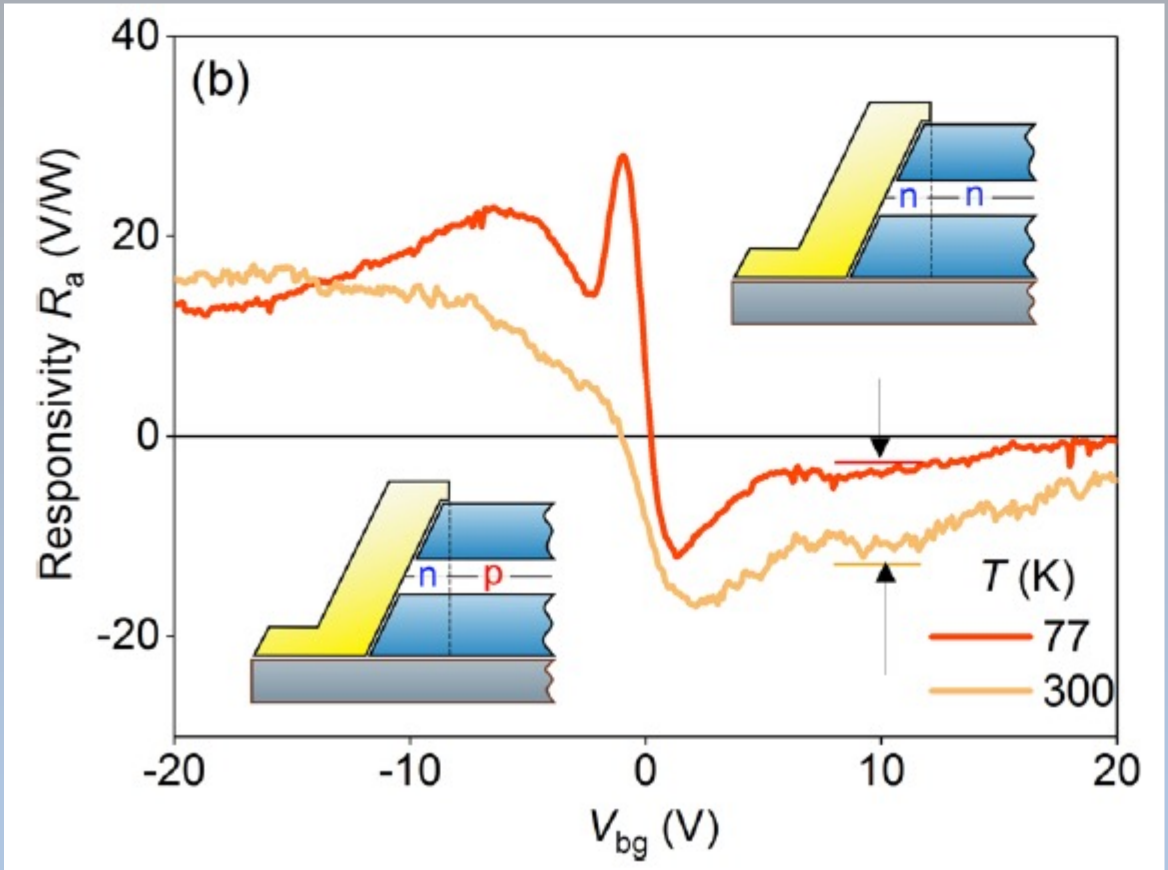




At 77 K peak responsivity increases as the radiation power goes down

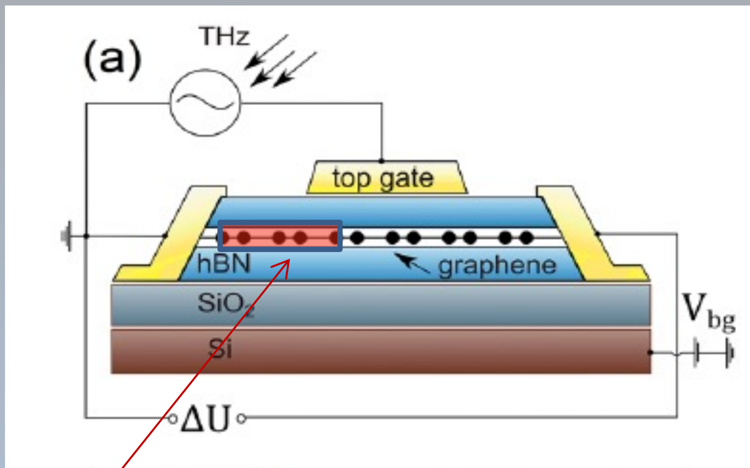
R(Vg) still follows the F(Vg)

