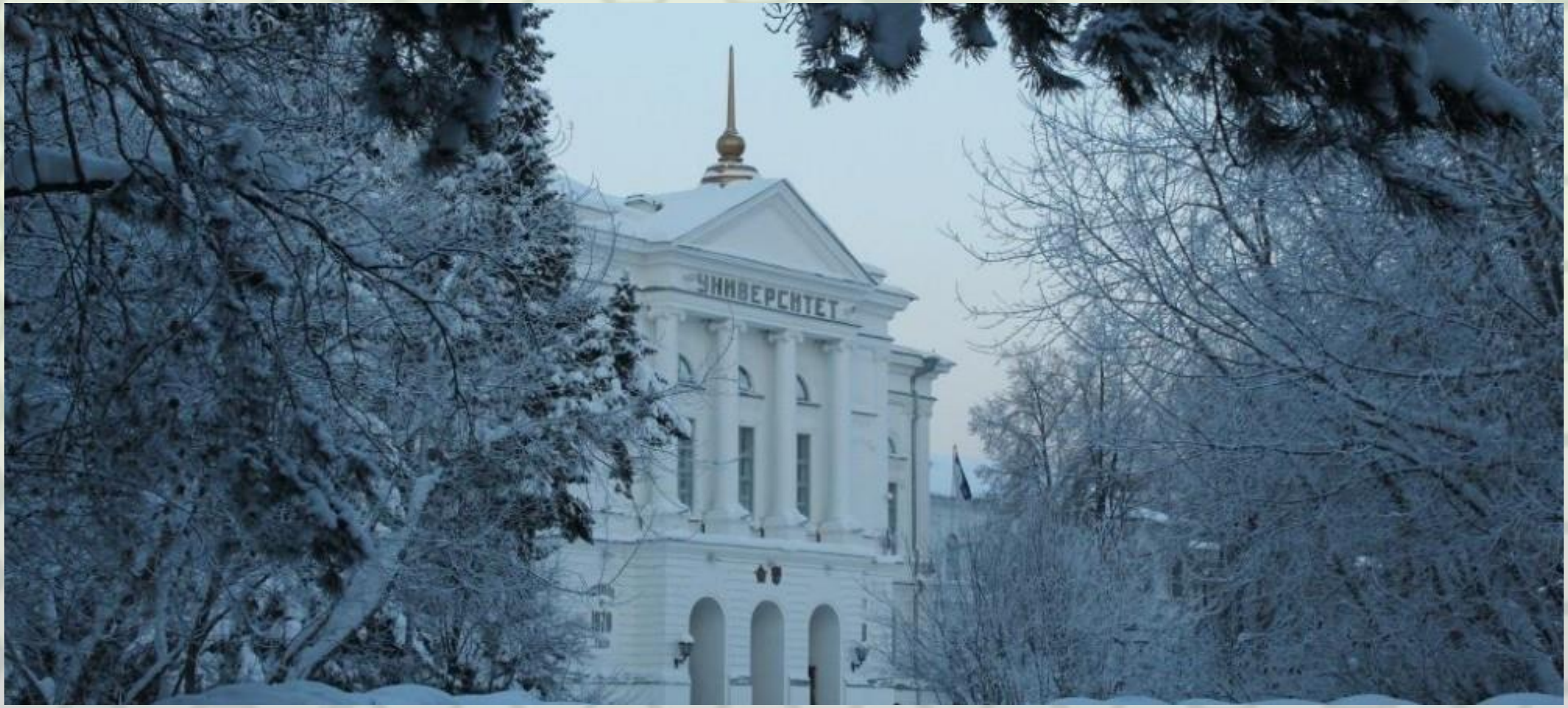
Graphene based nanostructures for detecting terahertz radiation.

Georgy Fedorov 21.09.2017

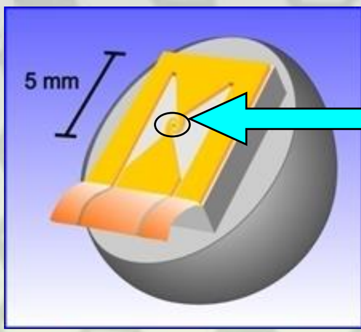


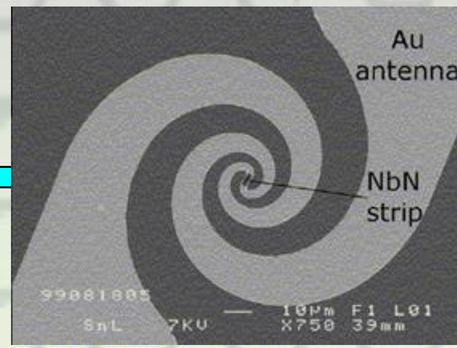
MSPU
Science and Education Radiophysics Center and Laboratory of Quantum Detectors, Moscow

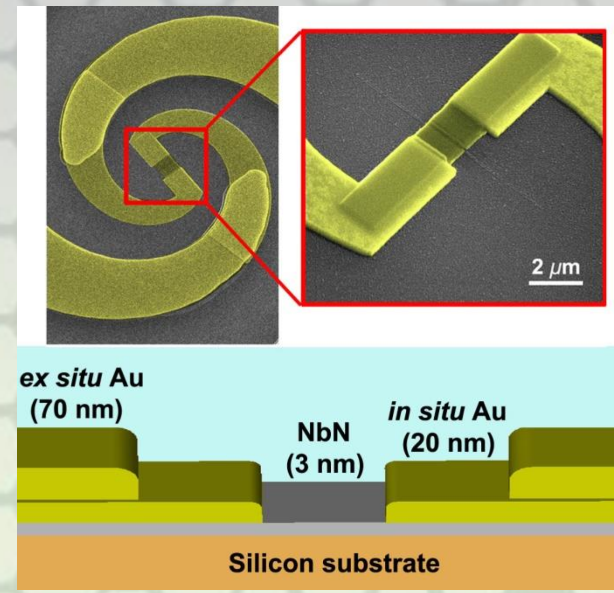
Hot electron bolometers as direct detectors

are capable to detect *aJ* pulse energy at GHz rate

Spiral antenna coupled bolometer



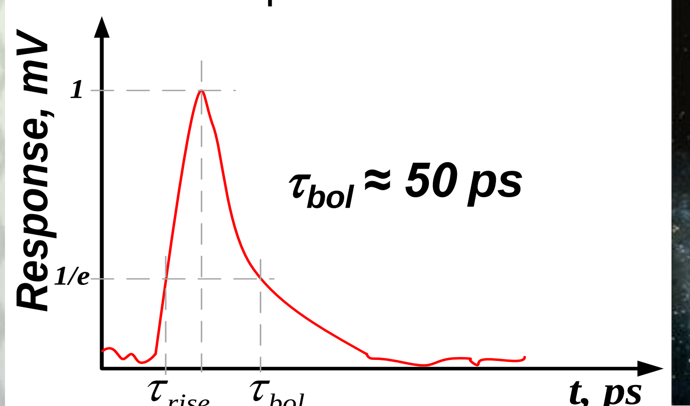


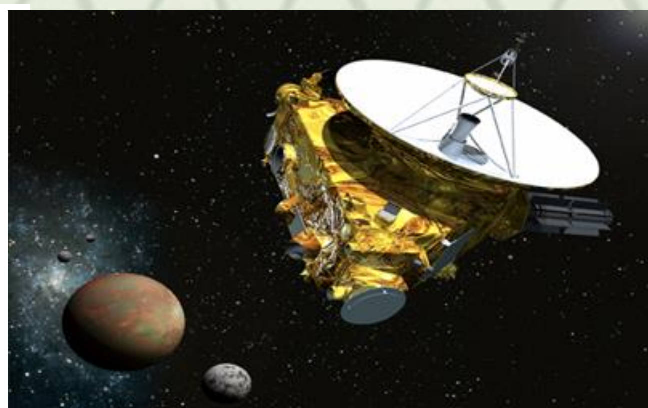


NEP ≈ 3×10 $^{-13}$ W/√Hz

No photon shot noise in THz!

Pulse response simulation



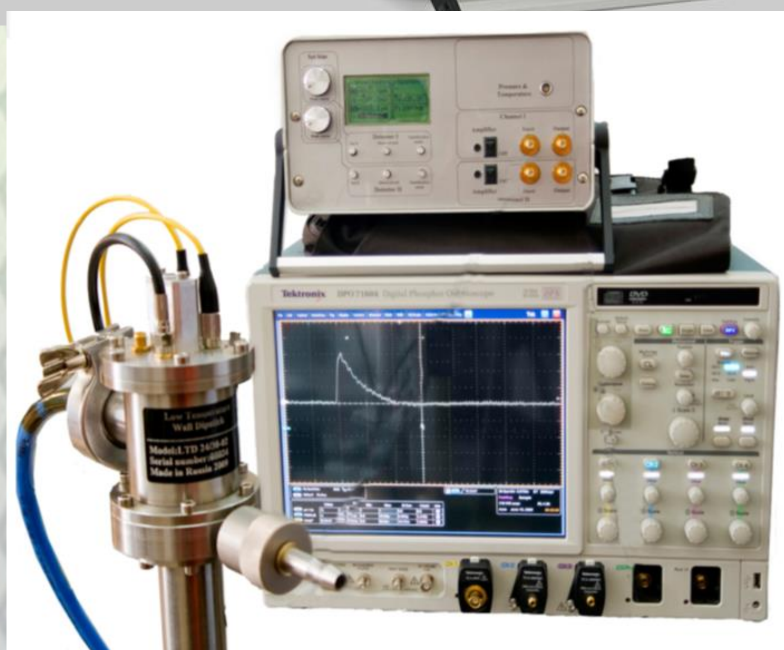


New Horizons: approaching Pluto
(artist's view, to happen in summer 2015)

2.1 m diameter dish antenna to communicate with Earth from 7.5 billion kilometers away

Credit: Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute (JHUAPL/SwRI)

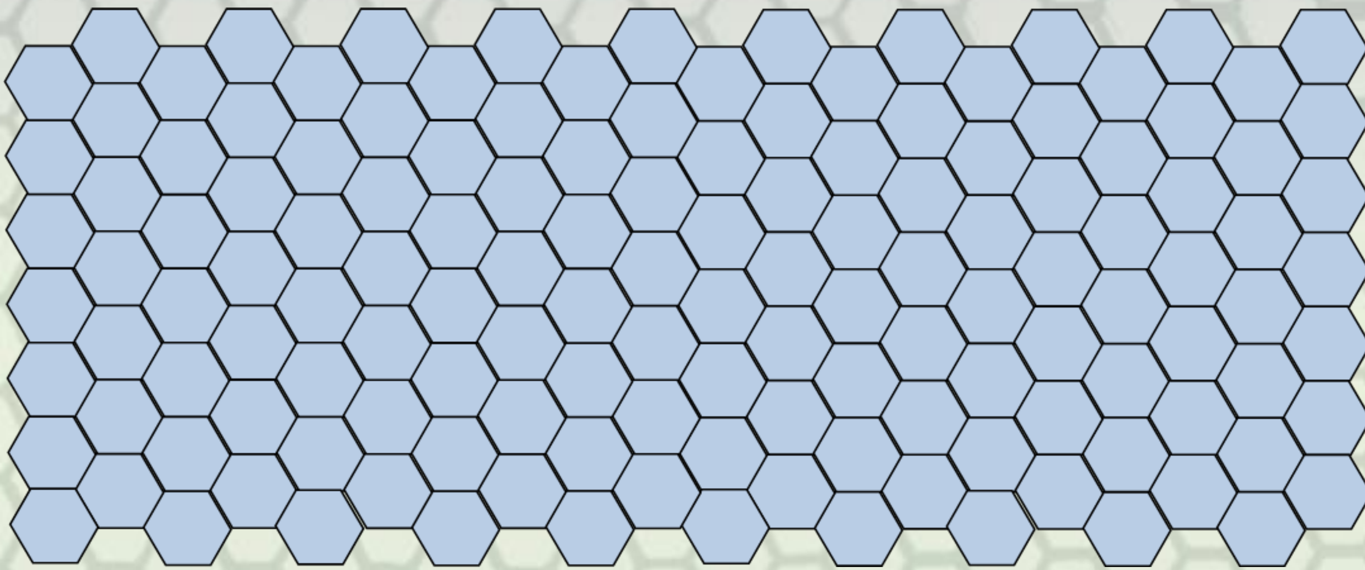

Helium-free
Closed-cycle cryostat system
You don't need to know
anything about superconductivity,
You just need the Source of Light.

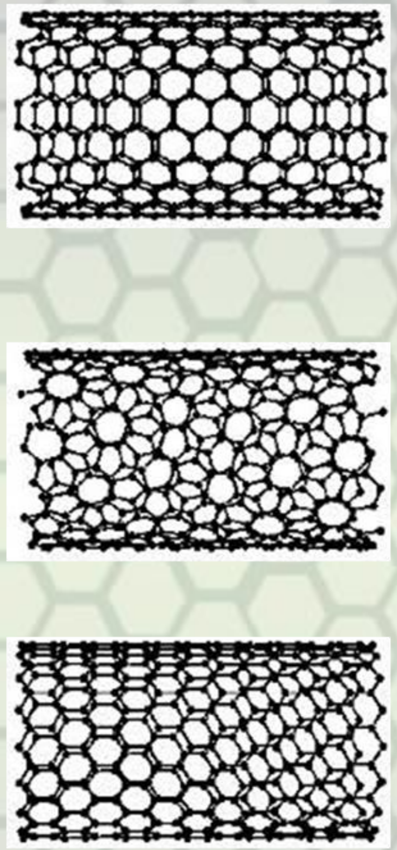

Tektronix


THz Receiver based on
liquid helium cryostat
Scontel offers the fastest
Terahertz receivers available today.

New materials for THz detection

Why graphene (graphene based)?





- Mostly because of higher mobility.
- Peculiar spectrum leads to geometric control of bandstructure
- Easy to fabricate

Outline:

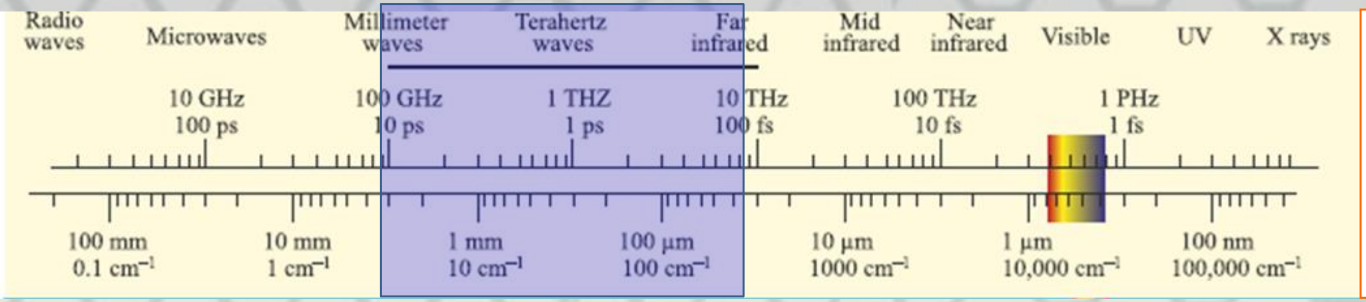
1. Introduction.
- Motivation
- Asymmetric structures. What does it mean? Asymmetric metallization

2. Experiment:
- Description of the samples
- Response of the samples to radiation
- Dependence of response on frequency and temperature

3. Analysis of the results and possible mechanisms of response to radition

4. Conclusions

MOTIVATION

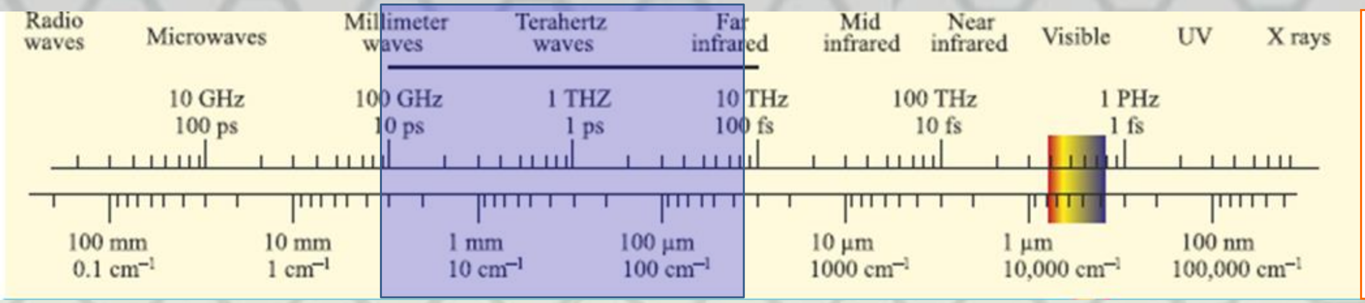


THz range is important for:
- Security
- Medicine
- Astronomy
- Etc.

Detectors. Why nanosturtures:

- Sensitive
- Fast
- Energy efficient
- Response controlled by gate
- Etc.

MOTIVATION



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Detectors. Why graphene (CNT) based:
- High mobility
- Geometric control of the band structure
- Easy to fabricate!
- Plasma waves

MOTIVATION

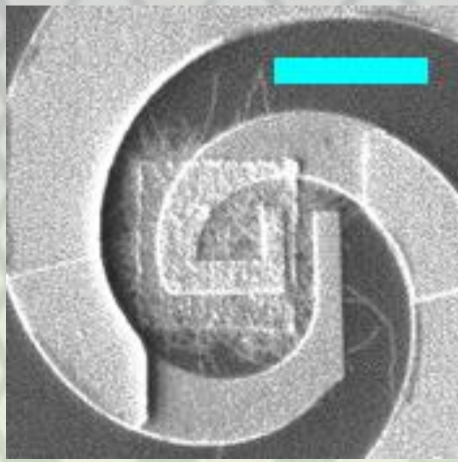
Detectors. Why graphene (CNT) based:

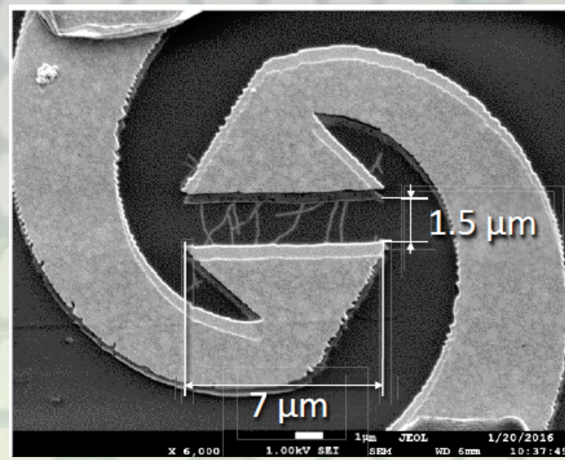
- **High mobility**
- **Geometric control of the band structure**
- **Easy to fabricate!**
- **Plasma waves**

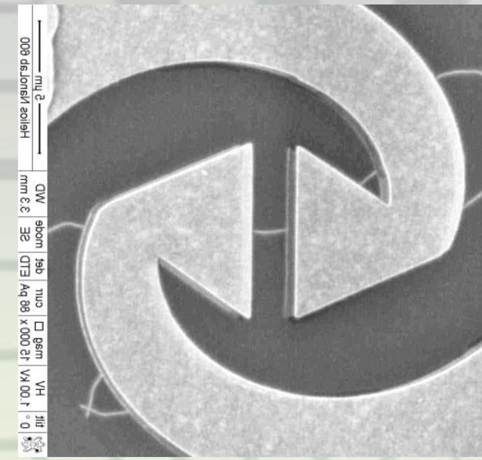
Plasmonics forms a major part of the fascinating field of *nanophotonics*, which explores how electromagnetic fields can be confined over dimensions on the order of or smaller than the wavelength.

