Graphene Nanostructures As Terahertz Photedetectors

Alessandra Di Gaspare

28/03/2017

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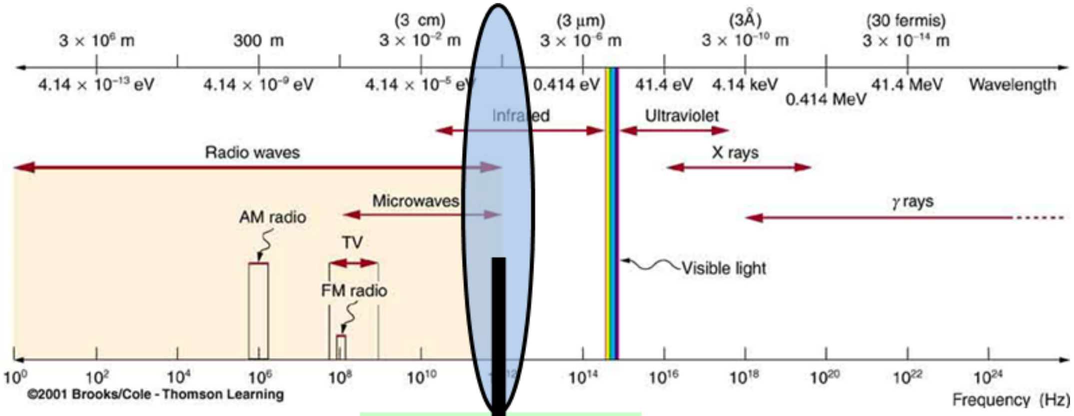
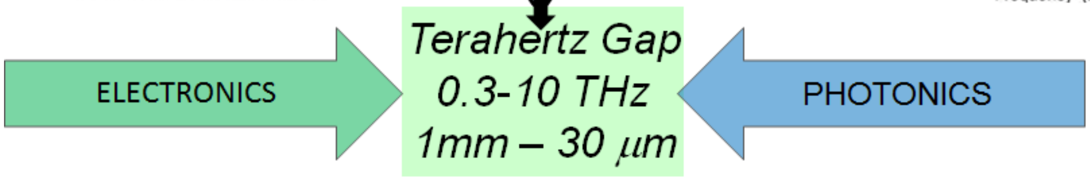
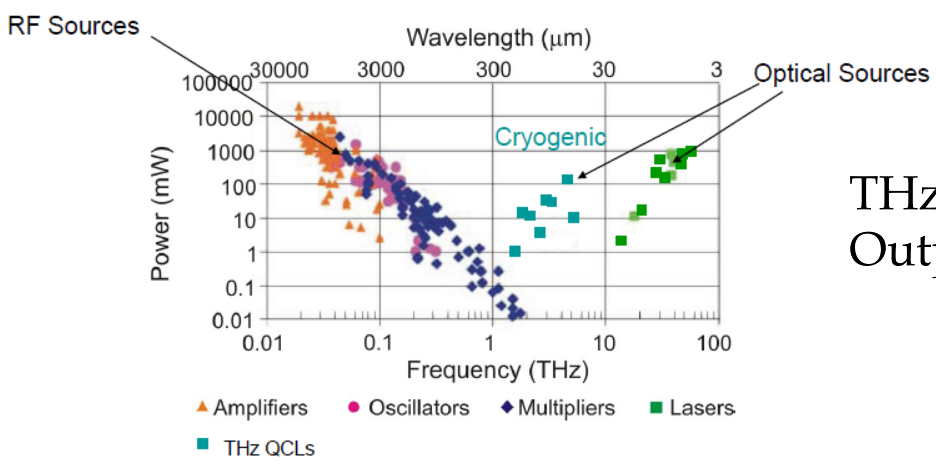
The THz Gap



Limited by parasitic RC time constant

Limited by band-gap and thermal Energy (1 THz = 4 meV)