2D FETs for THz detection: Graphene. Further research



Temperature evolution of responsivity is different for different gate voltages

Heating-induced photoresponce

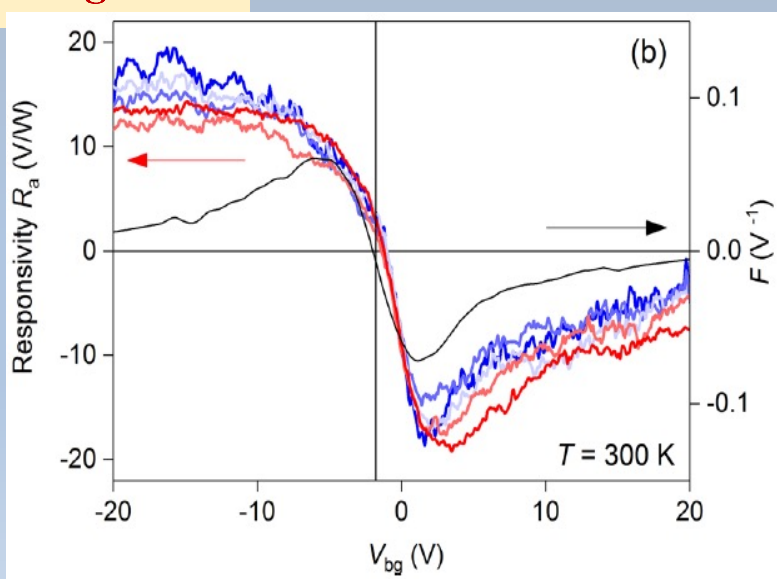


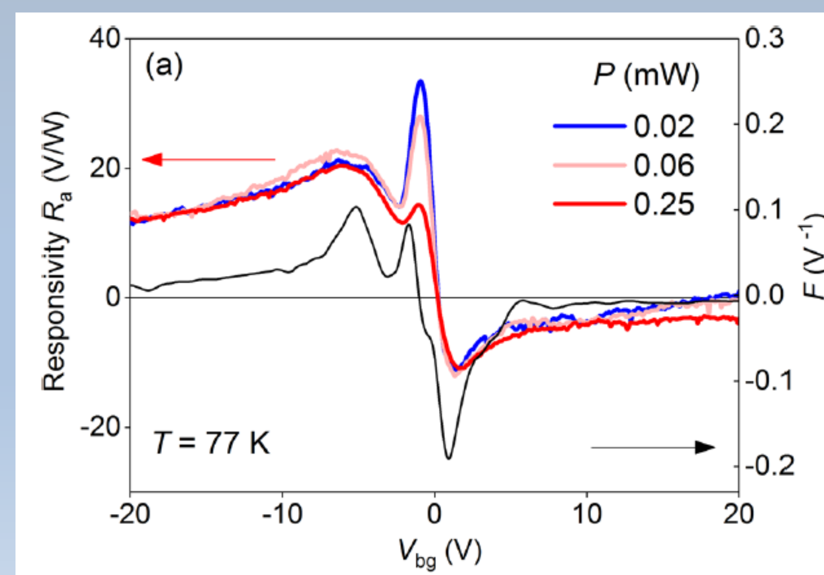
$$U_{PTE} = -\int S dT \approx S(T_S - T_D)$$

$$S \approx -\frac{\pi^2 k_B^2 T}{3e}\frac{1}{\sigma}\frac{d\sigma}{dE_F}$$ is the Seebeck coefficient

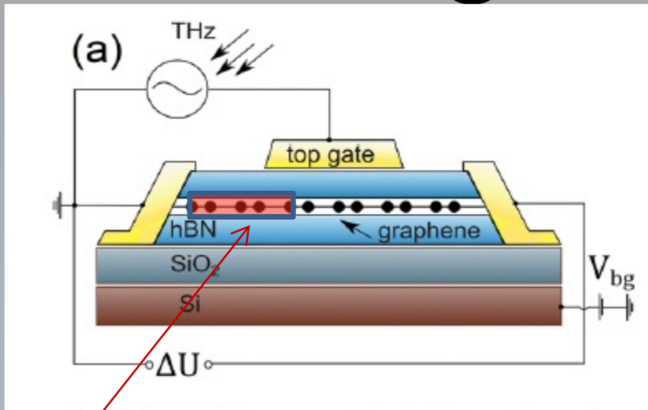
$$F = \frac{1}{\sigma}\frac{d\sigma}{dV_{bg}}.$$