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

Previous work on asymmetric structures







- M. Ryzhii, *et al.*, Dynamic Conductivity and Two-Dimensional Plasmons in Lateral CNT Networks, International Journal of High Speed Electronics and Systems 26 (01n02), 1740004 (2017)
- G.E. Fedorov, *et al.*, Asymmetric devices based on carbon nanotubes for terahertz-range radiation detection, Semiconductors 50 (12), 1600-1603. (2016)
- I.A. Gayduchenko *et al.*, Asymmetric devices based on carbon nanotubes as detectors of sub-THz radiation, Journal of Physics: Conference Series 741 (1), 012143 (2016)
- V. Ryzhii, *et al.*, Two-dimensional plasmons in lateral carbon nanotube network structures and their effect on the terahertz radiation detection, J. Appl. Phys. 120, 044501 (2016)
- I. Gayduchenko, *et al.*, Response of asymmetric carbon nanotube network devices to sub-terahertz and terahertz radiation, J. Appl. Phys. 118, 194303 (2015)
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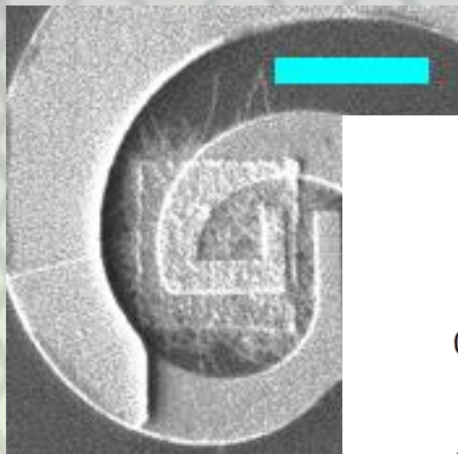

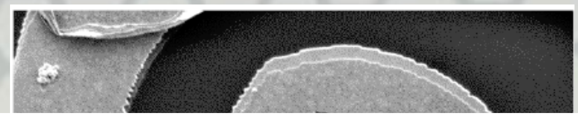

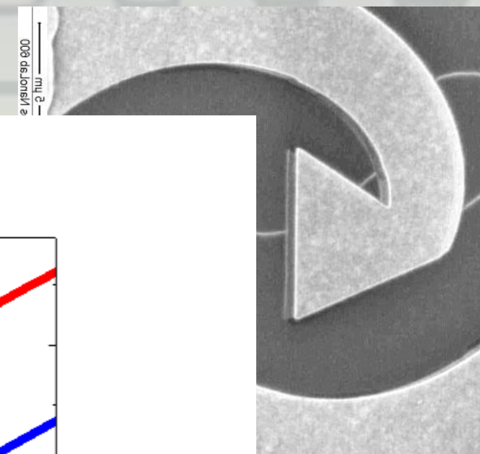

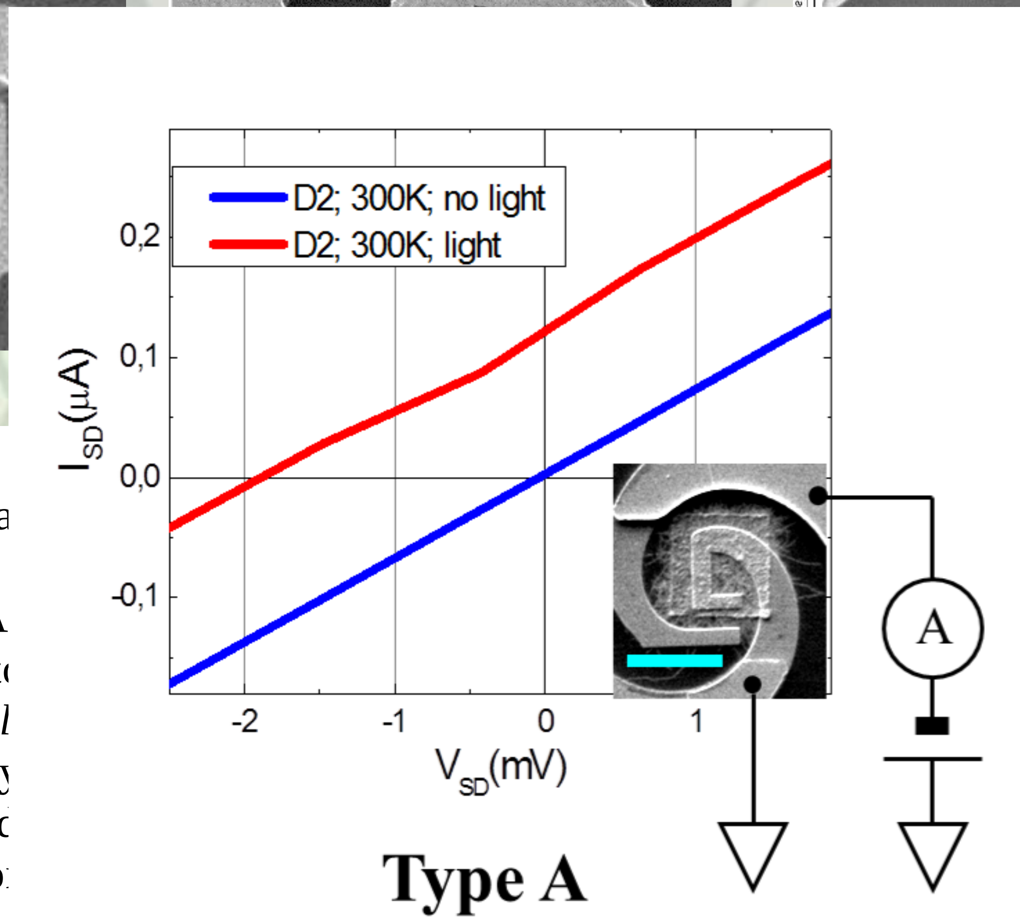

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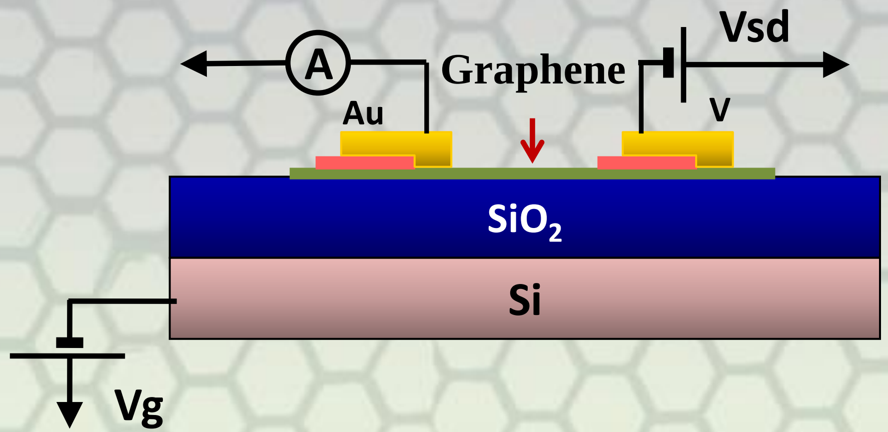
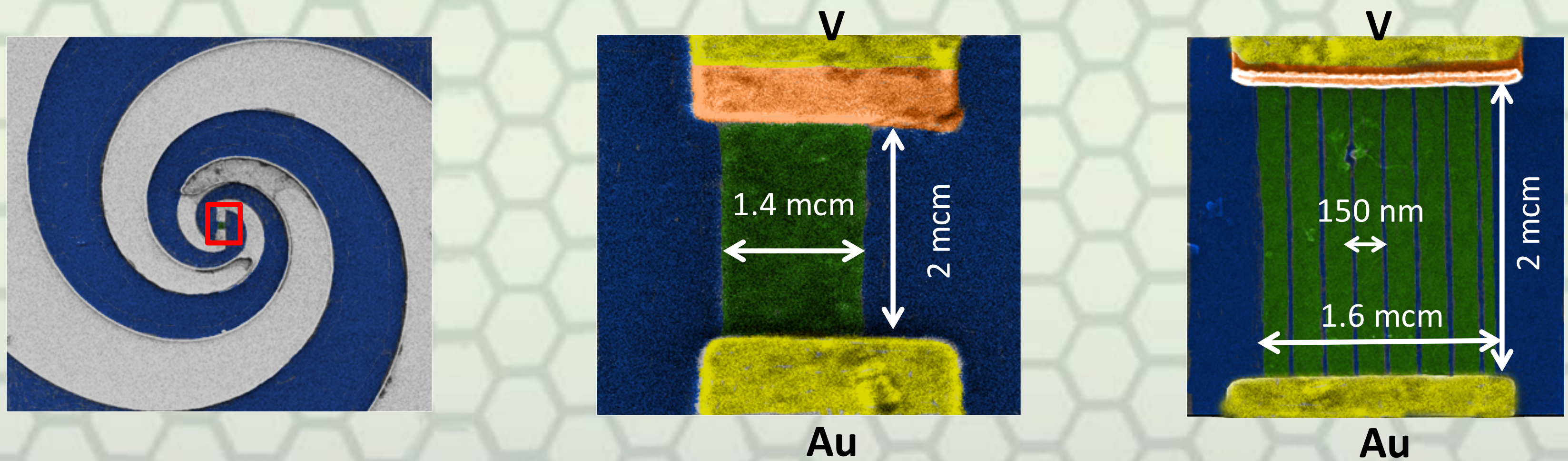
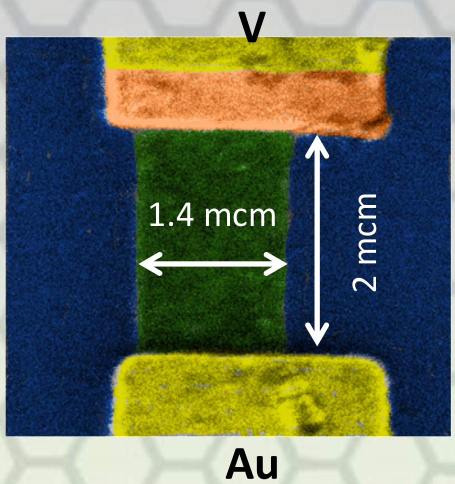
Asymmetric structures. What does it mean?

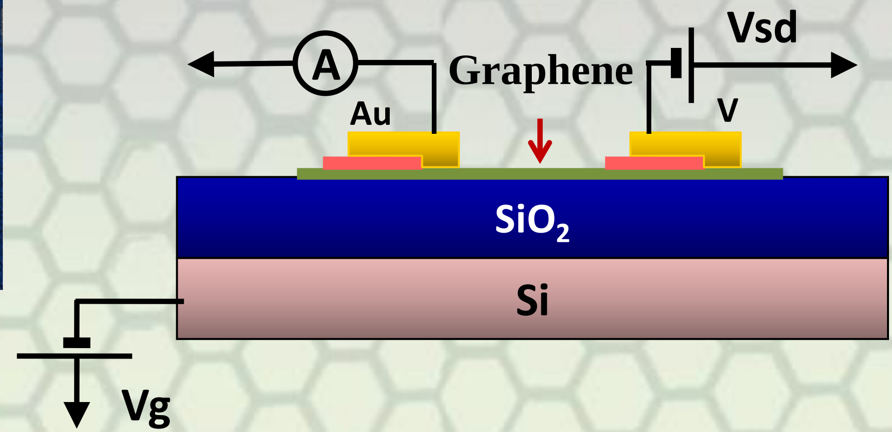


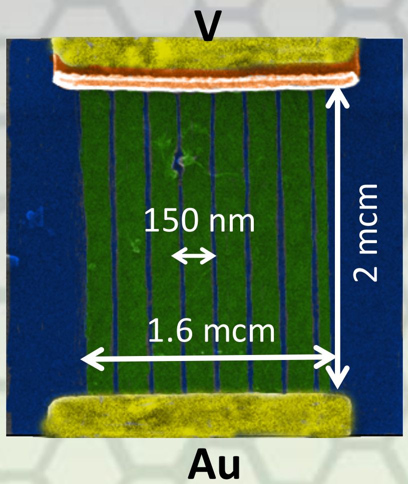


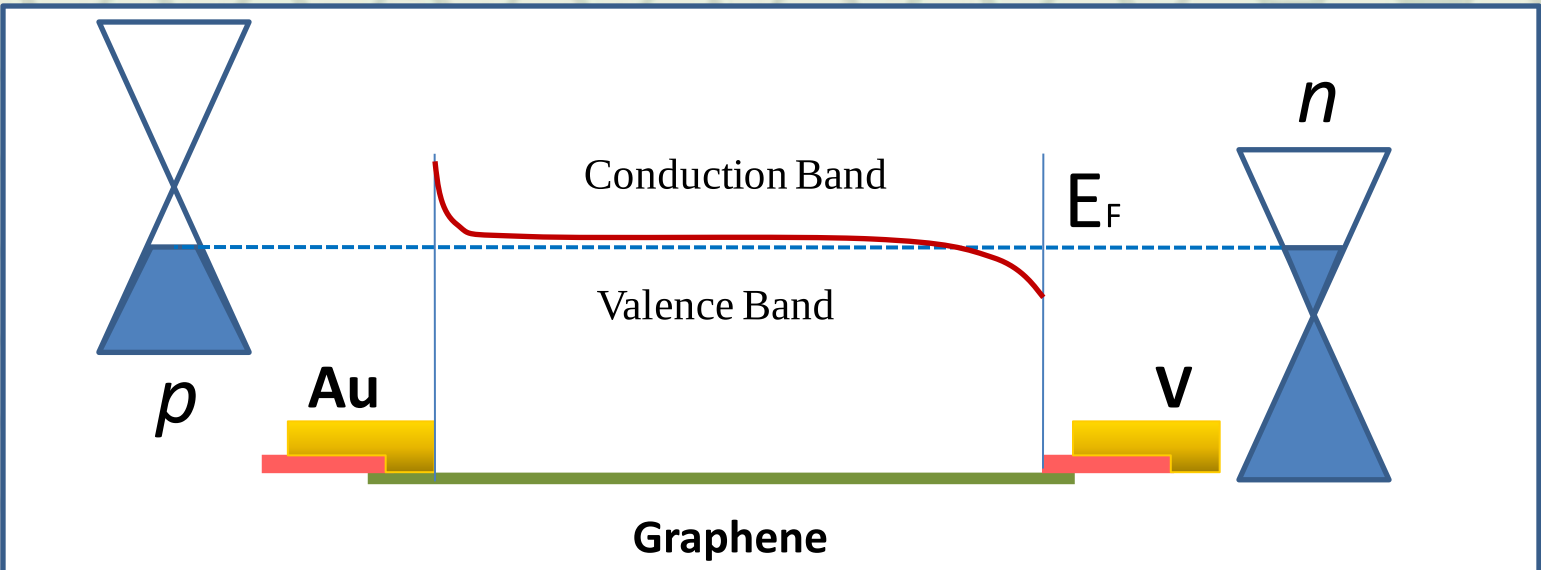
We use simple one-step lithography combined with shadow evaporation and lift-off in order to make asymmetric devices. Contact doping leads to formation of a p-n junction

Asymmetric structures. What does it mean?

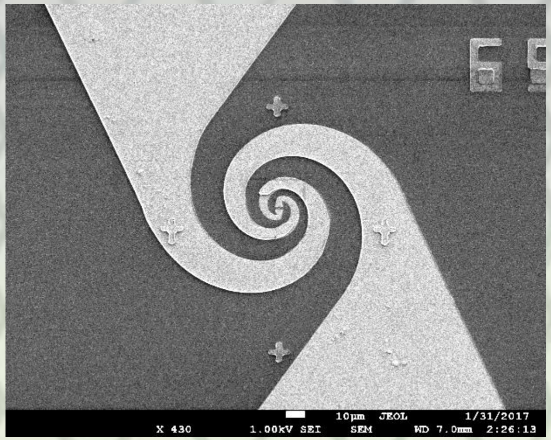


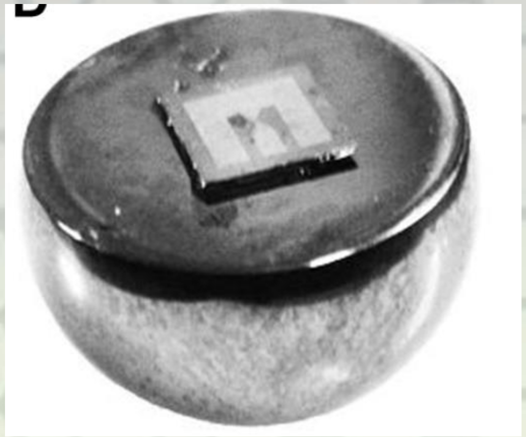


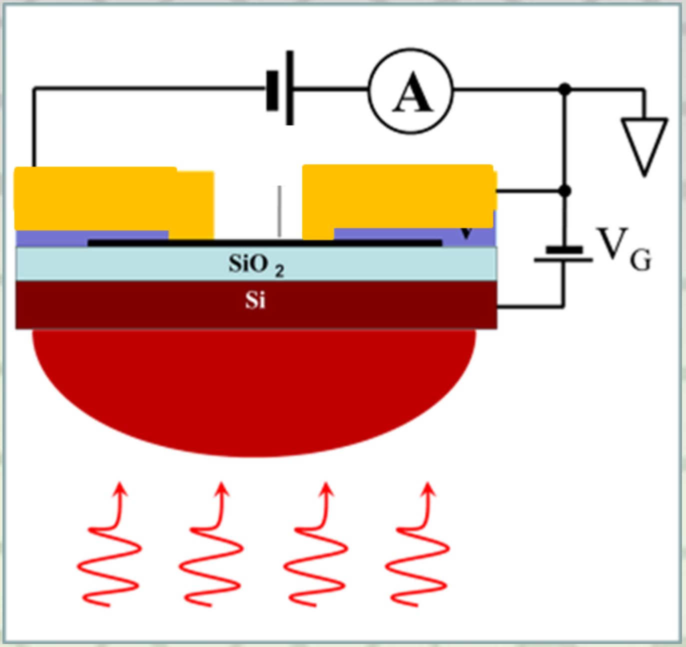




Main approach: we compare many varieties using same setup



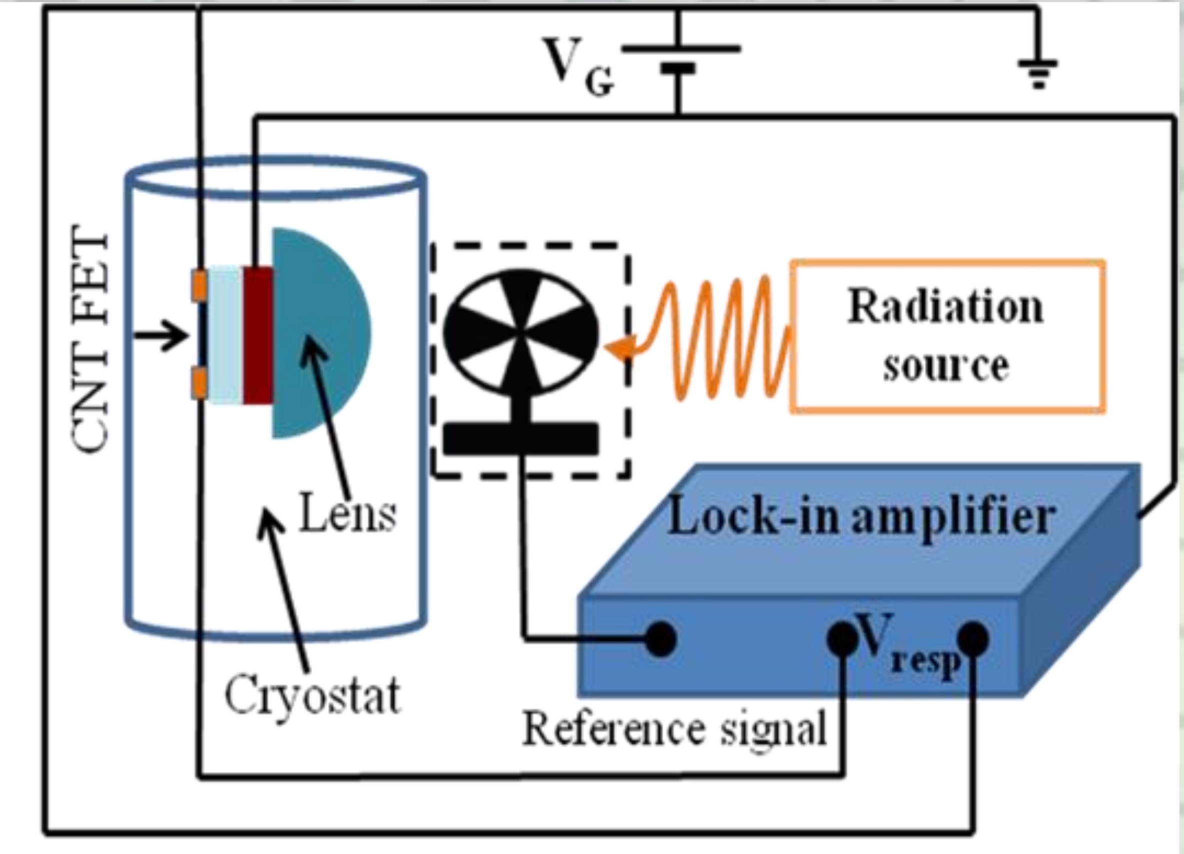




We studied many different structures using pretty much the same setup, the same antenna and the same definition of responsivity. This allows for more or less **direct comparison** of different detector configurations

The devices are coupled to the radiation with a logarithmic spiral antenna. A device chip was fixed on a flat surface of a silicon lens.