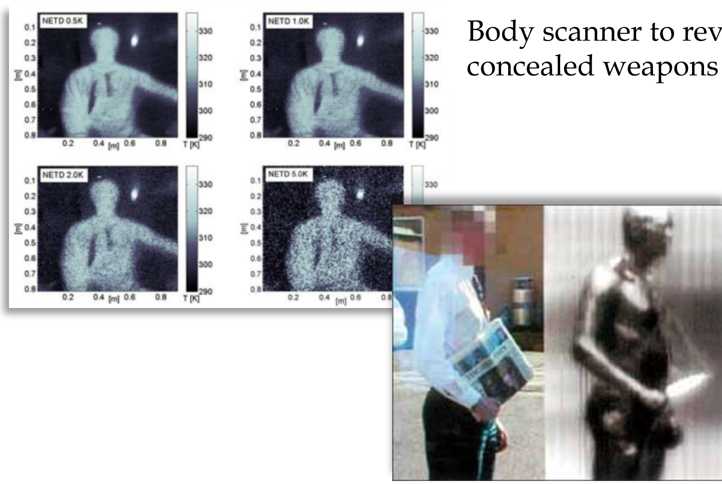


THz Sources Output Power

THz radiation applications

THz range offers many opportunities for applications

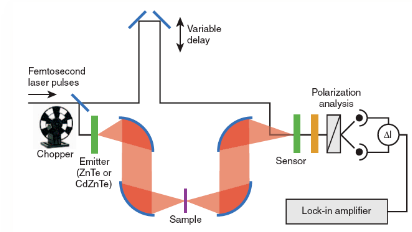
Security



Body scanner to reveal concealed weapons

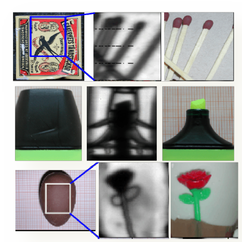
Fundamental Science

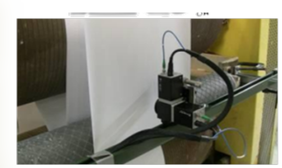
THz Time Domain Spectroscopy: dynamics of electrons, holes, phonons



Inspection of Material Devices, …

Industrial Process monitoring, food contamination





Plastic sheet lamination

Availability of sensitive detectors: main technological bottleneck
In R&D: new approaches and devices based on interaction between THz radiation and technologically important materials

OUTLINE

1. Semiconductors Nanostructures and Terahertz Radiation
   - Systems and State of the Art
   - Detection in Field Effect Transistors: theory and some experimental results
2. Low dimensional semiconductrors nanostrucures as effective active material for THz detection
   - Graphene, 1D systems
3. Reaching the photon-counting level in the THz range

THz Detection: figures of merit

Responsivity (R) [A/W] or [V/W] $\frac{\text{Electrical Output}}{\text{Input Power}}$

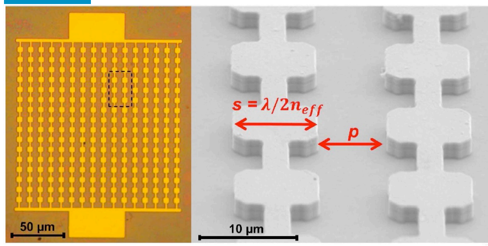
Noise Equivalent Power (NEP) [W/Hz$^{-1/2}$] $\frac{\text{Noise Spectral Density}}{\text{Responsivity}}$

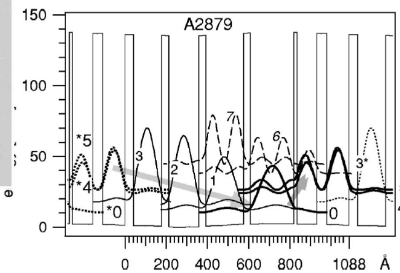
Response Time (t) [Max. modulation freq.]$^{-1}$

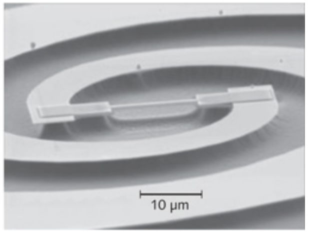
Portable/Integration On-chip/Scalable/Price