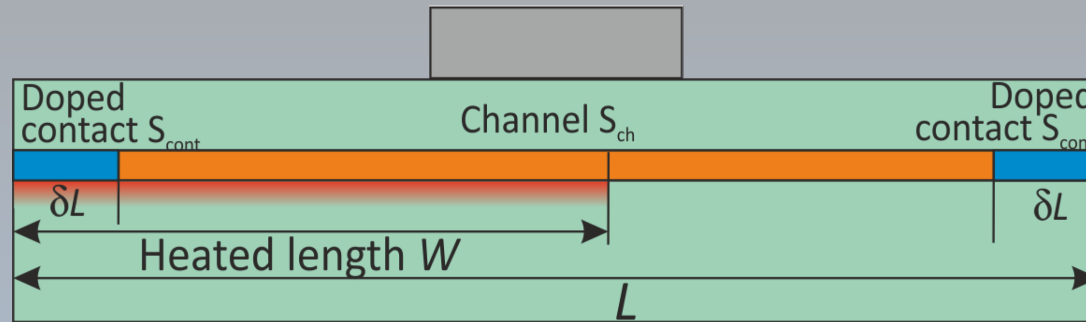
Heated region



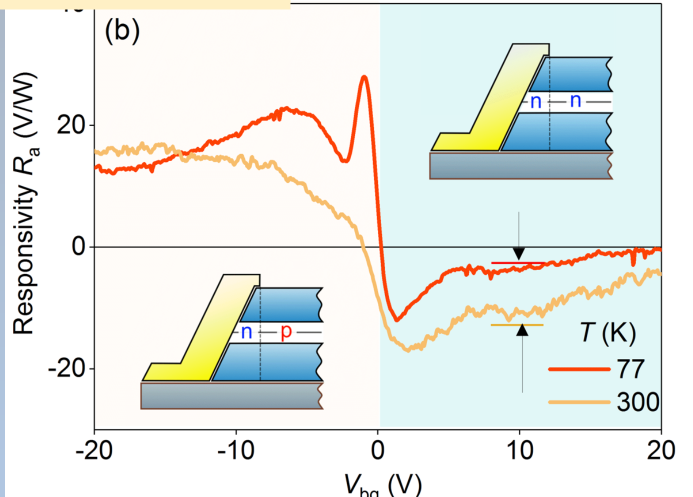


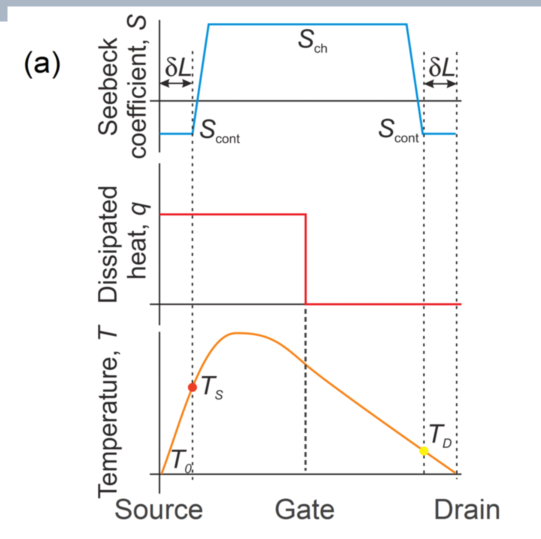
Heating-induced photoresponce

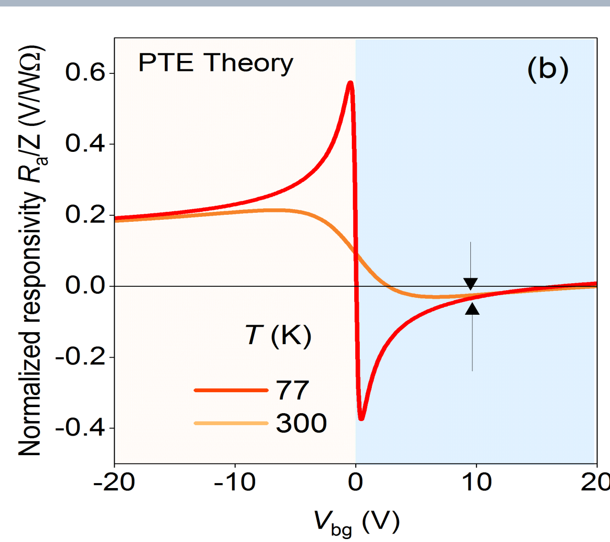




Heated region





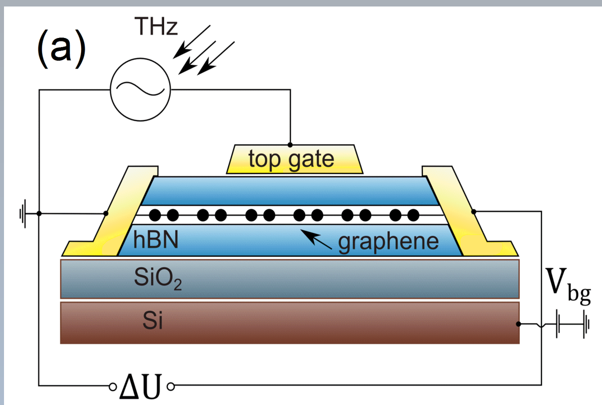


$$R_a \approx \frac{3}{2\pi^2}\left[\frac{e}{k_B}(S_{cont} - S_{ch})\right]\frac{eZ_a}{k_B T}\frac{\delta L}{L},$$