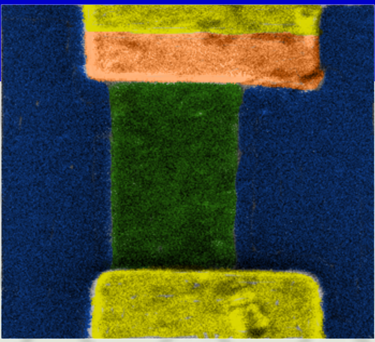
Main approach: we compare many varieties using same setup

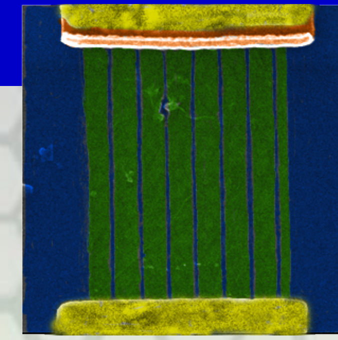


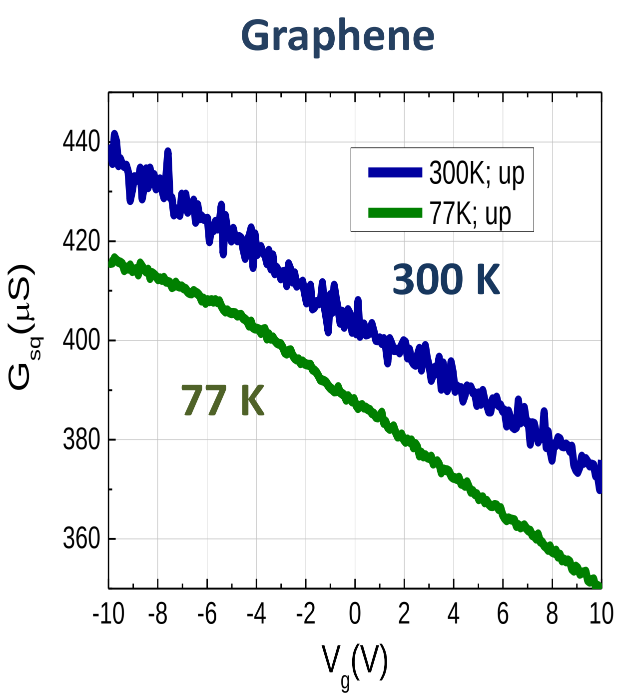
Responsivity = $\dfrac{\text{Voltage}}{\text{Power}}$

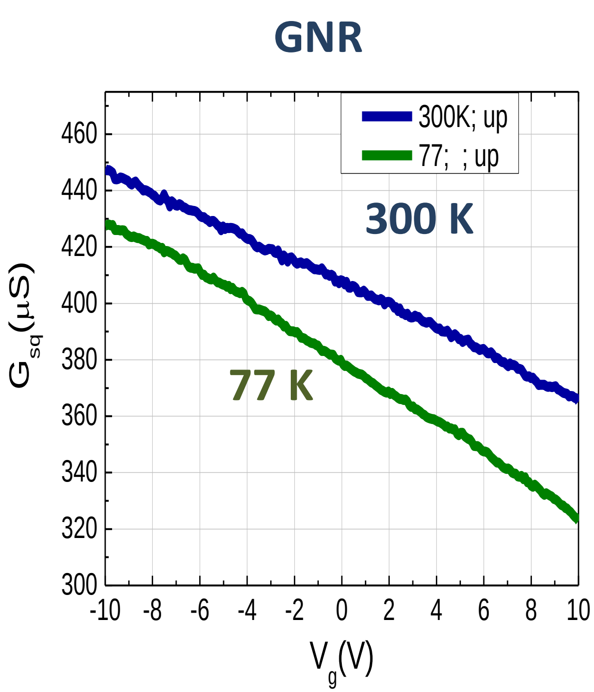
The terahertz radiation provided by a two backward wave oscillators (140GHz, 300 to 500 GHz) and used a gas discharge laser operating on a 2.5 THz H_2O line.

Asymmetric structures. Plain graphene vs GNRs. Device characterization

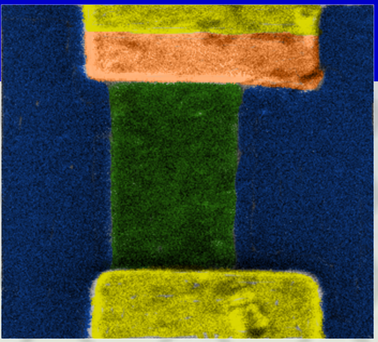


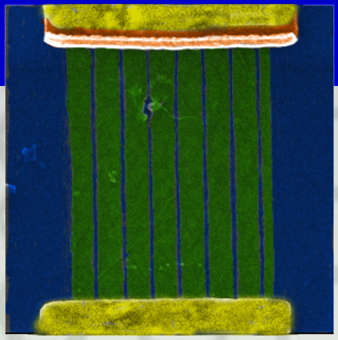


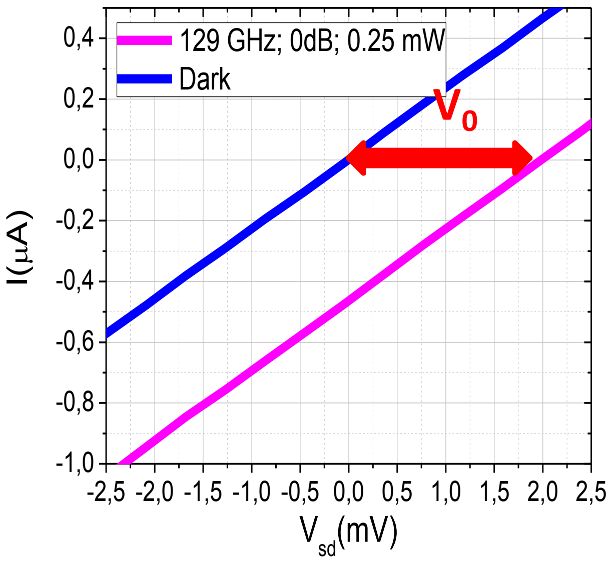


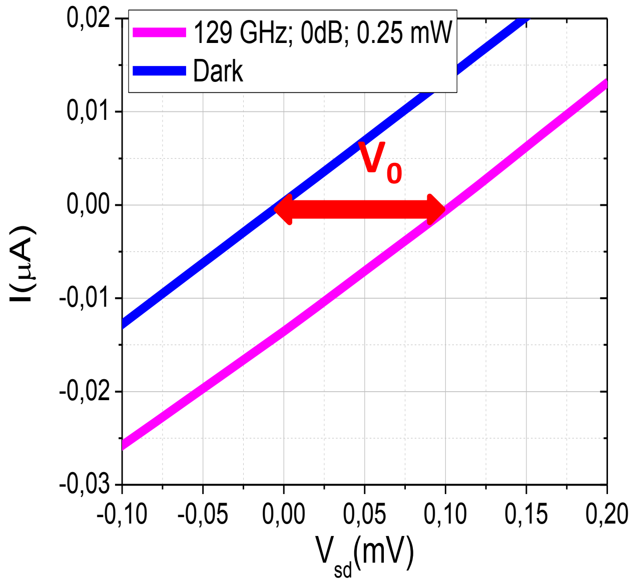


Asymmetric structures. Plain graphene vs GNRs. Response to radiation

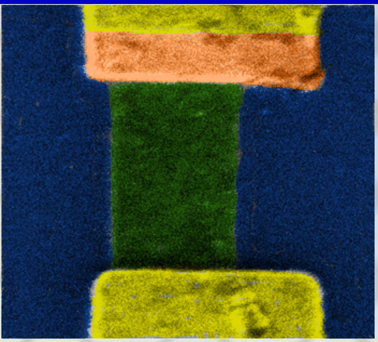


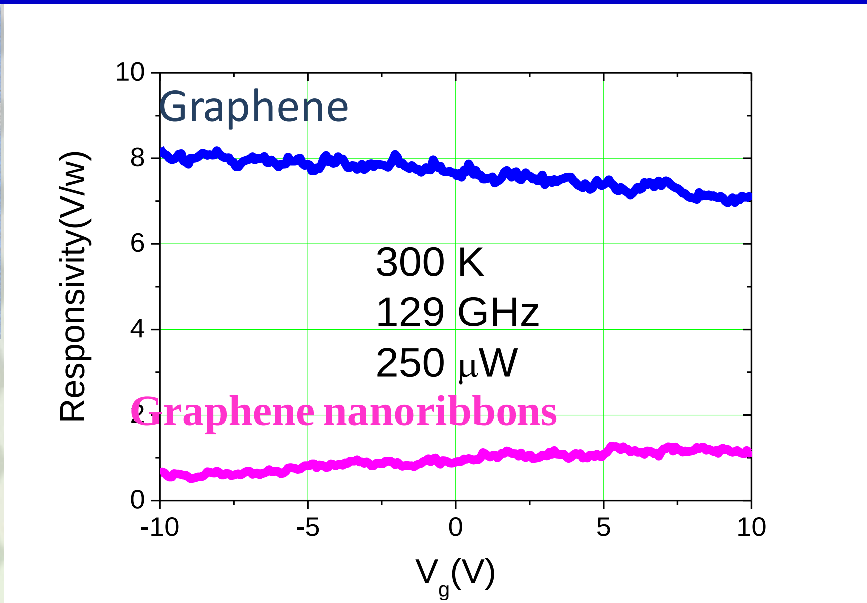


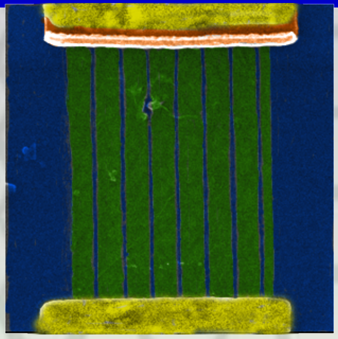


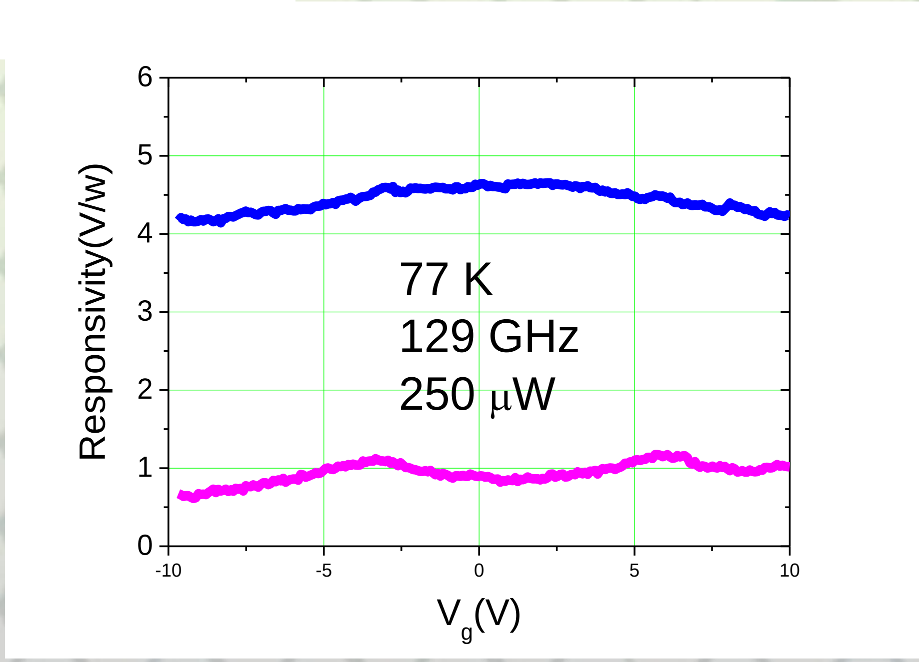


Asymmetric structures. What do we get? Plain graphene vs GNRs









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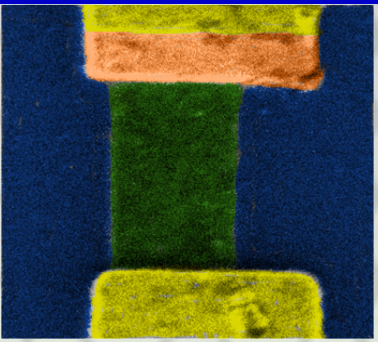

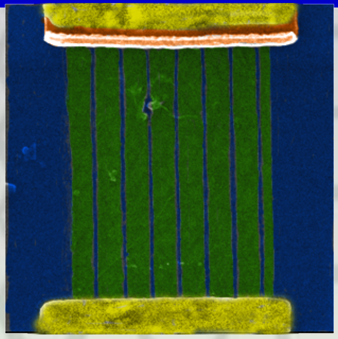

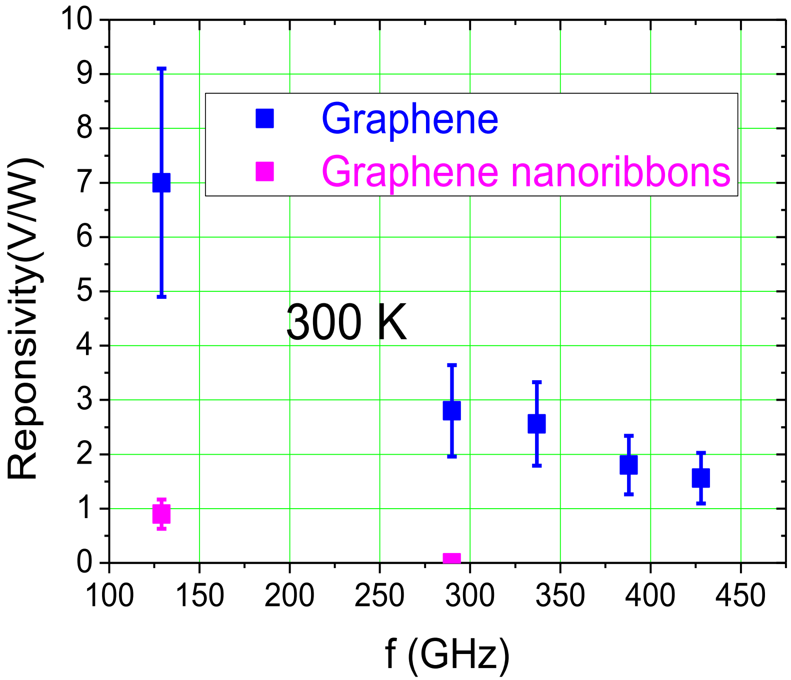

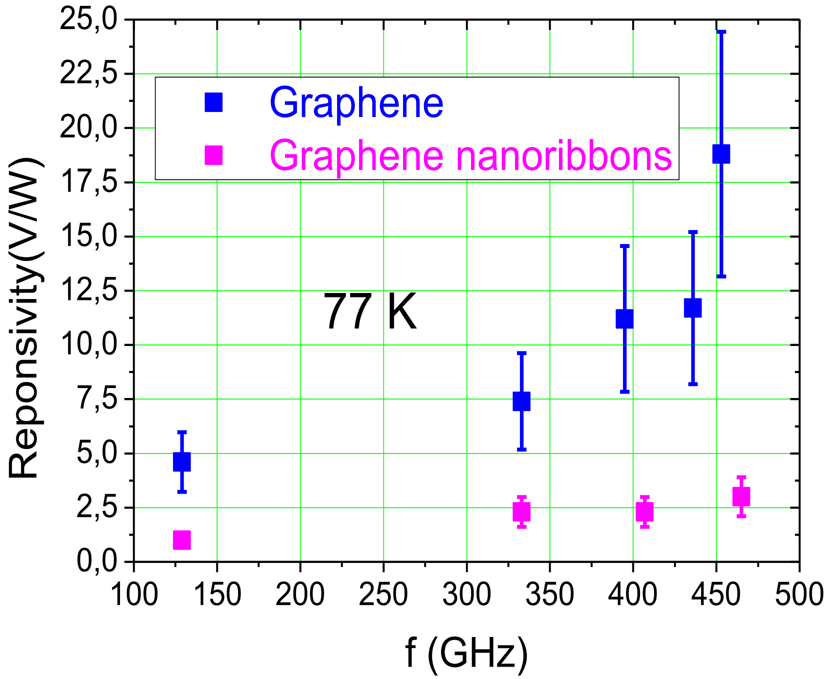

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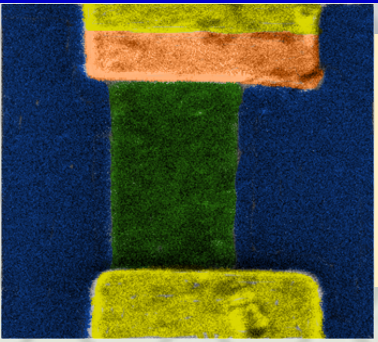
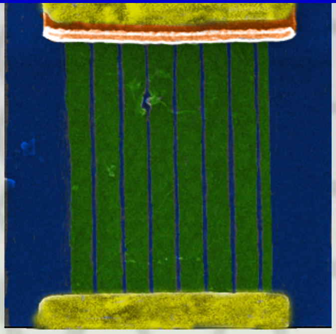
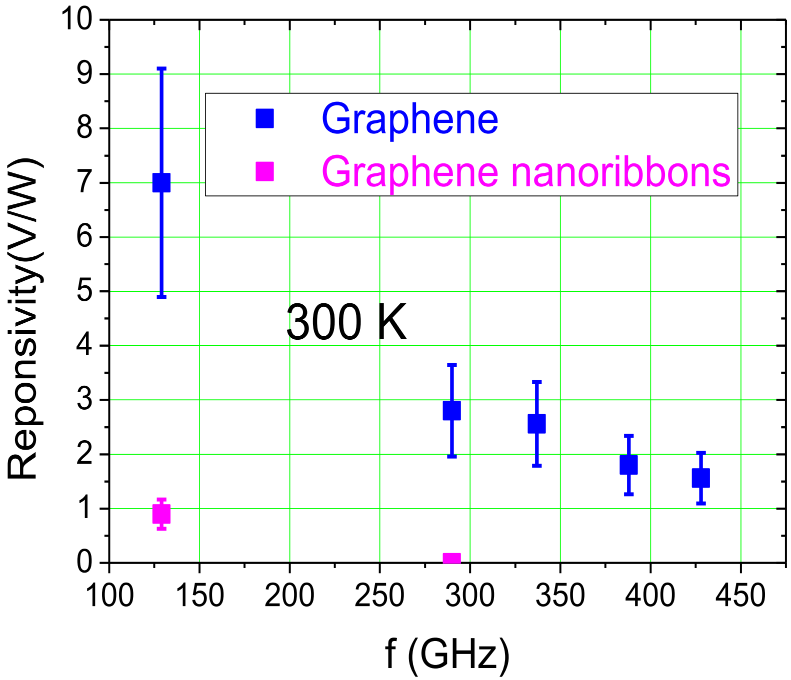
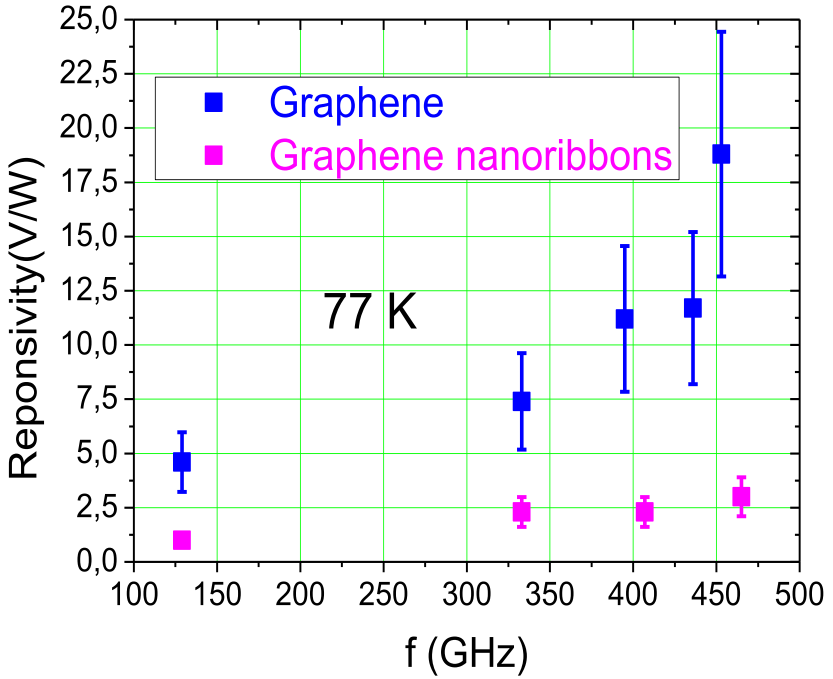


Change in frequency dependence of response probably indicates importance of the plasma waves in the channel



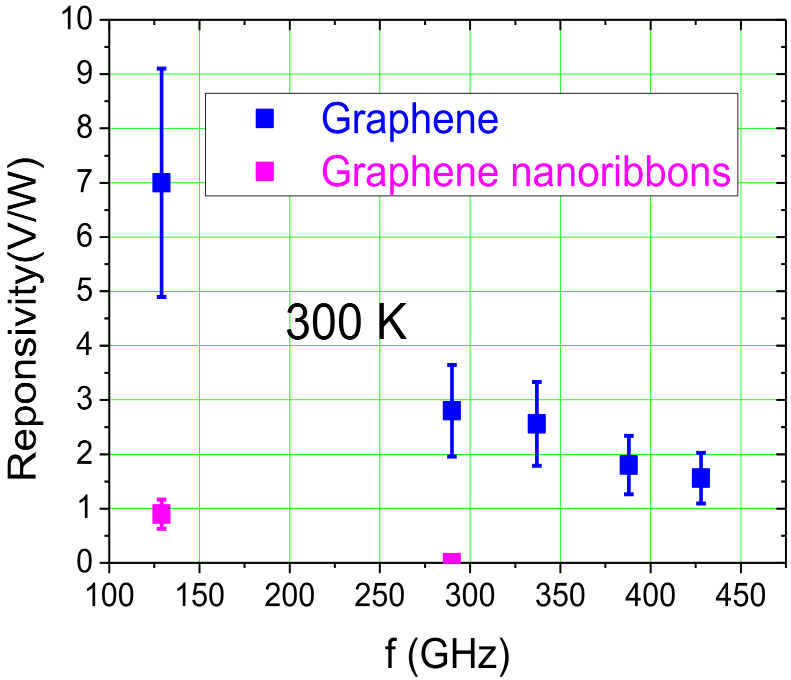


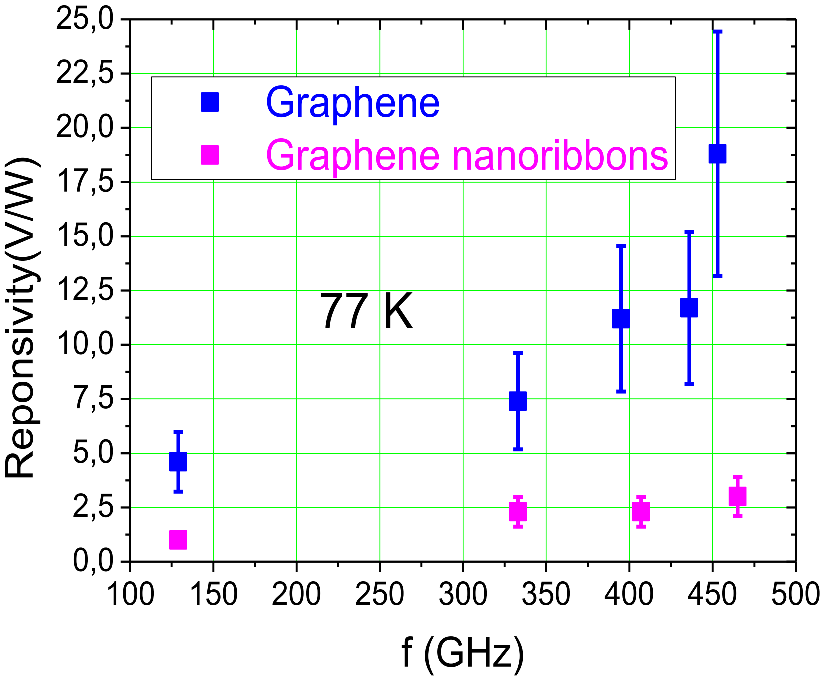


Asymmetric structures. What do we get? Plain graphene vs GNRs

Brief summery of the experimental data:

- *GNR exhibit smaller response*
- *Low frequency response decreases as the temperature is lowered*
- *Frequency dependence qualitatively changes as the temperature goes from 300K to 77K*





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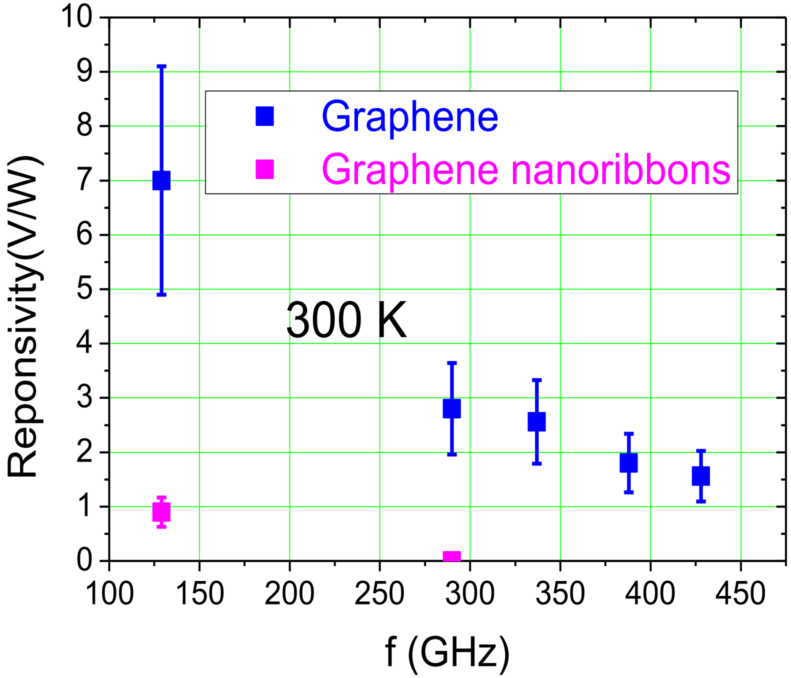
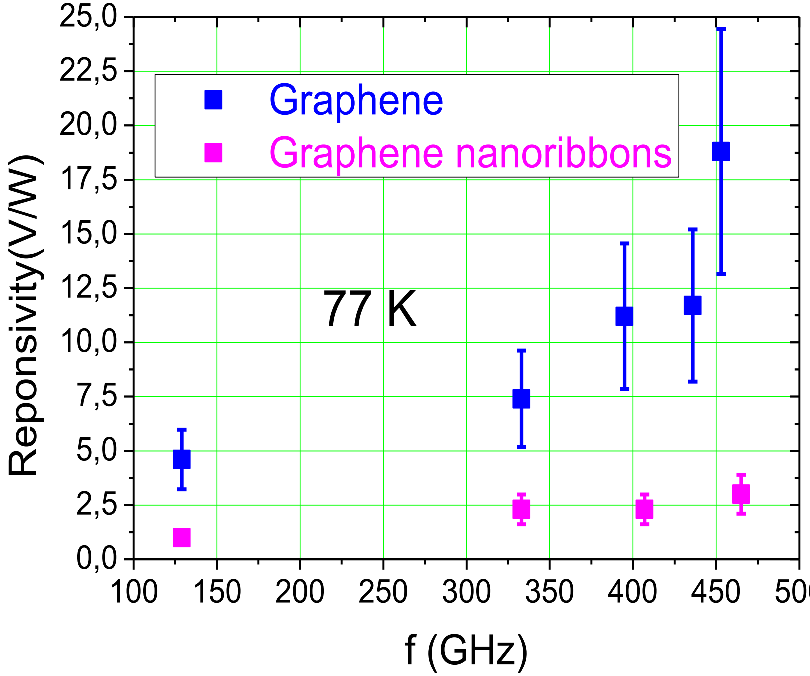




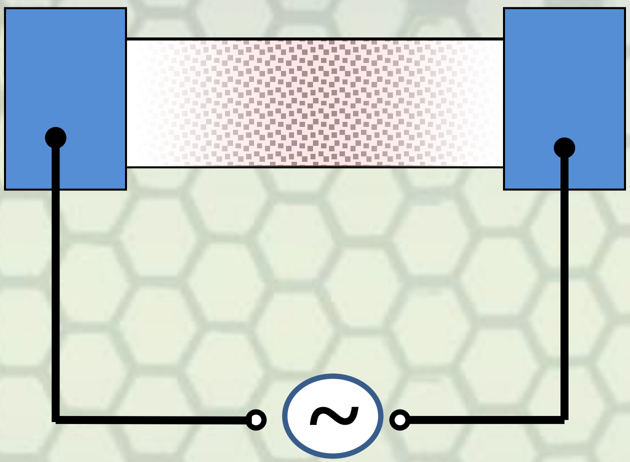
Detection mechanisms. Photothermoelectric vs diode

Photothermoelectric response

Diode response

Detection mechanisms. Photothermoelectric vs diode

Photothermoelectric response

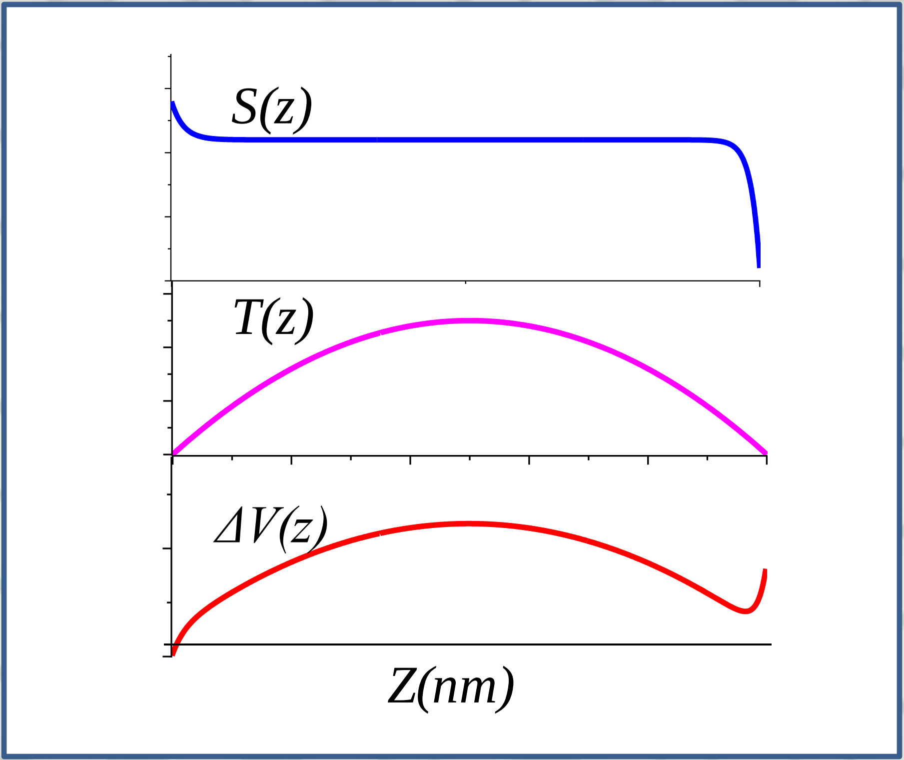


$$\Delta V = \int S(z)dT = \int \nabla T \, S(z)dz$$

Diode response

Detection mechanisms. Photothermoelectric vs diode

Photothermoelectric response



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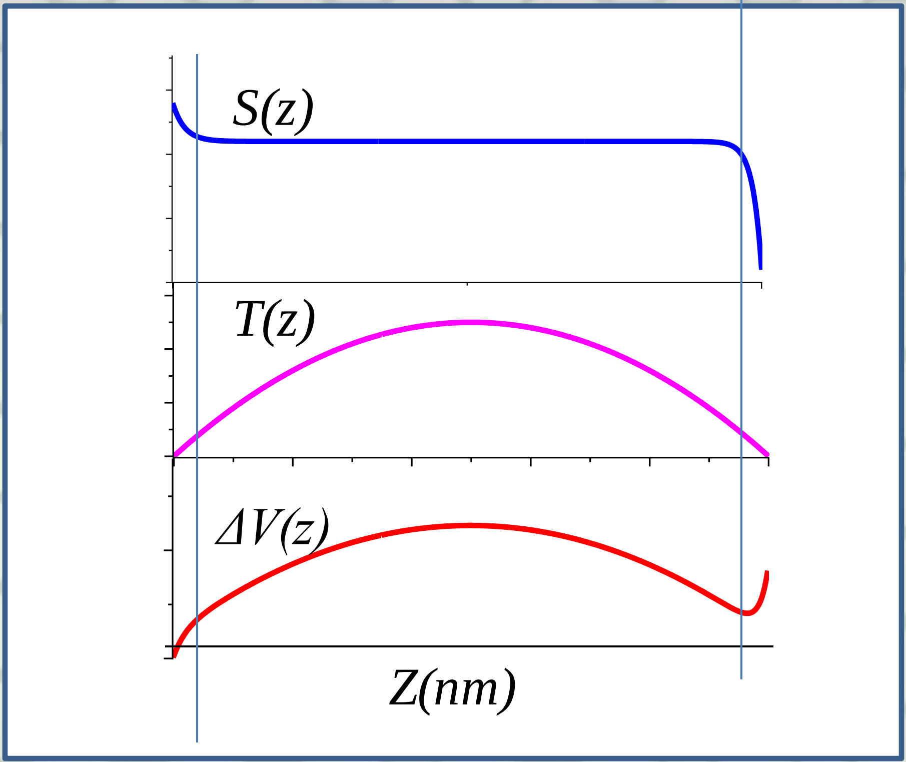

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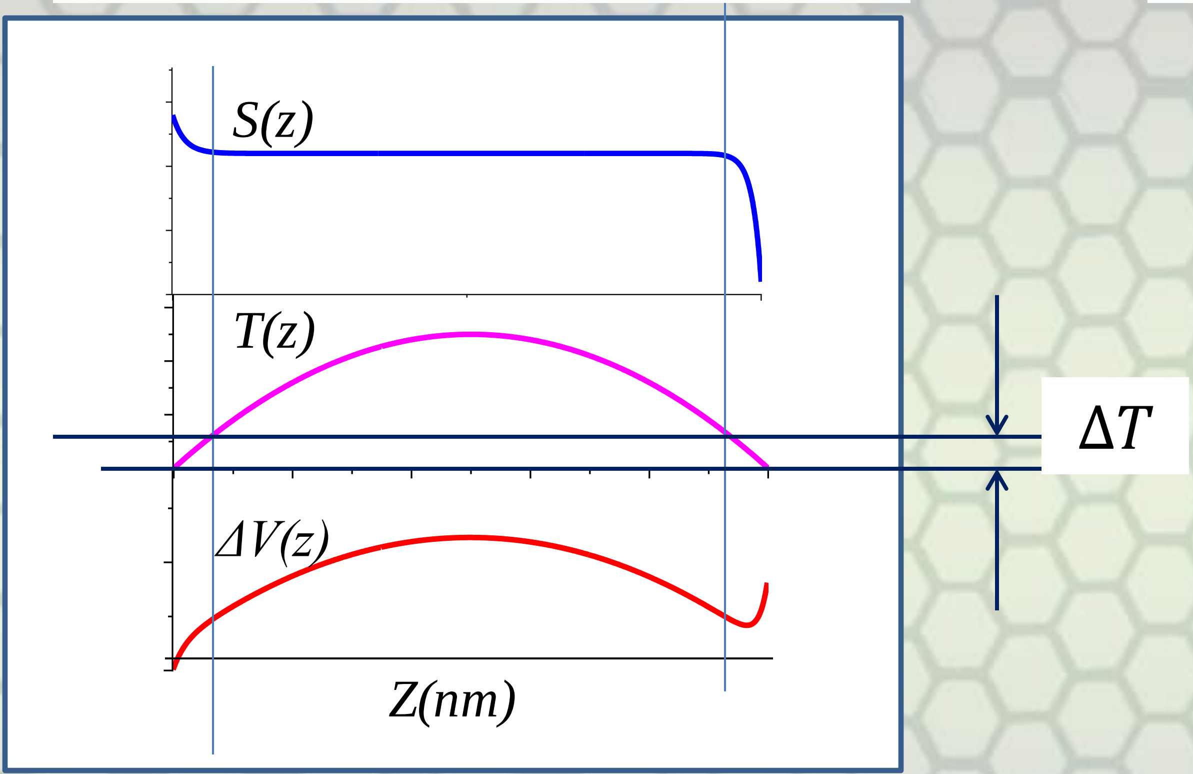

$$\Delta V \approx (S_{\mathrm{n}} - S_{\mathrm{p}}) \cdot \Delta T$$

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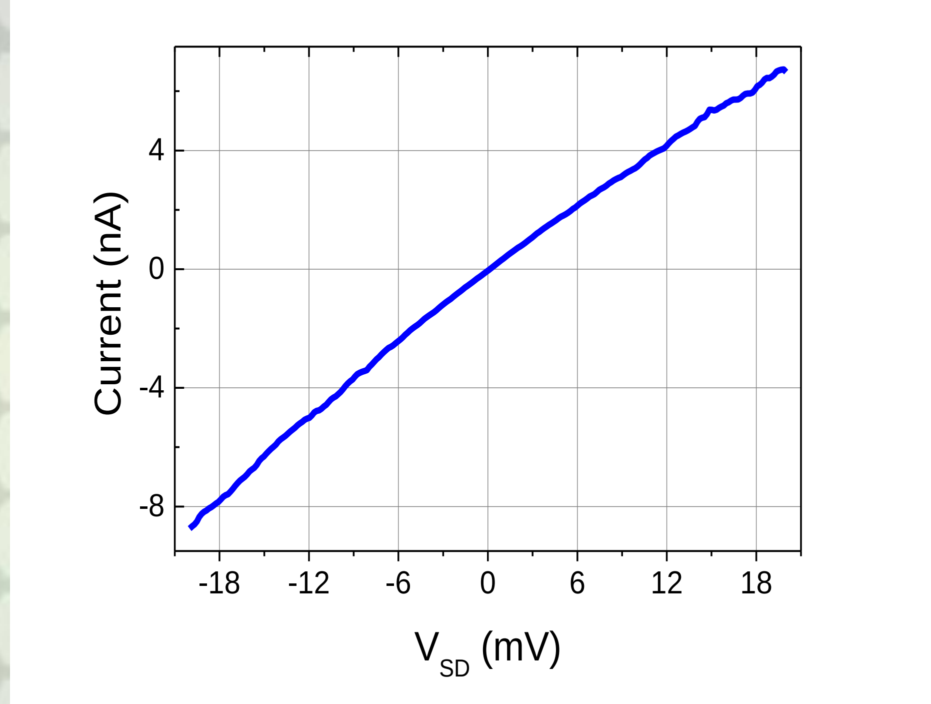

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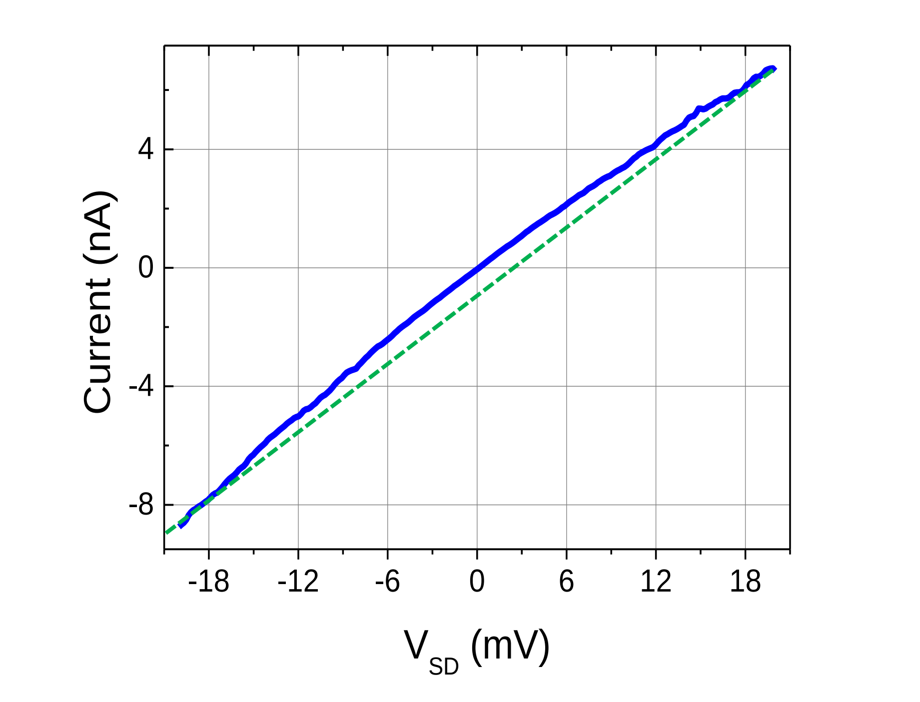

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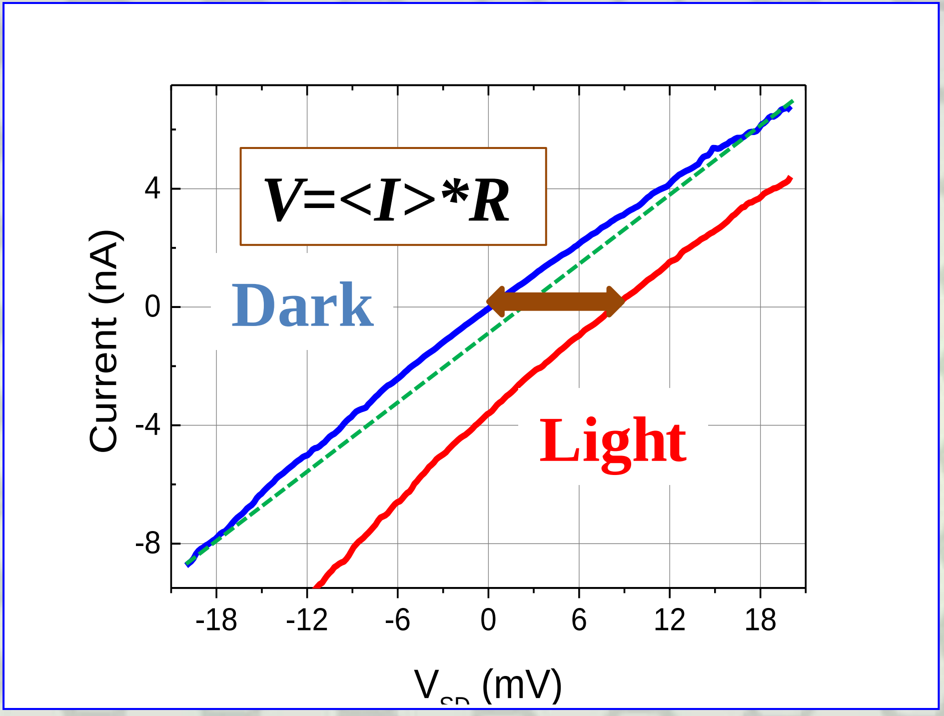