THz Direct Detectors

QWIPs





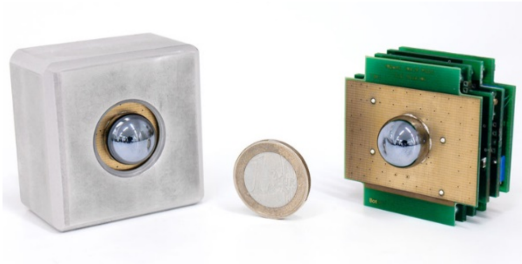


Hot Electron Bolometers
NEP = 3 x 10^{-19} WHz$^{-1/2}$

Higher performances, cryo needed

T < 10 K

Pyroelectric
NEP = 3 nWHz$^{-1/2}$



CMOS Multipixel Camera, Schottky Diodes
NEP = 100 pWHz$^{-1/2}$

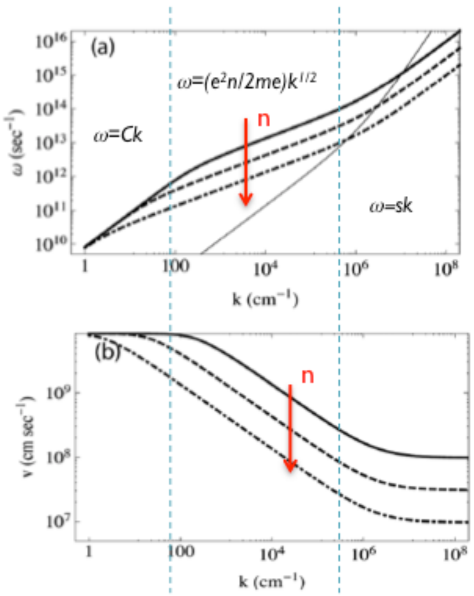
1-Portability
2-In electronic systems, time response very fast

THz Detection in FETs

Rectification of THz plamsa waves in the 2D active channel
(Dyakonov and Shur, PRL 1993)

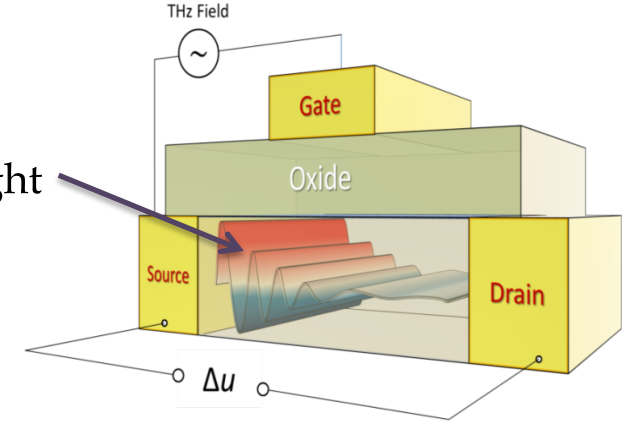
1-Low-dimesnional systems, 2DEG (**Two-dimensional electron gas**) gas of electrons free to move in two dimensions, quantum-confinement in the third dimension...

2- 2D plasmons @ THz frequencies can be coupled to radiation provided there is a **wave vector defined by geometry** (grating or antenna) to **compensate for the momentum mismatch**