$$U_{PTE}=(S_{ch}-Sc_{ont})(T_S-T_D)$$

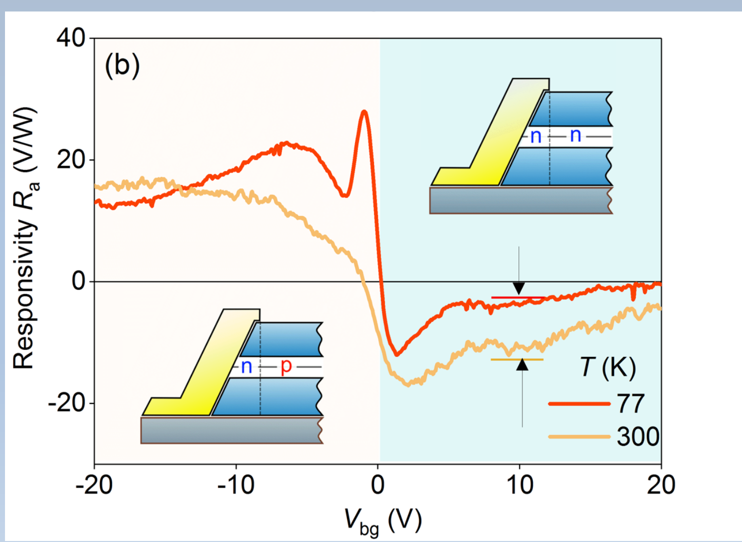
Temperature evolution of responsivity is different for in case of PURE PTE accounting for the p-n junction at the Ti-Graphene interface (*simulations performed by D. Svintsov)*

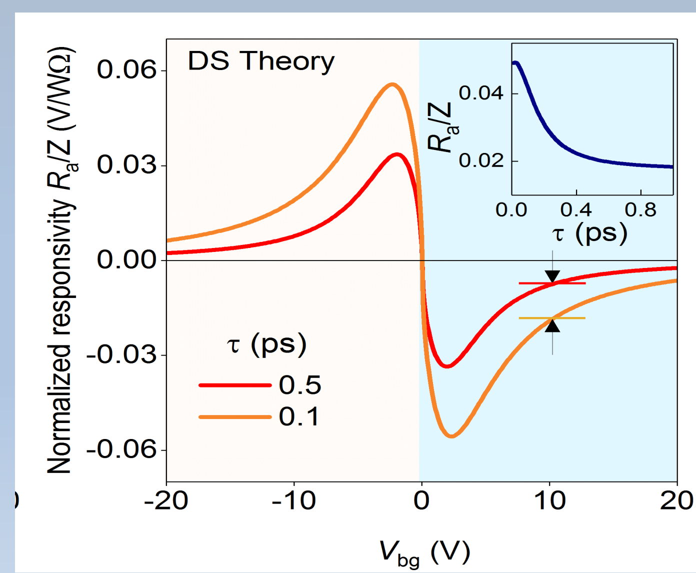
Dyakonov-Shur photoresponse



$$\Delta U_{\mathrm{DS}} = \frac{U_{\mathrm{a}}{}^{2}}{4}\frac{1}{\sigma}\frac{d\sigma}{dV_{\mathrm{bg}}} g(\omega) \propto U_{\mathrm{a}}{}^{2}F, \quad (3)$$

where U_{a} is the antenna voltage, L is the channel length, $g(\omega) = (\sinh^2 kL - \sin^2 kL)/(\sinh^2 kL + \cos^2 kL)$ is the "form factor" depending on the wave number $k = \sqrt{\omega/(2s^2\tau)}$ of the overdamped plasma wave characterized by the group velocity $s = \sqrt{4\alpha_{ee} d\sqrt{\pi n}}$, n is the carrier density and α_{ee}~1 is the parameter describing the strength of e-e interactions in





Conclusions

- FET based on graphene encapsulated in hBN can serve as high-responsivity THz detector
- Terahertz detection in graphene FETs is a combination of resistive self-mixing, photothermoelectric effects and p-n junction rectification
- Hydrodynamics, strong electron-electron and electron-hole scattering are good for photodetection