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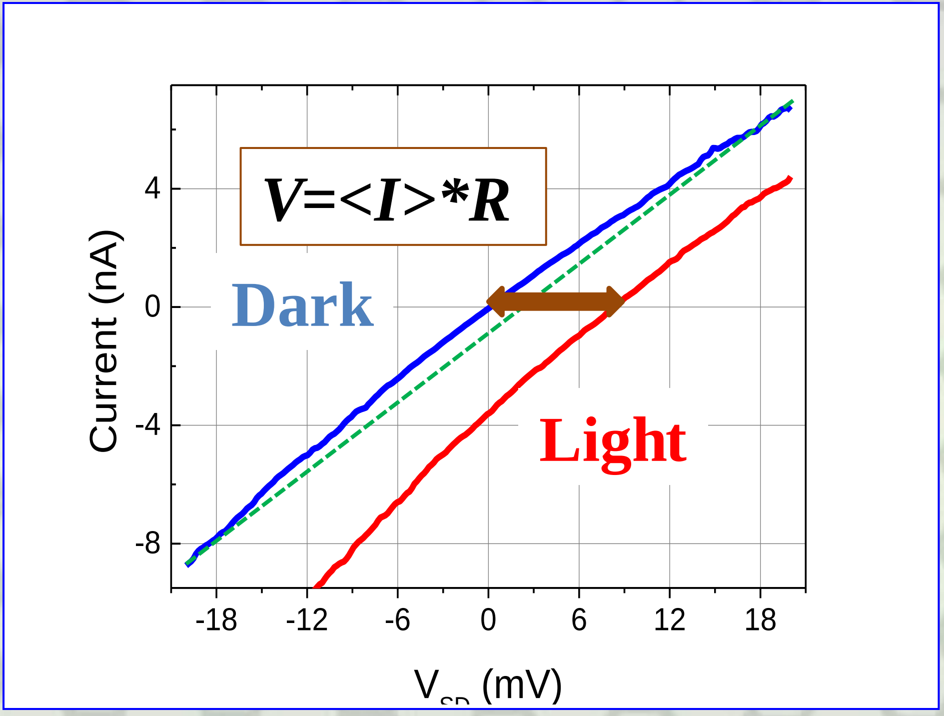
Photothermoelectric response

Diode response



$$R_s = \frac{<V>}{P} = \frac{1}{4}|Z|\left(\frac{d^2I}{dV^2}\right)\left(\frac{dI}{dV}\right)^{-1}$$

Photothermoelectric vs GNRs. Frequency dependence

Photothermoelectric response

$$\Delta V = \int S(z)dT = \int \nabla T\, S(z)dz$$

Diode response

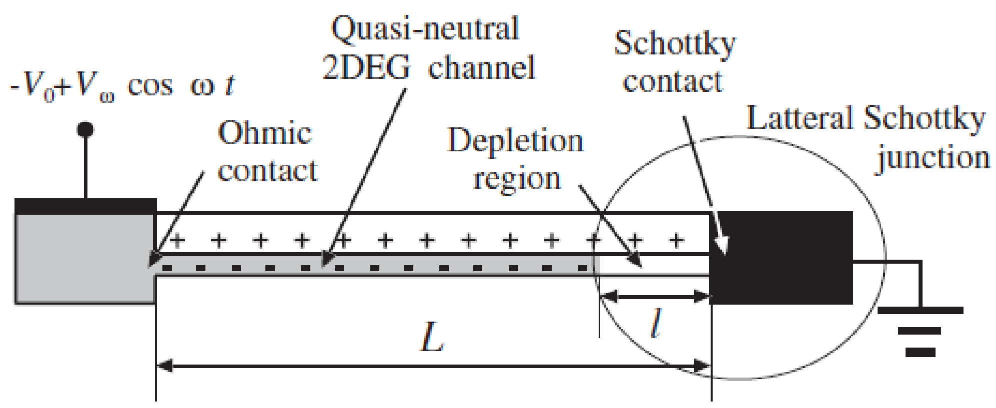
$$R_s = \frac{< V >}{P} = \frac{1}{4}|Z|\left(\frac{d^2I}{dV^2}\right)\left(\frac{dI}{dV}\right)^{-1}$$

In both cases response can be either suppressed or enhanced due to excitation of plasma waves in the channel.

$$\frac{\partial \Sigma}{\partial t} + \Sigma_0 \frac{\partial u}{\partial x} = 0,$$

$$\frac{\partial u}{\partial t} + \nu u = \frac{e}{m}\frac{\partial \psi}{\partial x}\bigg|_{z=0},$$

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2} = \frac{4\pi e^2(\Sigma - \Sigma_\mathrm{d})}{æ}\delta(z).$$



V. Ryzhii, M. Shur, JJAP, Vol. 45, No. 42, 2006, pp. L1118–L1120

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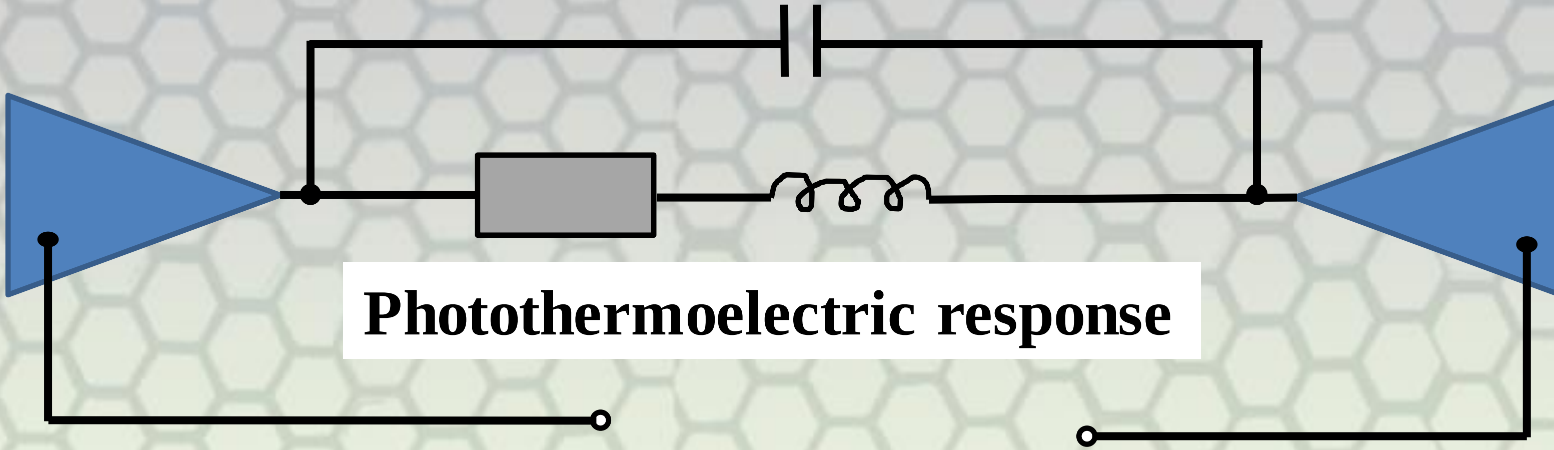
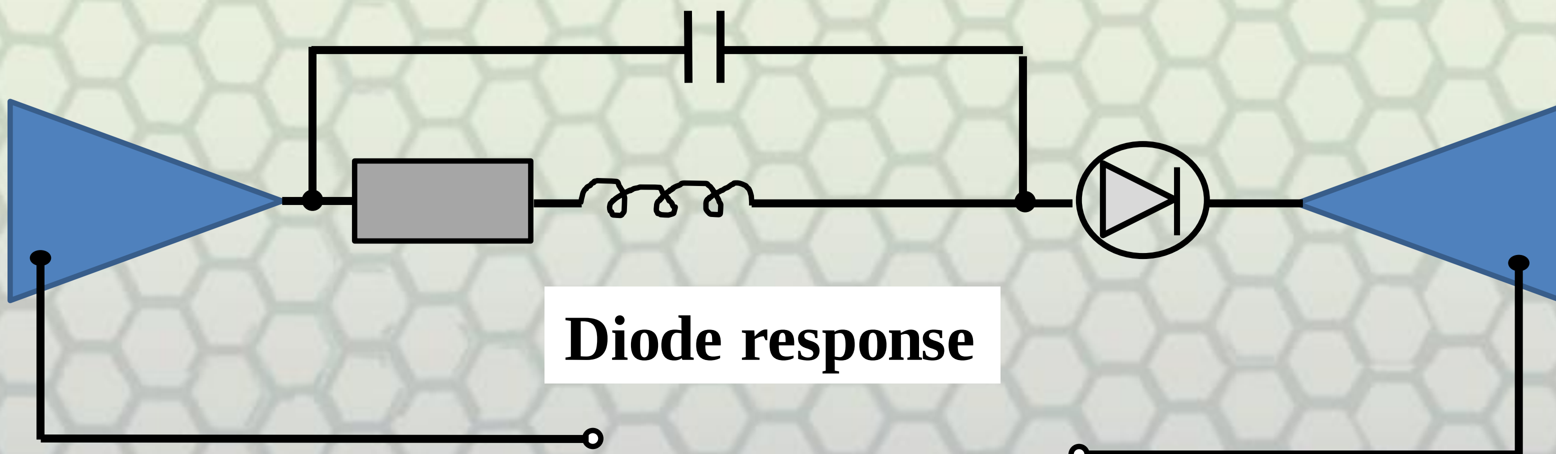


Photothermoelectric response

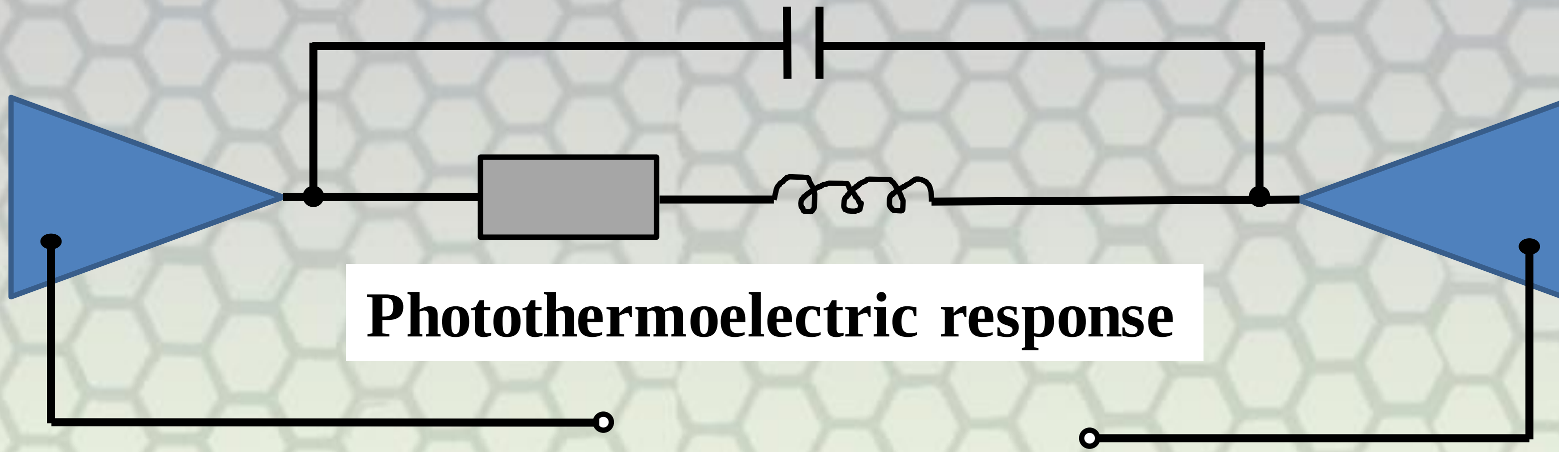
In linearized approximation in both cases you get

$$V_{\mathrm{RESP}} \sim I_0^{\,2}$$

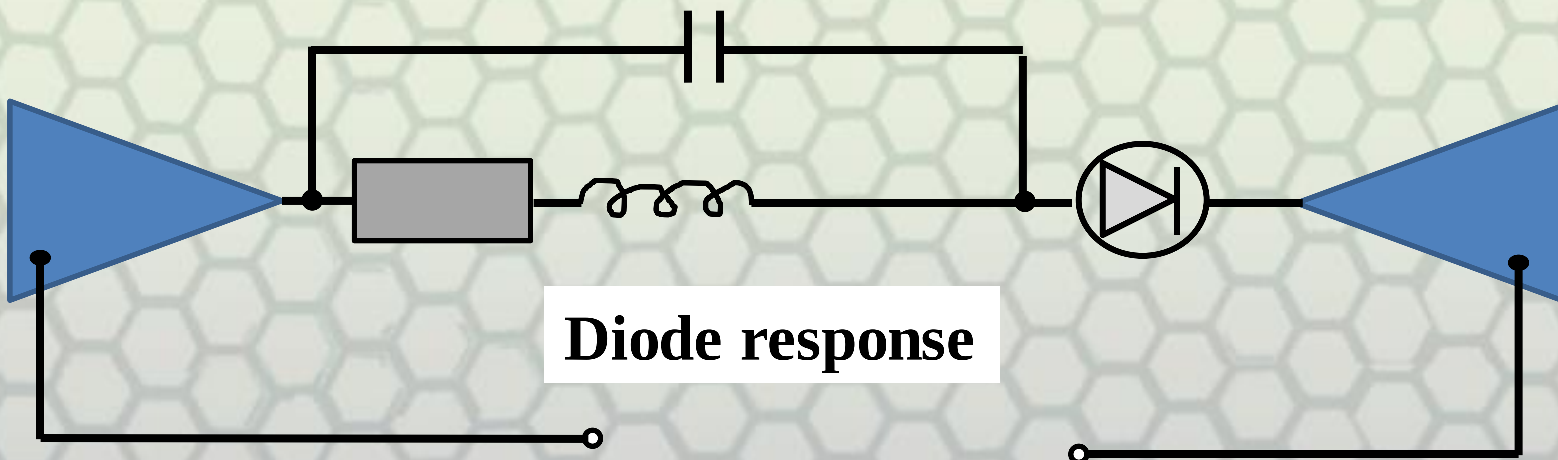


Diode response

Photothermoelectric vs GNRs. Frequency dependence



$$\frac{R_\omega}{R_0} \simeq \frac{1}{\cos^2(\pi\omega^2/2\Omega^2) + \sinh^2(\pi\nu\omega/2\Omega^2)}.$$



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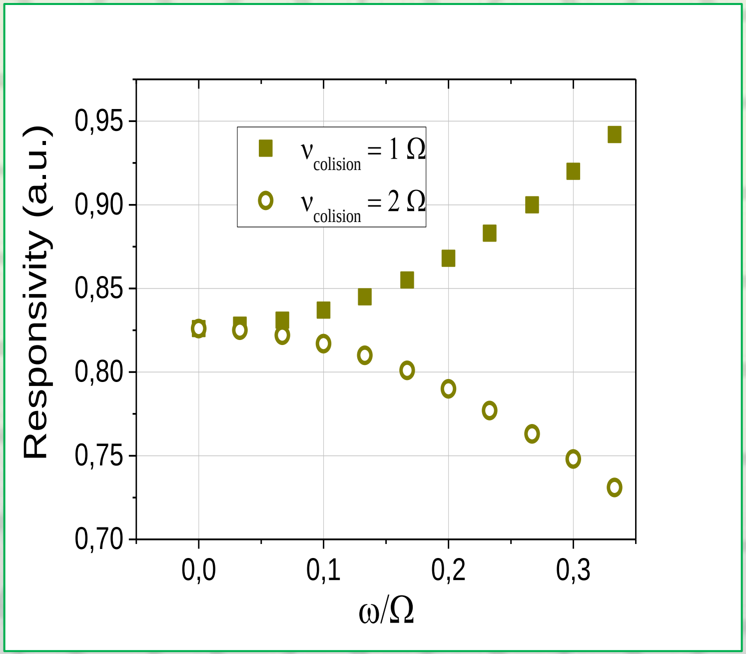
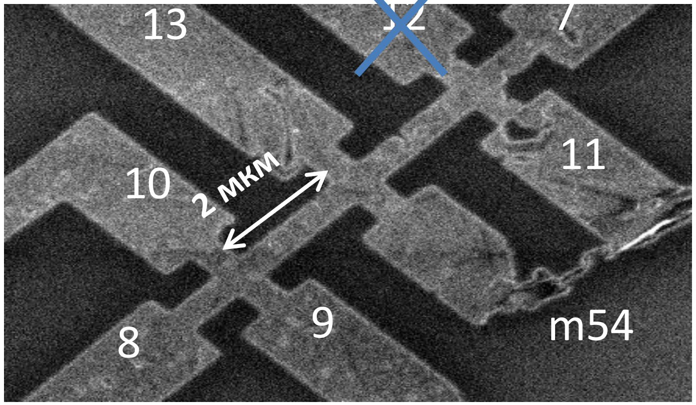
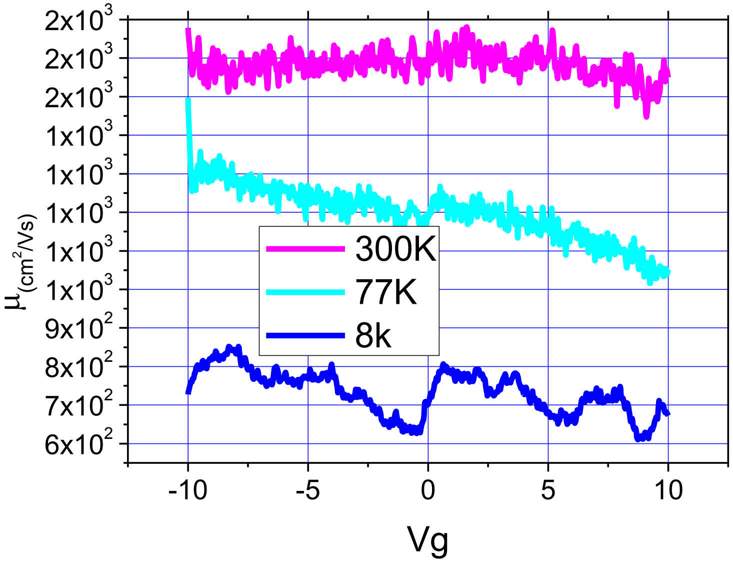