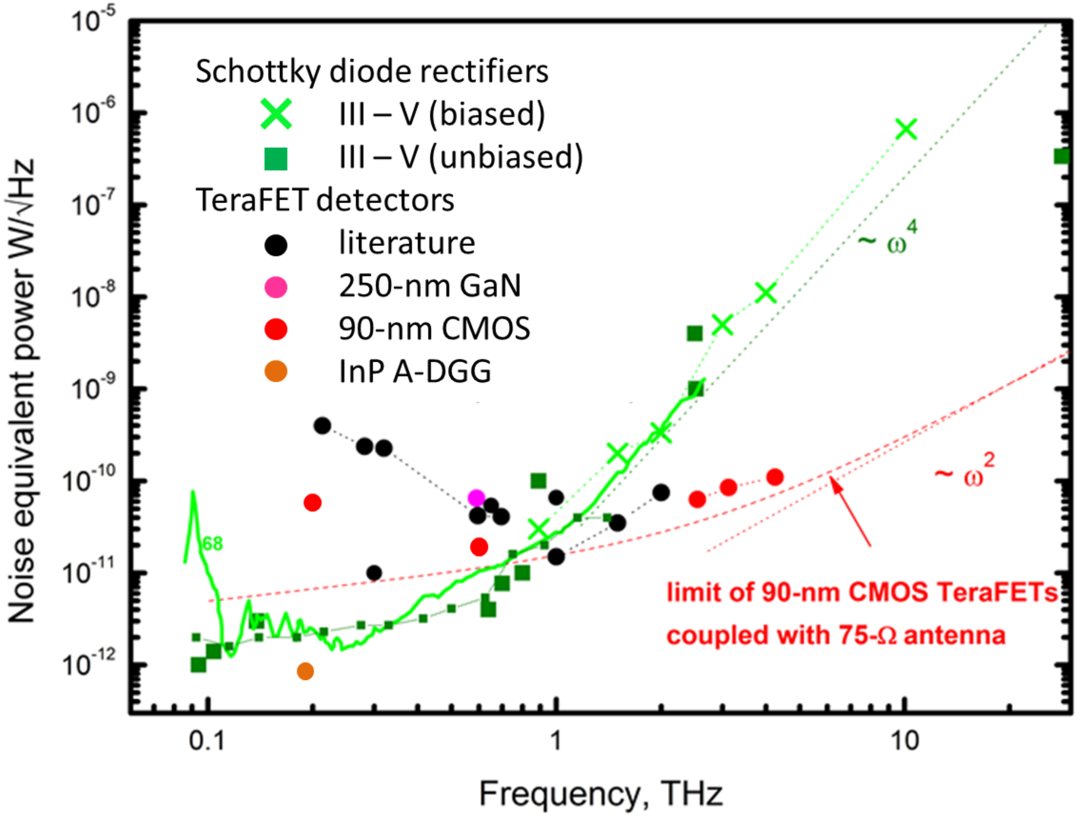
F. Evangelisti, JAP 2013

Confinement of THz radiation in subwavelenght cavity

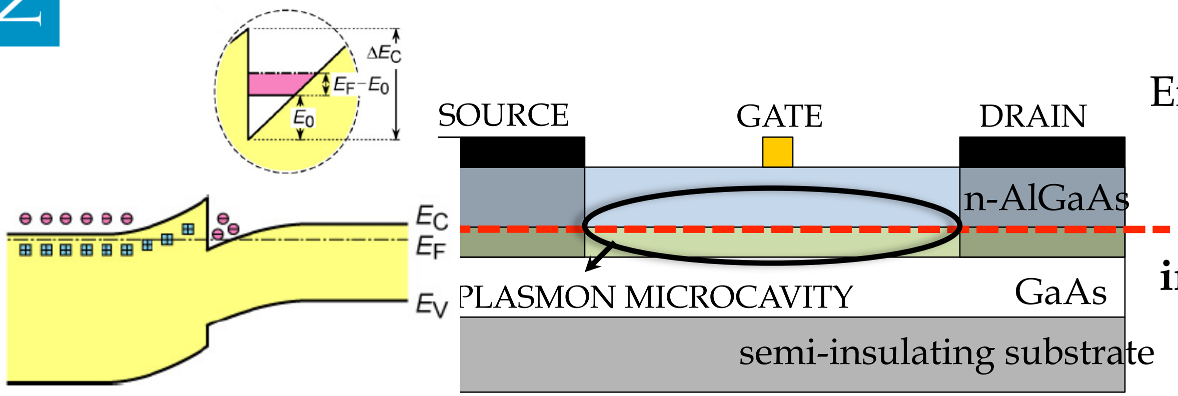


Tunability of the plasma frequency in 2D systems

Why FETs for THz detection?