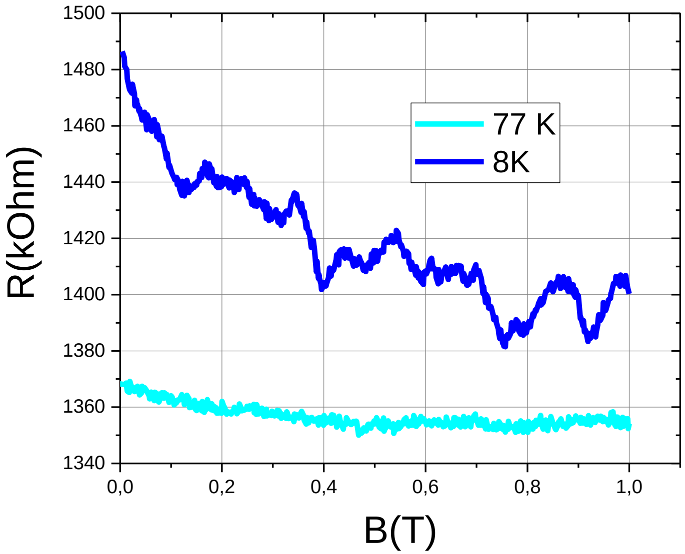
Low T, small ν

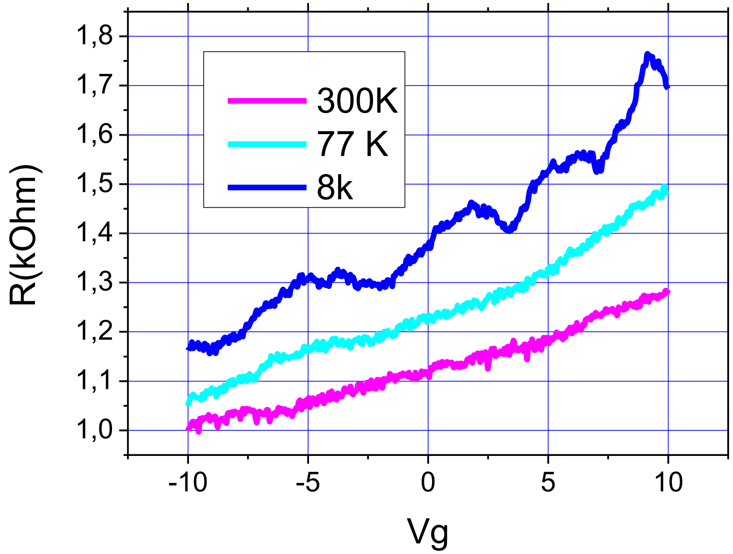
High T, large ν

Graphene structures. Probing the scattering rate

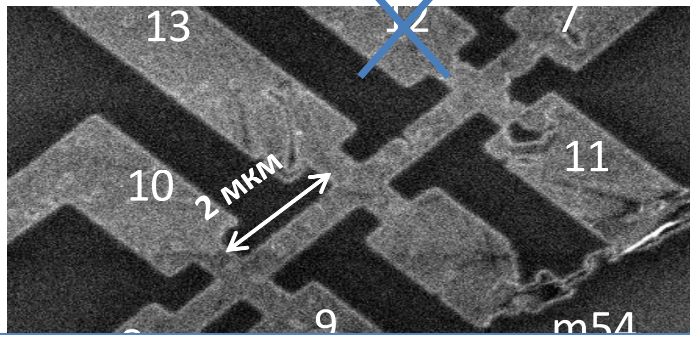


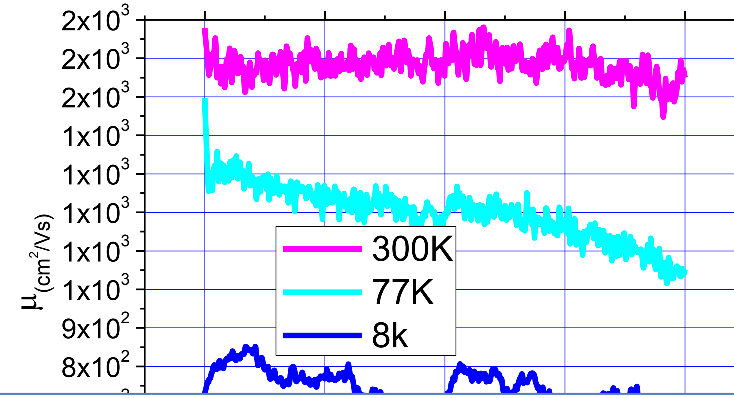




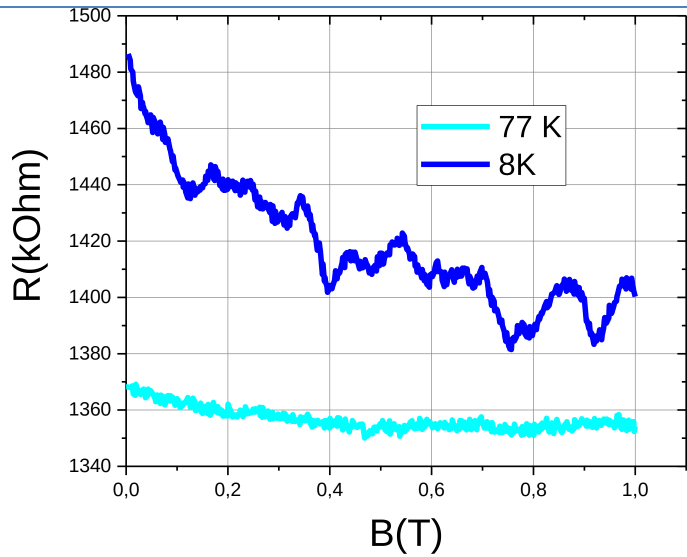


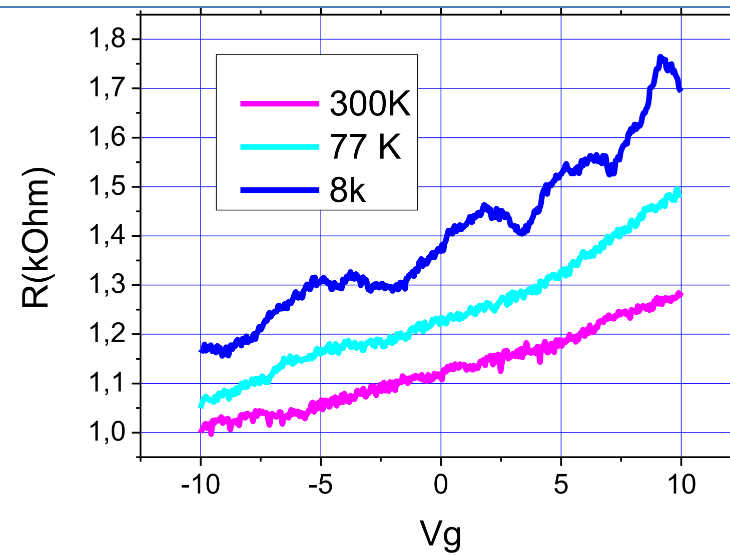
Graphene structures. Probing the scattering rate





The obtained data show that the elastic scattering rate is constant between 4 and 300 K while the 4probe resistance at low temperatures is enhanced due to weak localization





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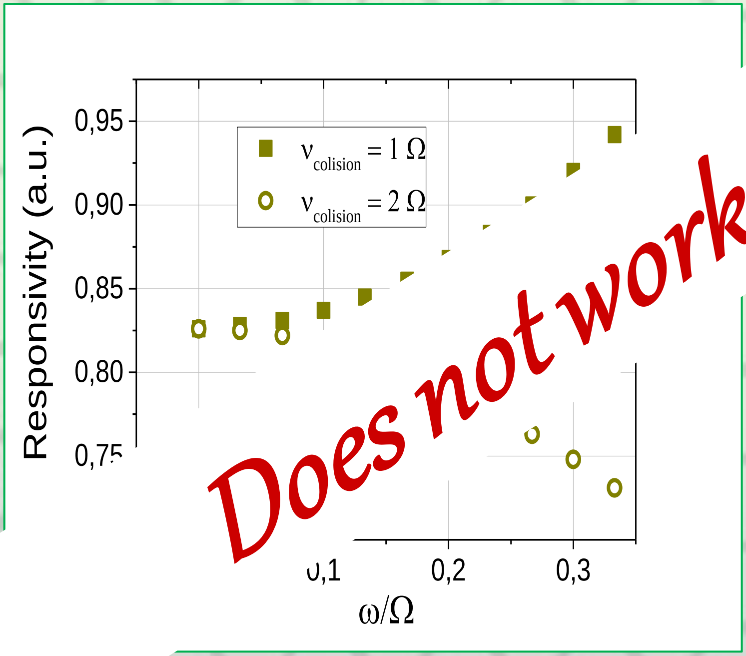
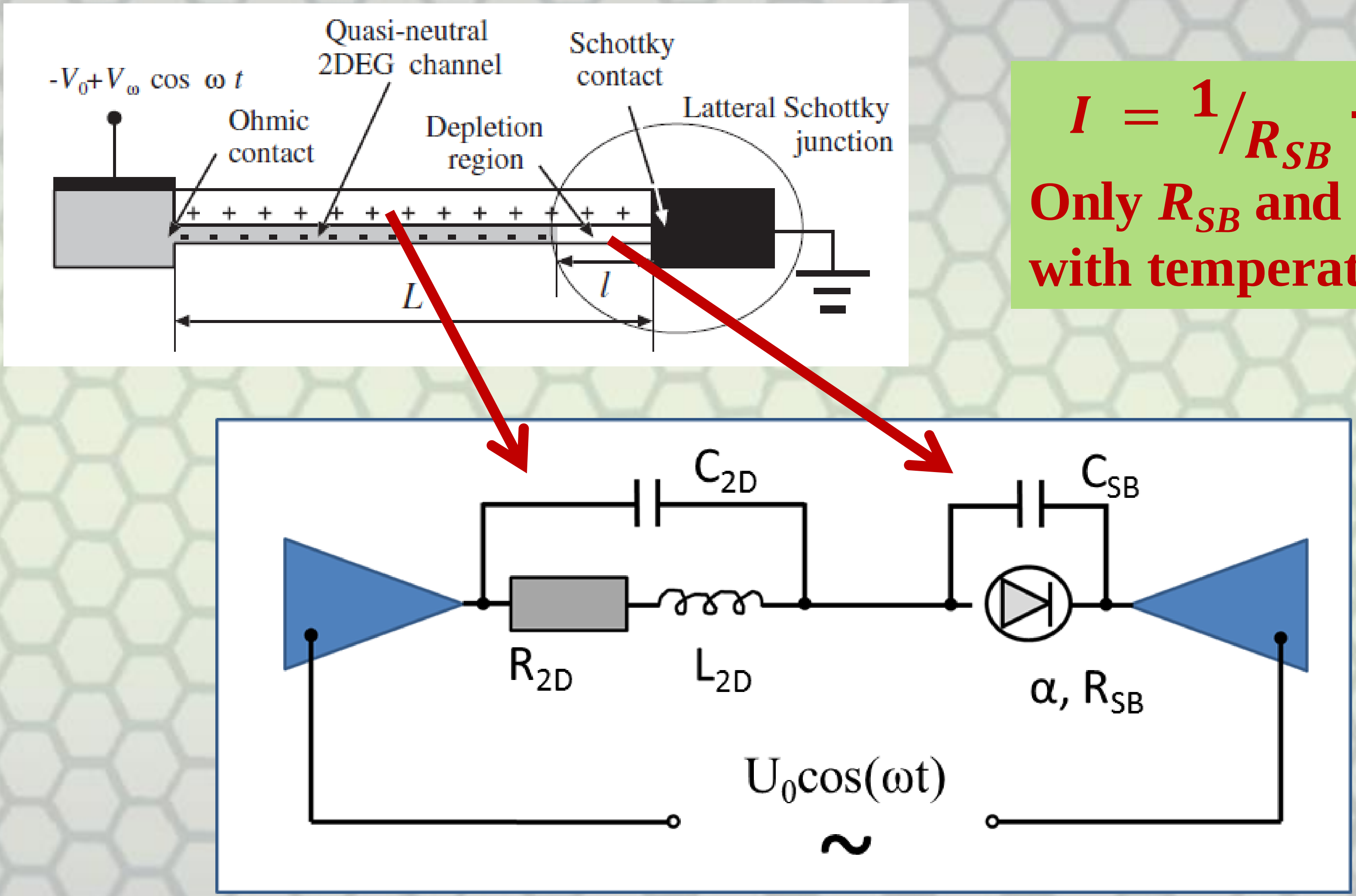


...all ν

High T, large ν

Diode response. Role of the intrinsic barrier capacitance combined with plasmonic resonance



$$I = {}^{1}/_{R_{SB}} \cdot V + \alpha V^2$$

Only R_{SB} and α change with temperature

Model suggested by V. Ryzhii, to be submitted in 2017

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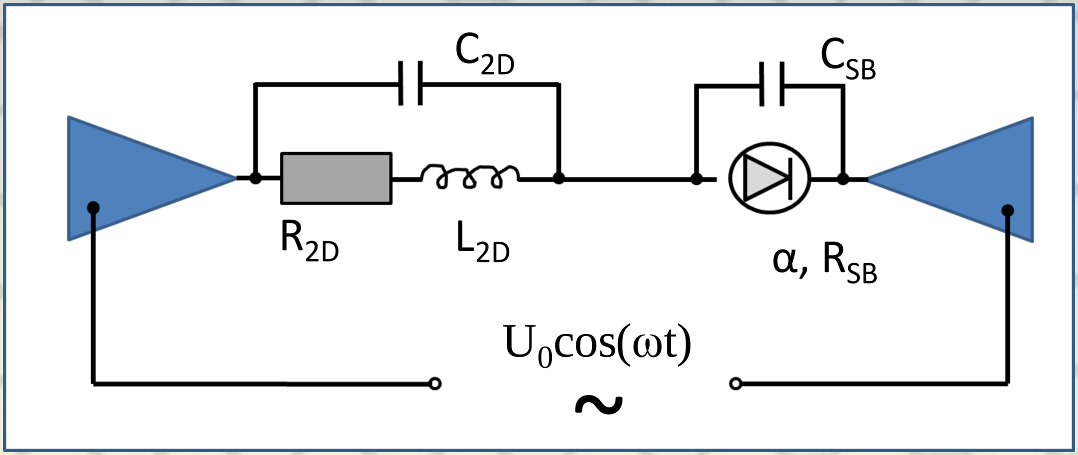

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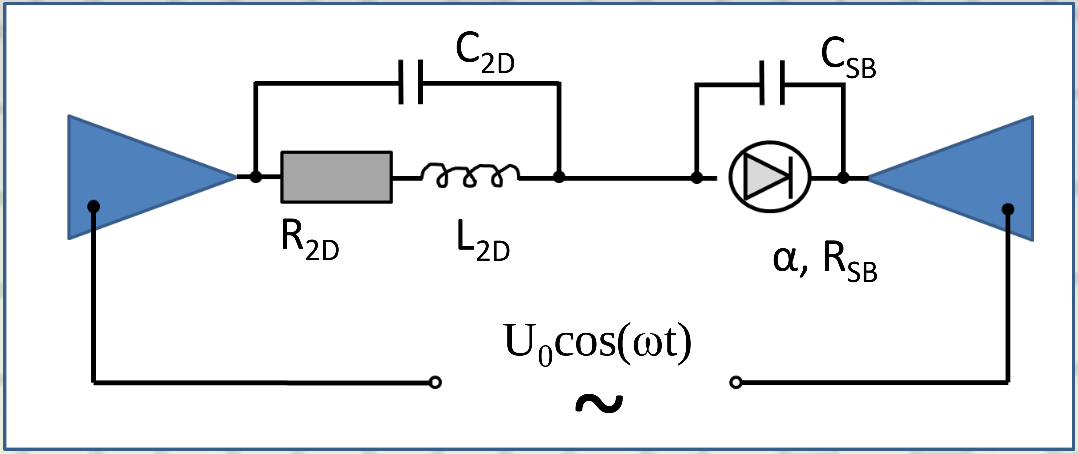

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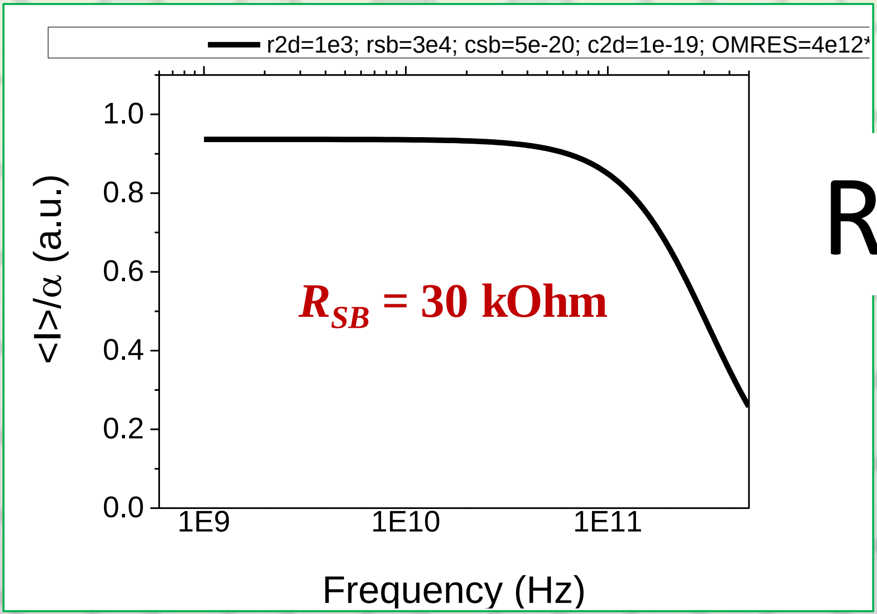
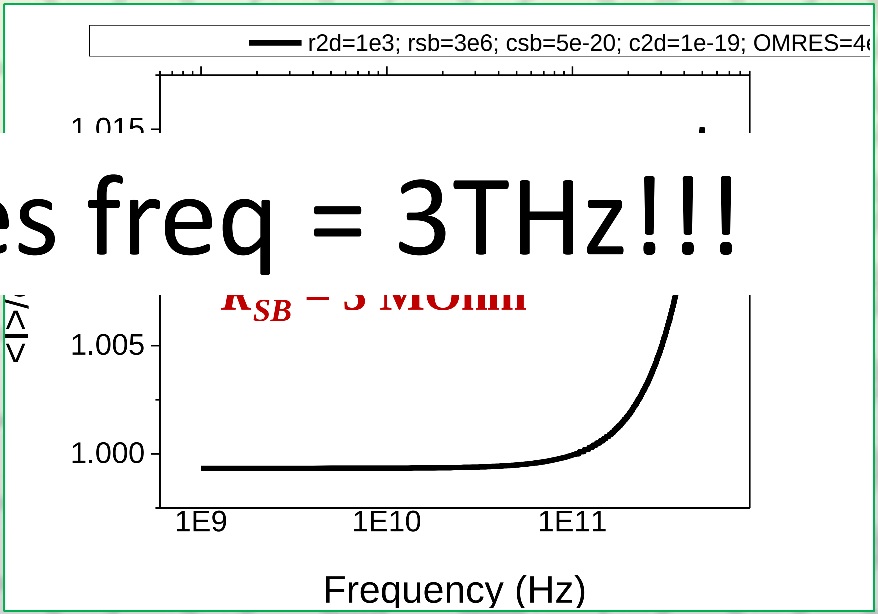
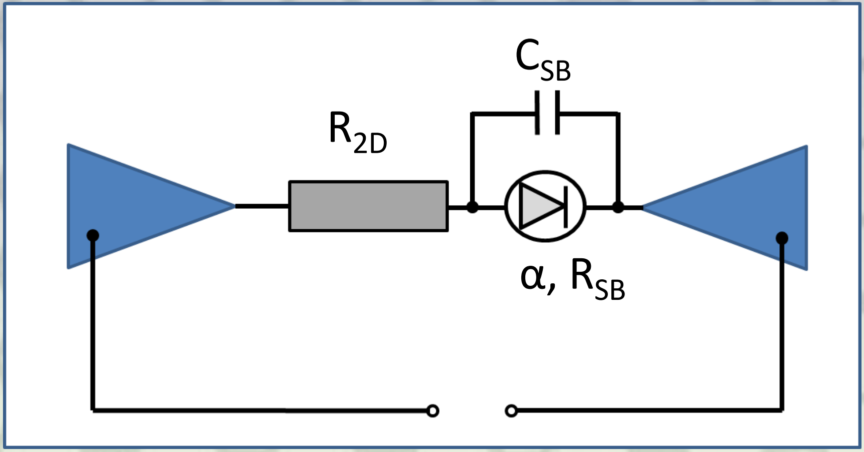




Res freq = 3THz!!!

Model suggested by V. Ryzhii, to be submitted in 2017

Diode response. Role of temperature at low frequency



The diode symbol stands for the Schottky barrier with an *I(V)* dependence described by:

$$I = {}^{1}/_{R_{SB}} \cdot V + \alpha V^2$$

The responsivity will be given by:

$$R_S = \frac{1}{2}\alpha \cdot R_{SB} \cdot {Z_A}^{-1}$$

We can approximate current with the simple formula

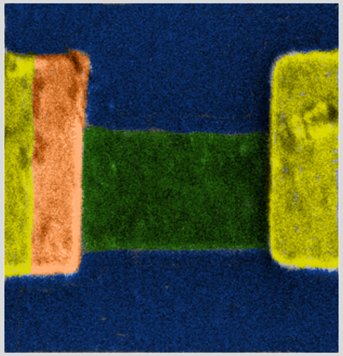
$I(V) = I_0(T) \cdot e^{-\frac{\Phi - eV}{kT}}$; Using it we get:

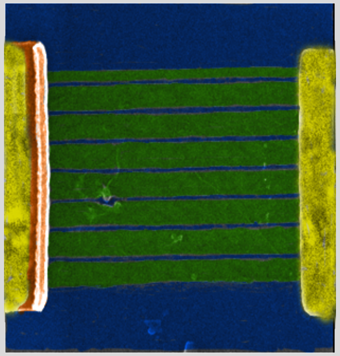
$R_{SB} = \left(\frac{dI}{dV}\right)^{-1} = \frac{kT}{e}(I_0(T))^{-1} \cdot e^{\frac{\Phi - eV}{kT}}$; grows as T goes down

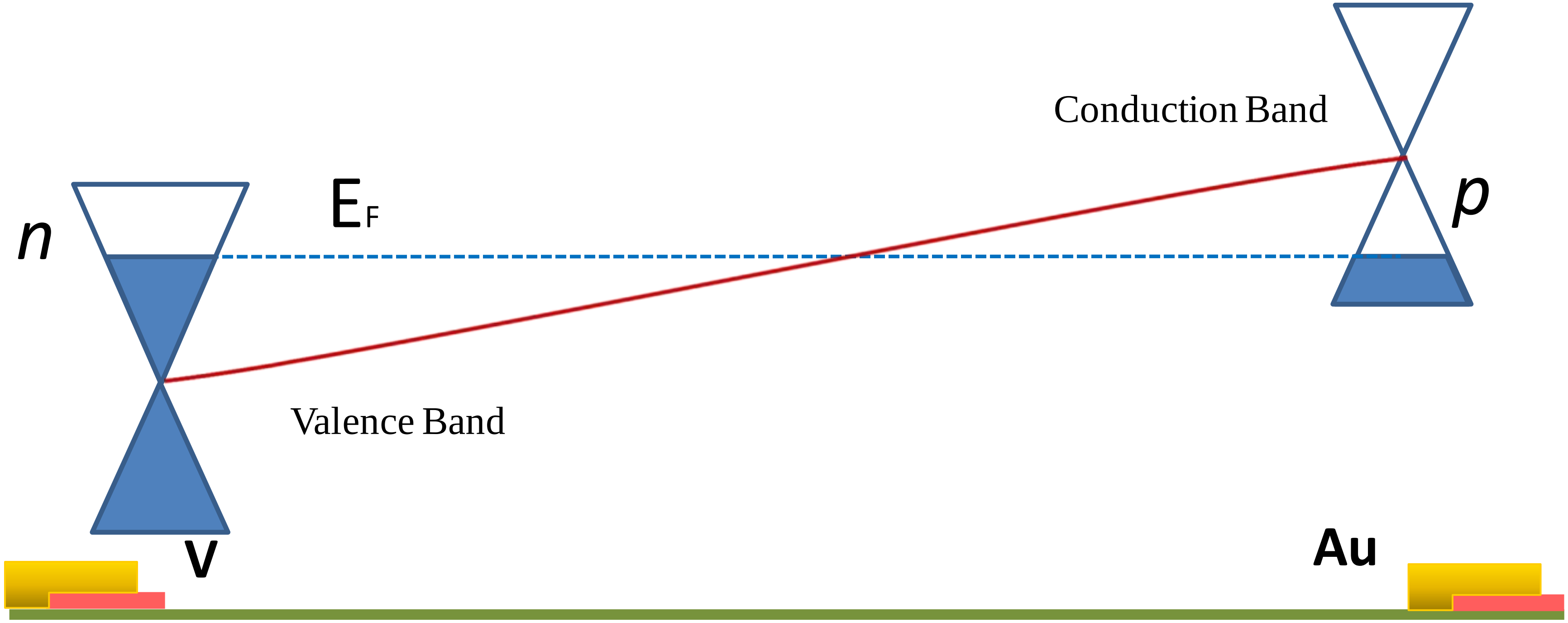
$\alpha = \frac{1}{2}\left(\frac{d^2 I}{dV^2}\right) = \frac{e^2}{(kT)^2} I_0(T) \cdot e^{-\frac{\Phi - eV}{kT}}$; probably decreases as T goes down

$R_s \sim T^{-1}$; inversely proportional to the temperature!