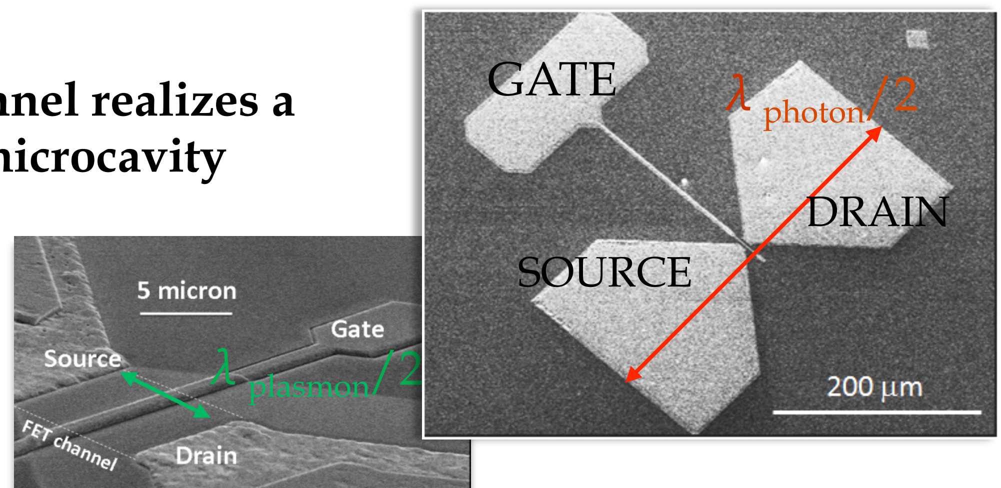


Plasma wave devices



Exeprimental approach: **fabrication of field effect transistors** whose conducting channel is a 2DEG, **integrated with** a **planar antenna**

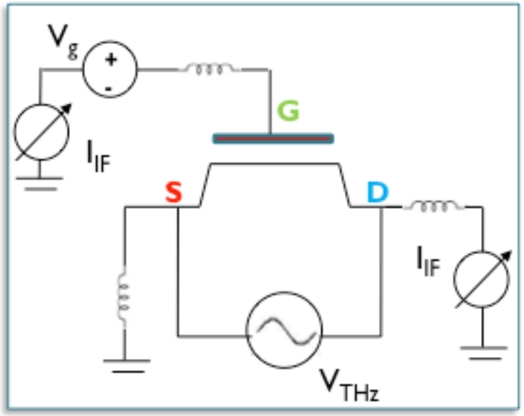
The 2DEG channel realizes a plasmonic microcavity



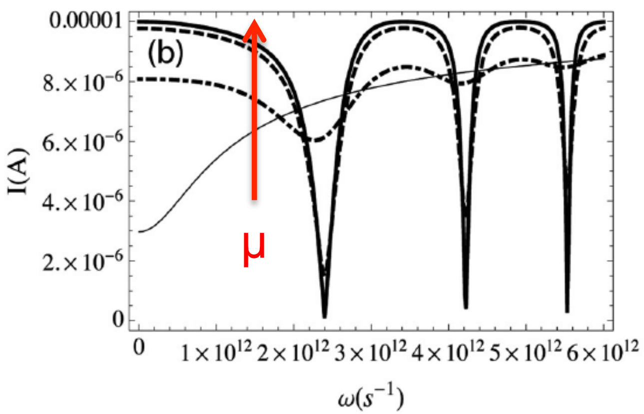
Charge modulation in time and space at ω → *2DEG in hydrodynamic regime*

THz-down conversion: DC photocurrent

- Self-mixing in FETs (Dyakonov-Shur mechanism) THz modulation of the channel charge density imposed by the gate terminal
- Intrinsic nonlinearity in the 2DEG-hydrodynamic response
- Heating of the 2DEG
- …