Diode response. Why a Schottky barrier in a gapless material?







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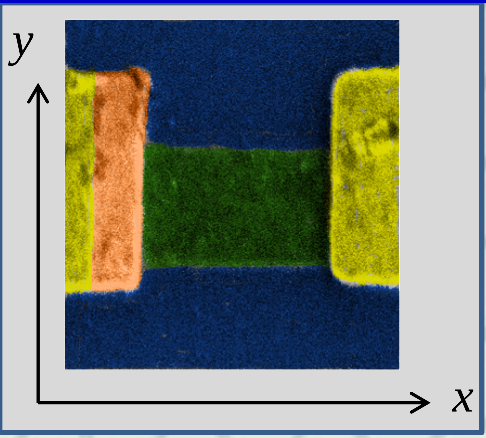
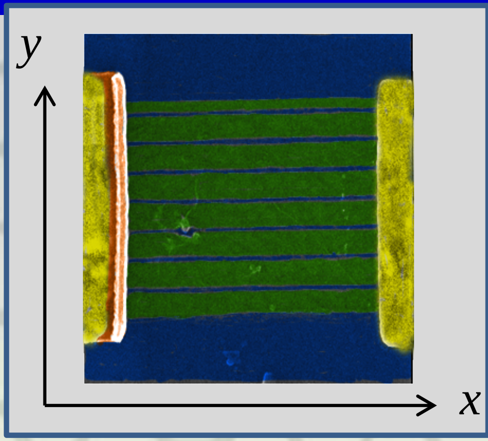
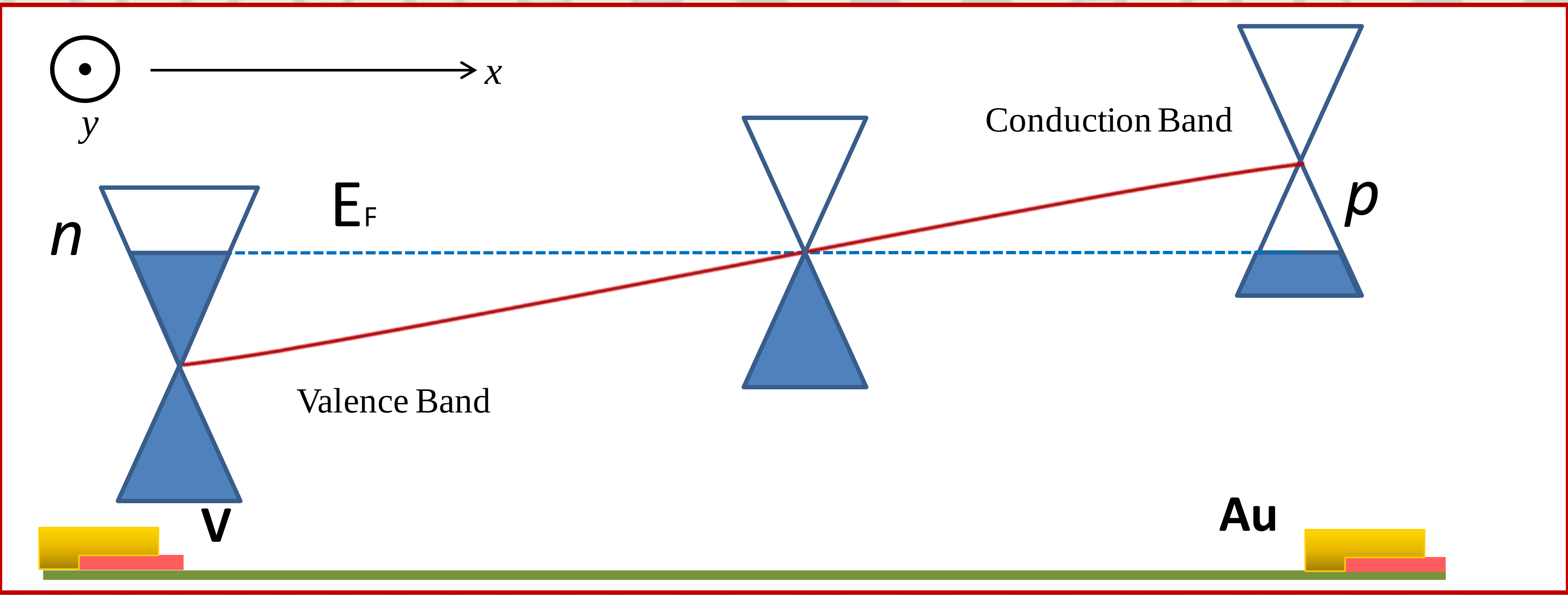
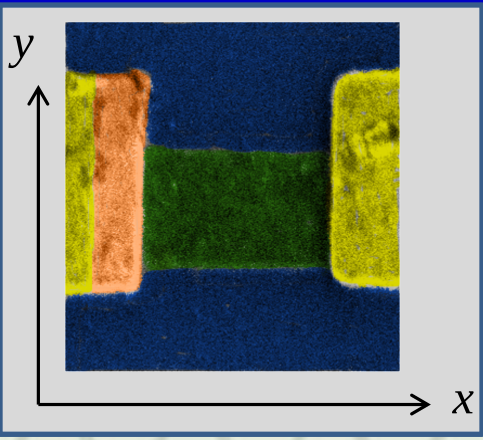


$$E(\vec{p}) = v_F\sqrt{{p_x}^2 + {p_y}^2}$$

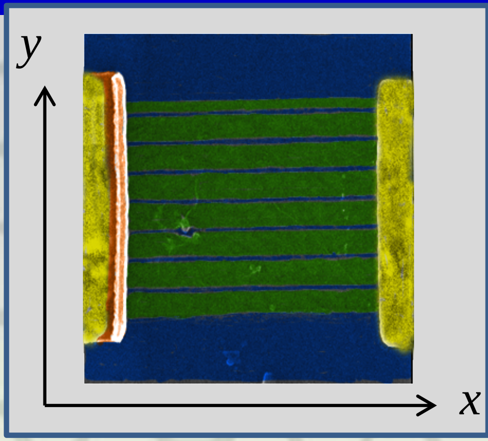


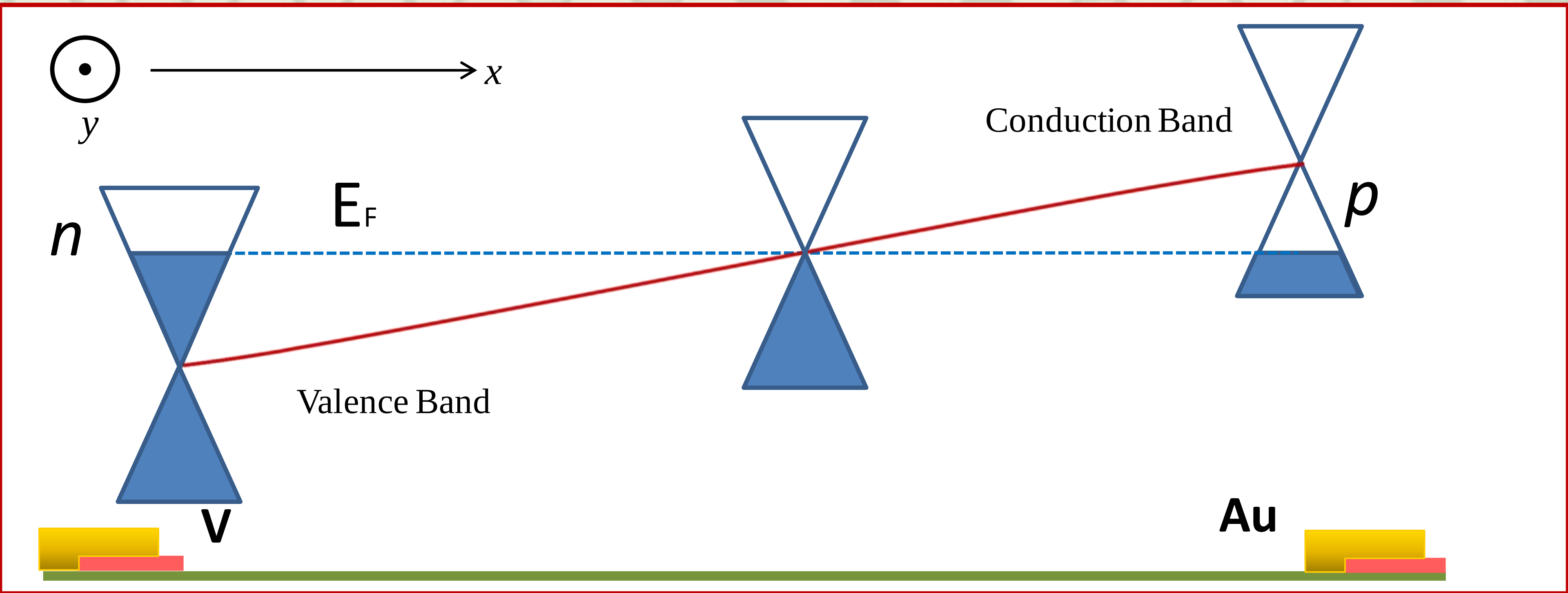


Diode response. Why a Schottky barrier in a gapless material?



$$E(\vec{p}) = v_F\sqrt{{p_x}^2 + {p_y}^2} = \sqrt{{v_F}^2{p_x}^2 + \Delta^2}$$





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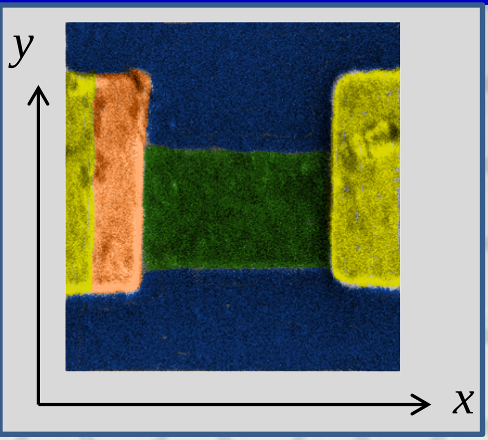

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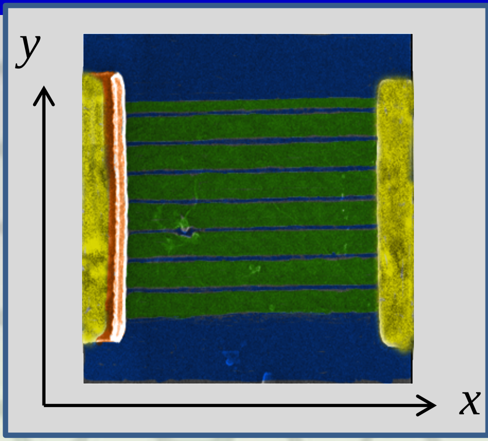

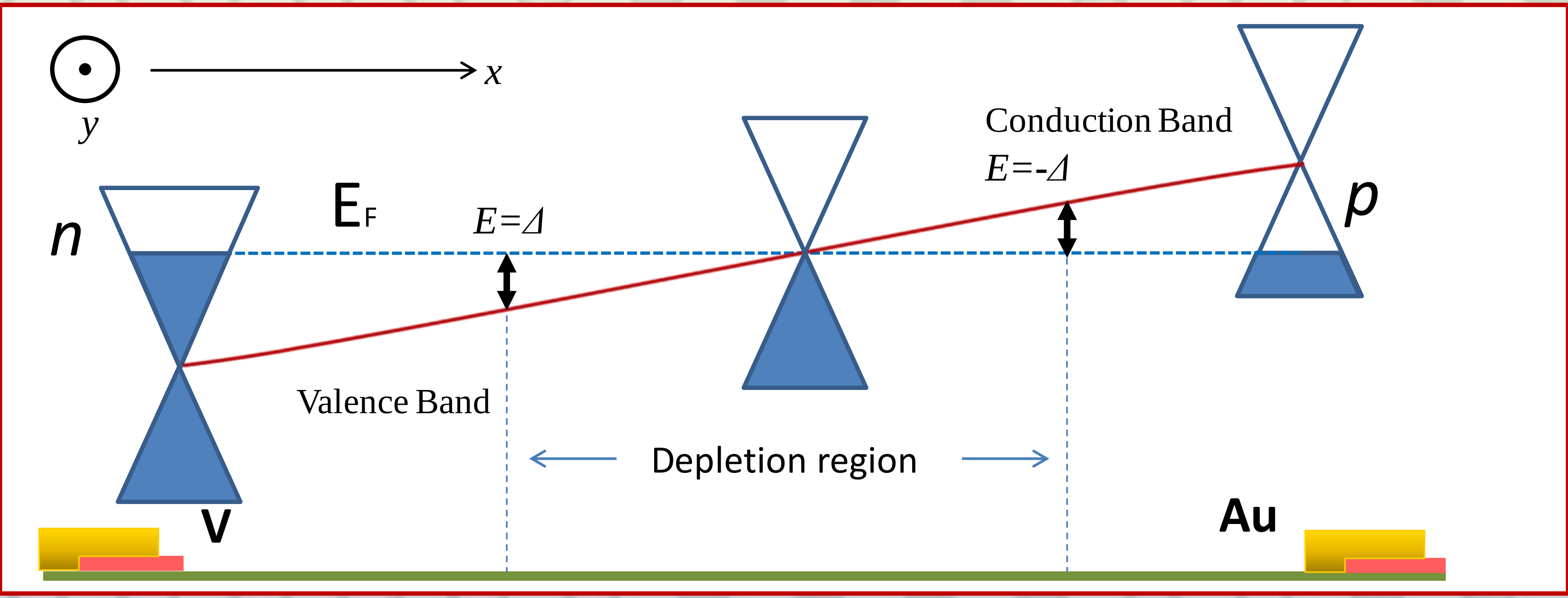

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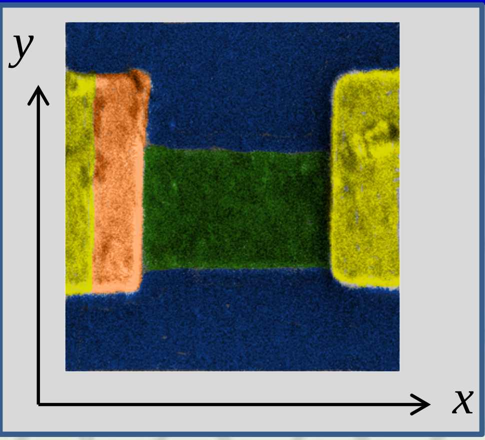

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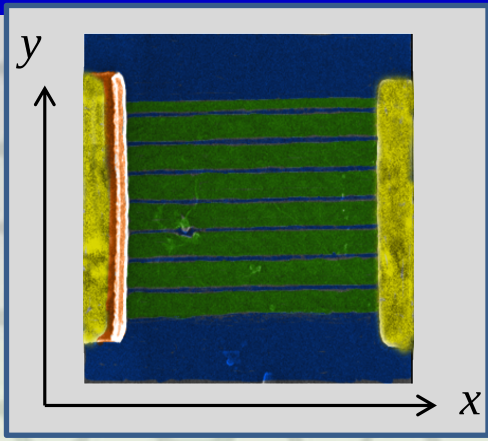

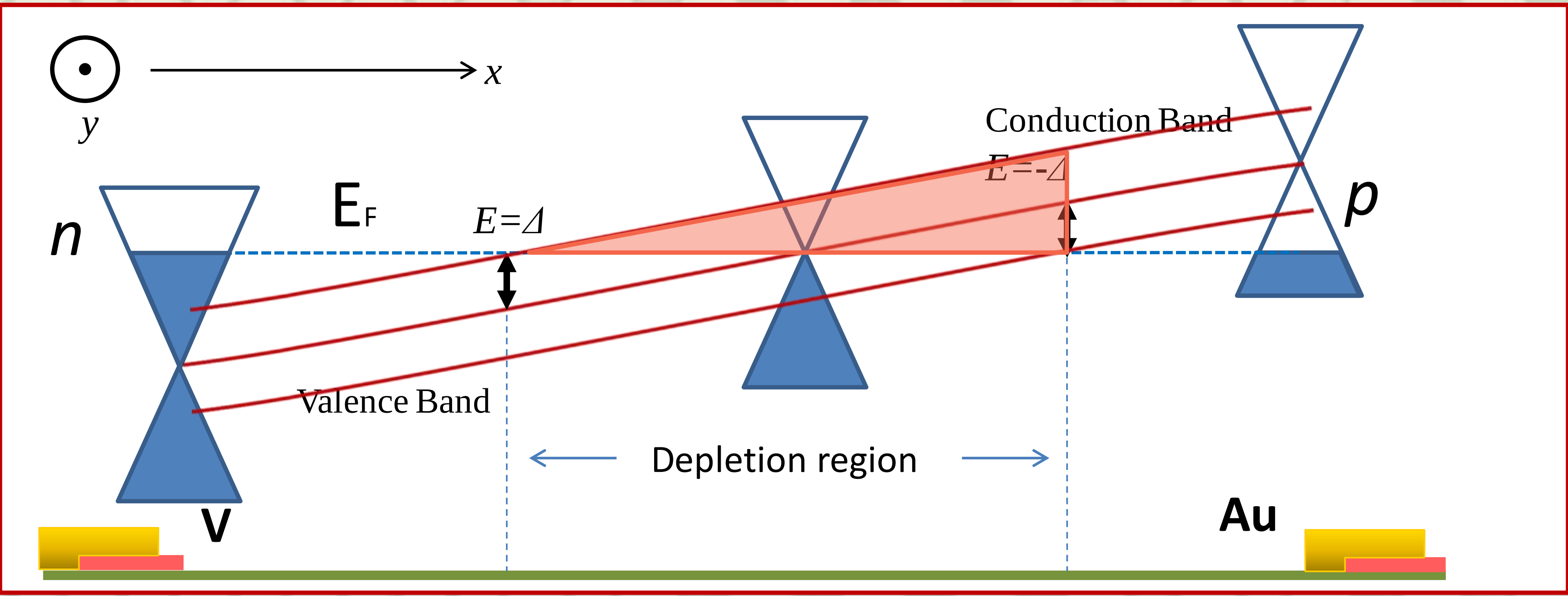

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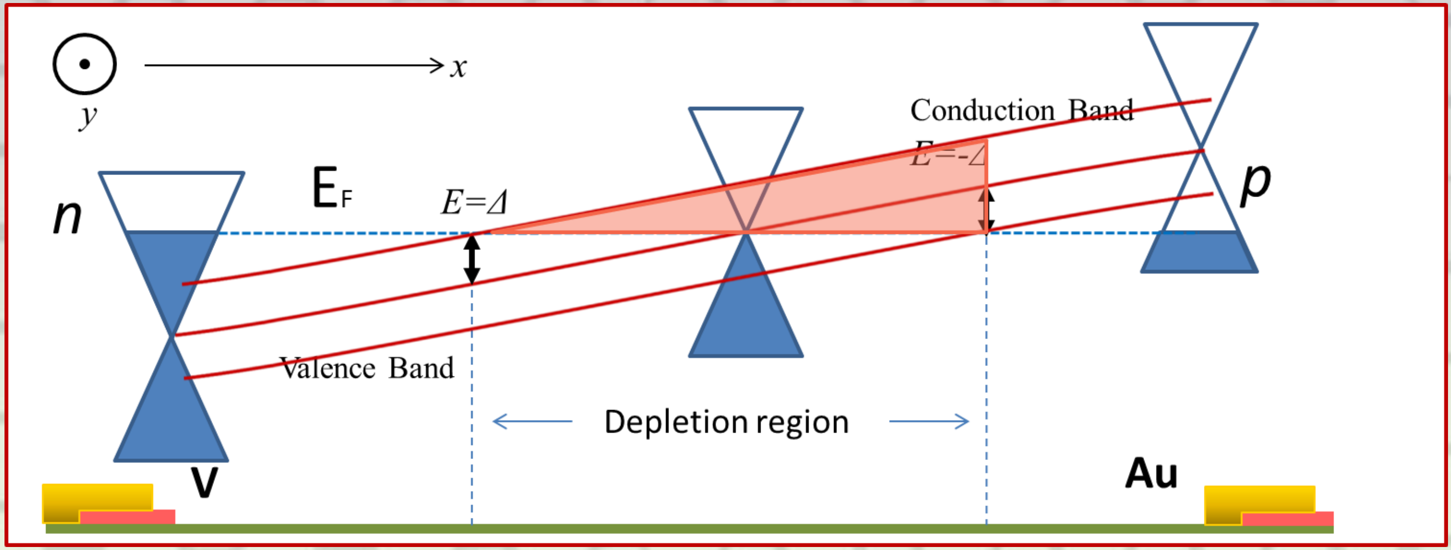