Absorption of THz radiation



Damped (broadband) detection

μ

Resonant detection

Inversion symmetry of the E field must be broken (antenna, channel design)

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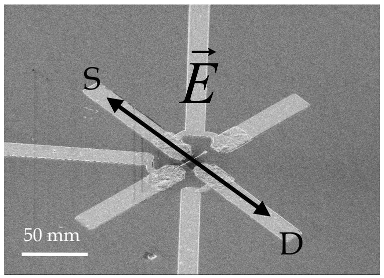
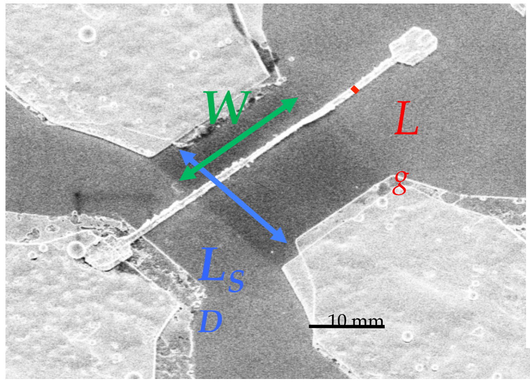
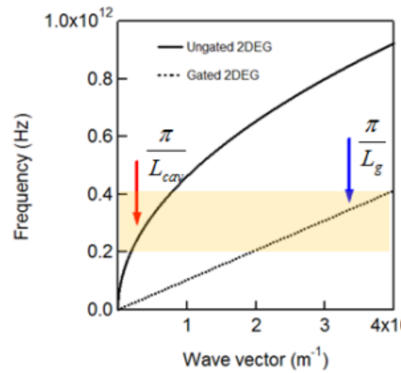
Spectral Response







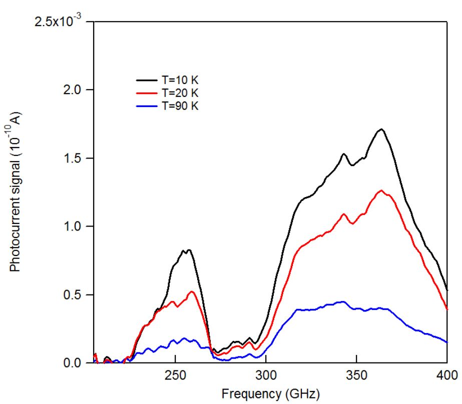
- Two-terminal device with asymmetric design
- Hydrodinamic regime of the ungated 2DEG in the investigated spectral range