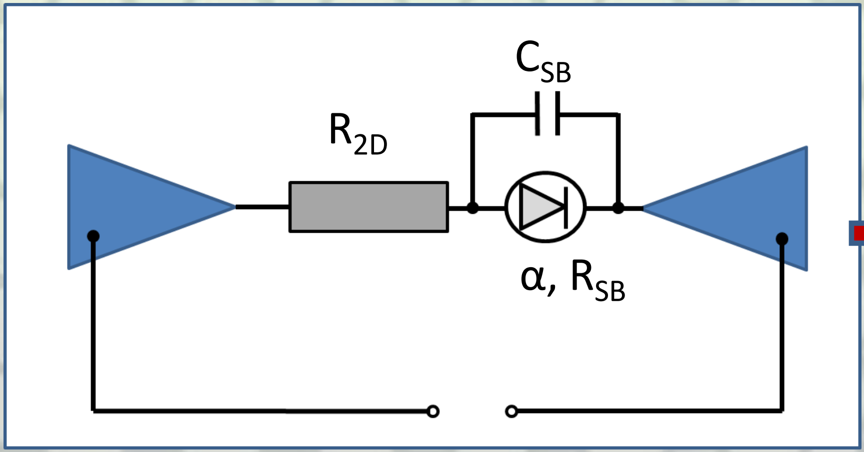

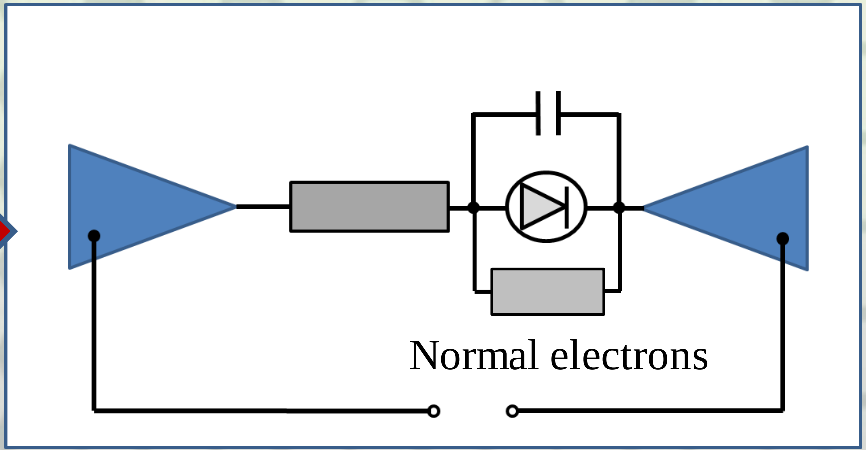

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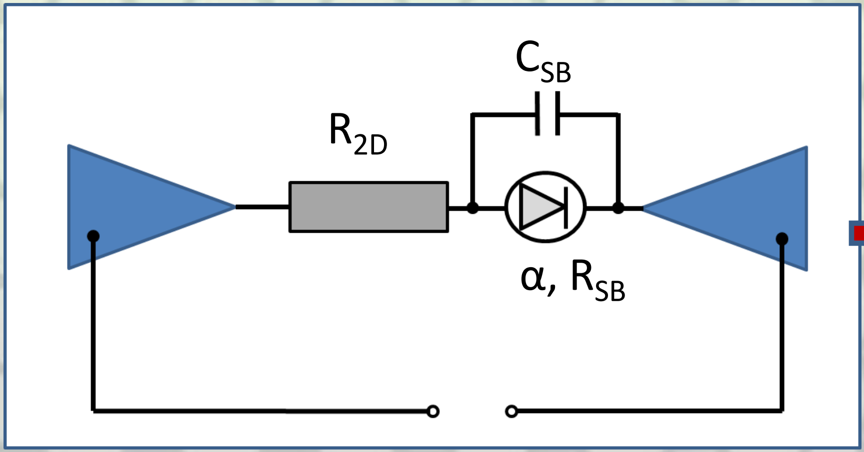

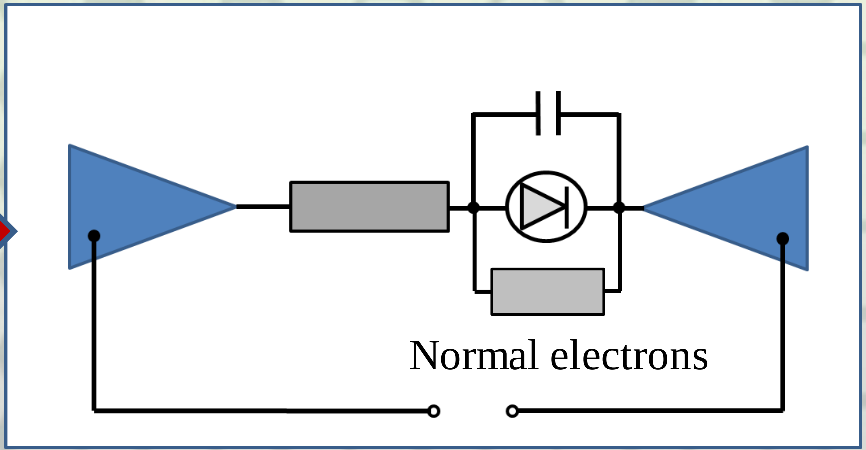

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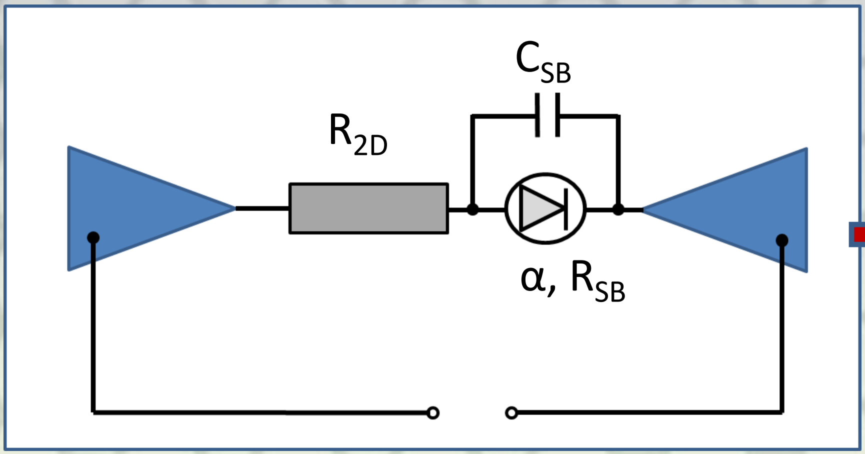
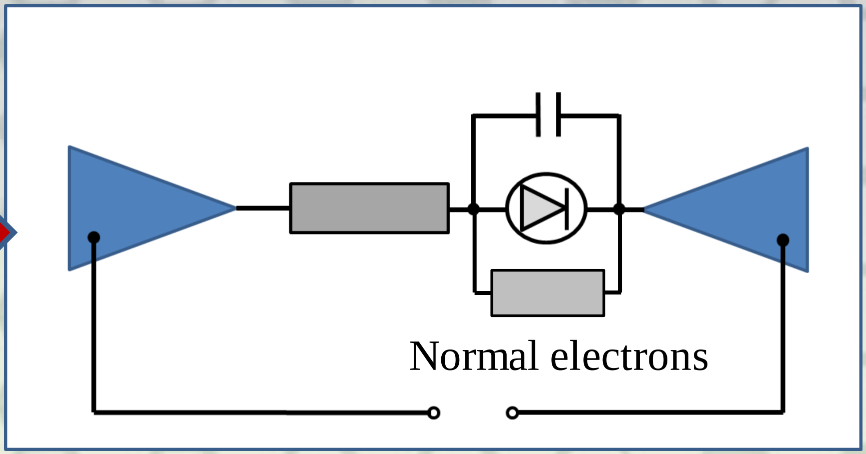
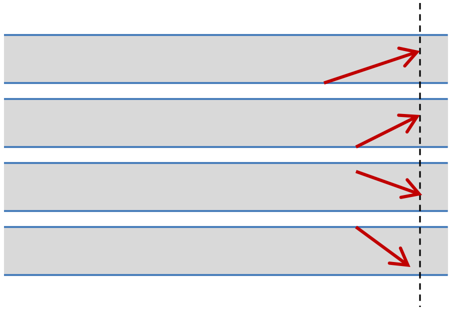
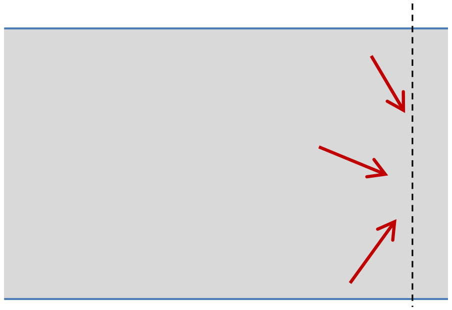


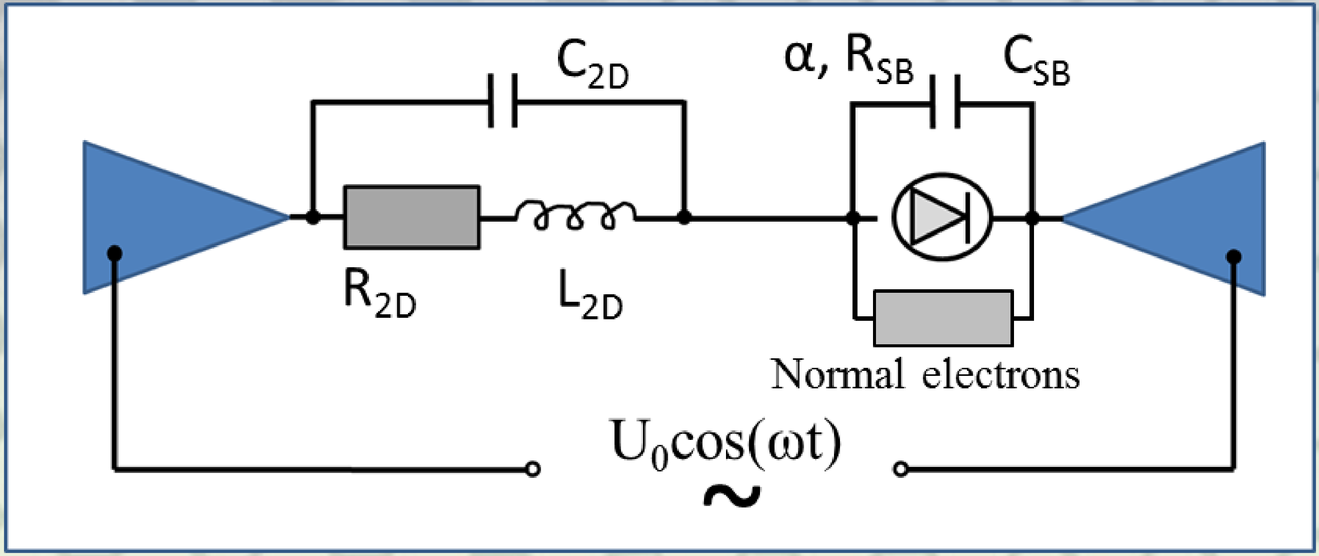




Fraction of normal electrodes is LARGER in nanoribbons which explains smaller response in GNR devices



Summary



ALL of the observed experimental data can be explained if we take into account:

1. Unusual properties of the Schottky barrier in graphene
2. Intrinsic capacitance of the barrier
3. Plasmonic resonance in graphene channel

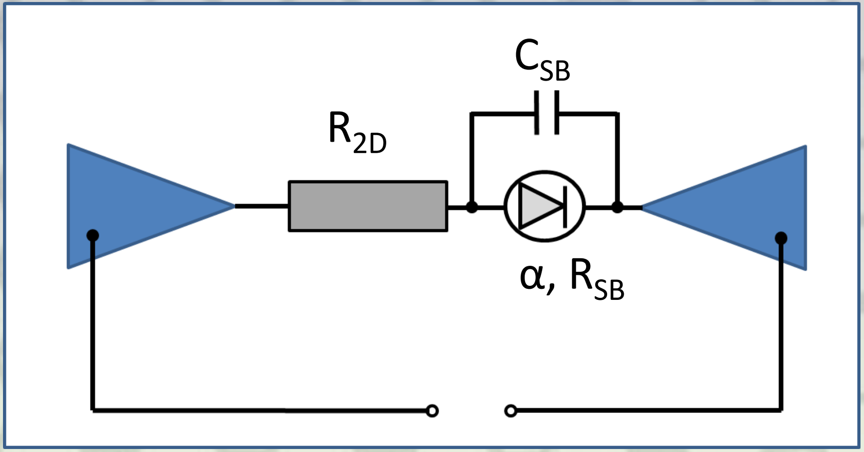
Summary

Conclusions:

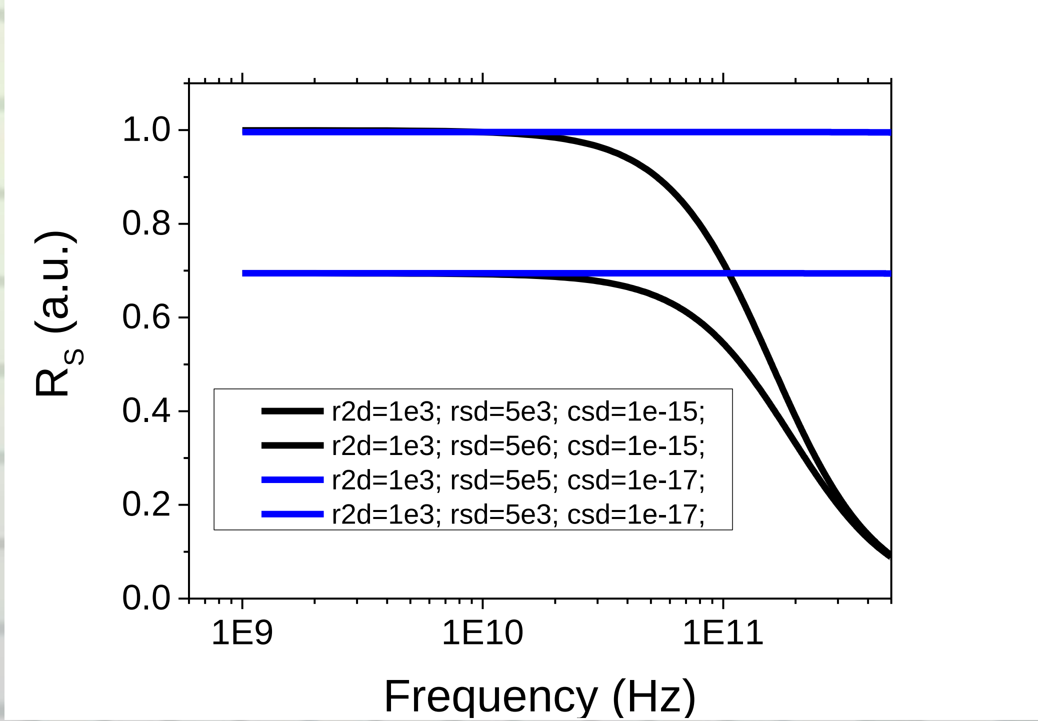
1. Manifestation of plasmonic response in the detection of radiation
2. Frequency dependence of the response is affected by plasma waves excitation FAR from the first plasmon resonance
3. Unusual properties of the Schottky barrier in graphene explain:

- The evolution of the response with temperature
- Supression of the response in the GNR devices

Diode response. What's the big deal?



Regular Schottky diode operates up to a certain frequency
While plasma waves will help it to work in a wider frequency range



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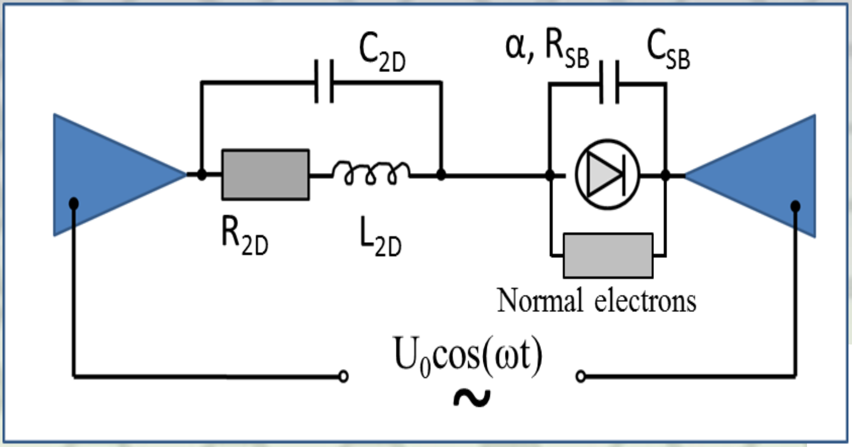

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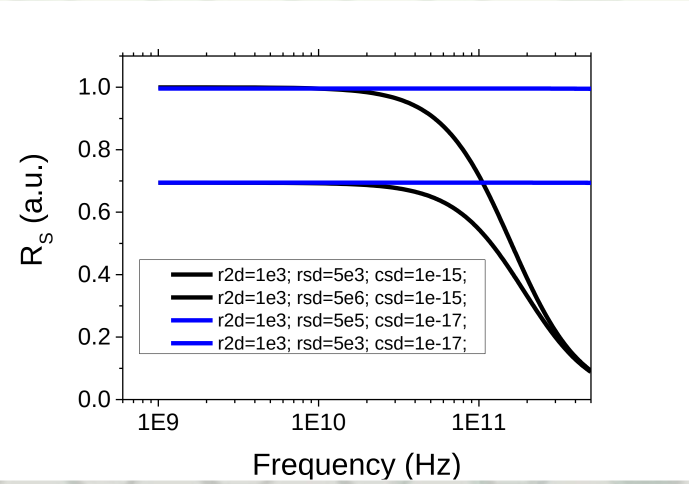

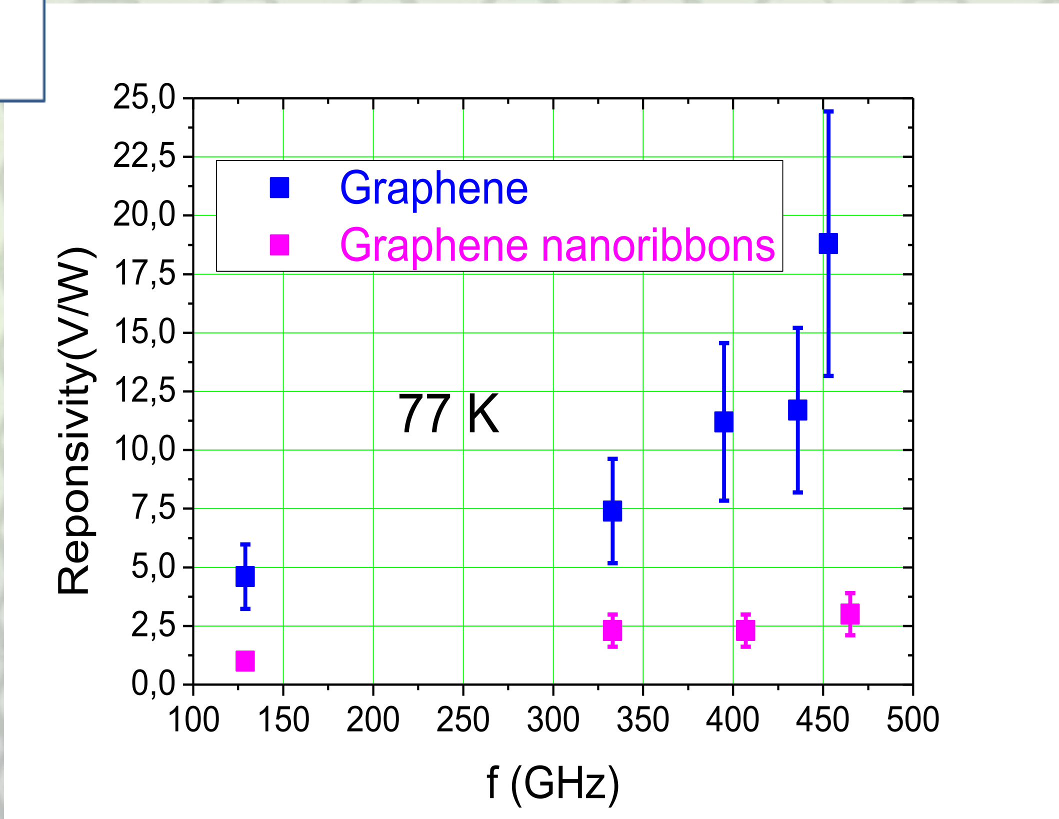

Collaboration

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E.D. Obraztsova, M. Rybin, **Prokhorov General Physics Institute, Moscow, Russia**

D. Svintsov, ***MIPT, Russia***

Research Institute of Electrical Communication Tohoku University RIEC

V. Ryzhii[4], M. Ryzhii, ***RIEC, Japan***

A. Kuntsevich, CCU, Lebedev Institute

Results overview

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2. Frequency depend… …ected by plasma waves … …st plasmon resonance
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Thank you for attention!!!