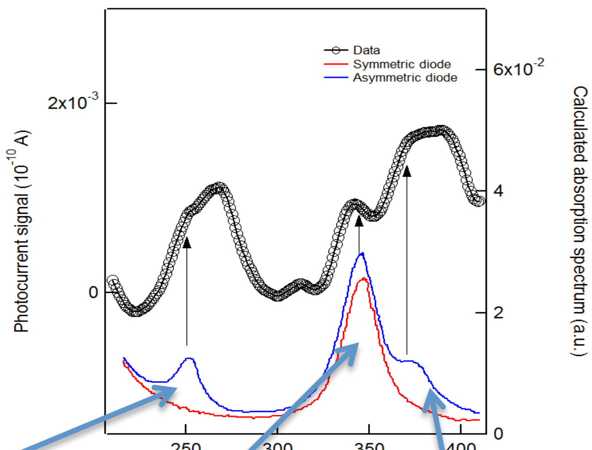
Two perpendicolar linear dipole antenna

Strong indication of plasma waves

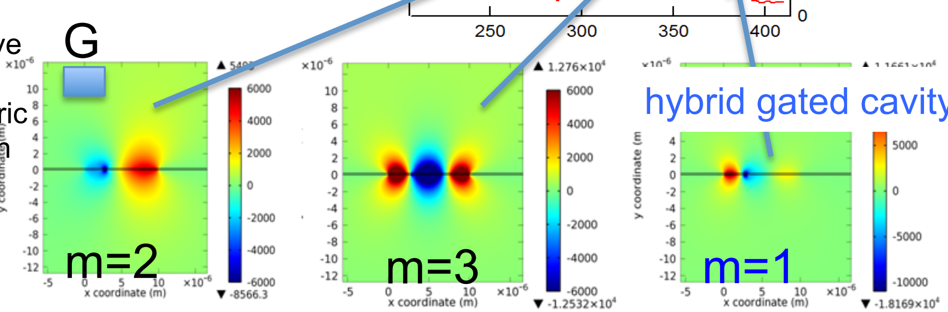
Modes assignement:

- interaction btewteen 2DEG gated and ungated (hybrid cavity)
- Activation of optically inactive mode





Optical inactive even mode with asymmetric E distribution



A. Di Gaspare, APL 2012
A. Di Gaspare, J. Opt 2013
V. Giliberti, PRB 2015

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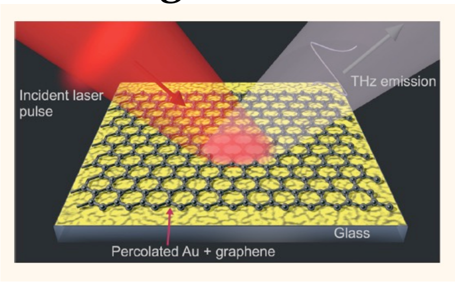
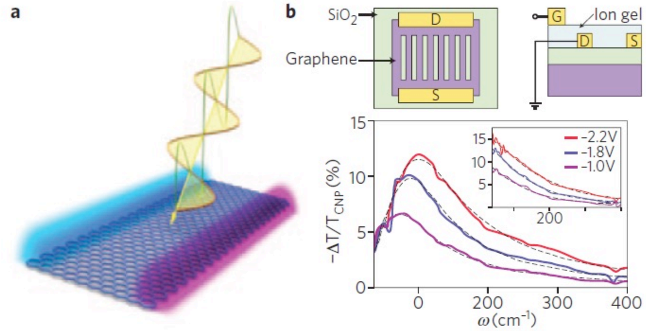
The Terahertz gap & graphene

THz generation



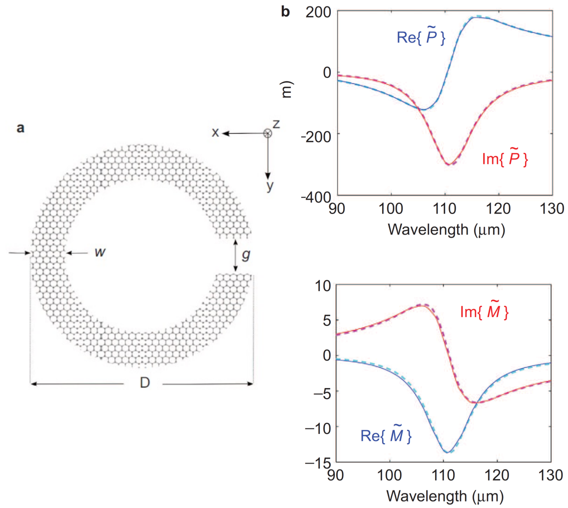
Y. M. Bahk *et al*, *ACS Nano*, **2014**, *8* (9), pp 9089–9096

THz plasmonic devices



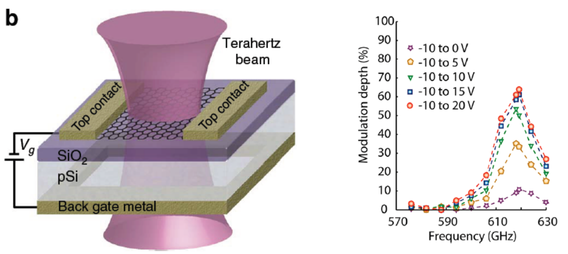
A. N. Grigorenko *et al*,*Nature Photon.*, vol. 6, pp. 749–758 (2012)

THz metamaterials



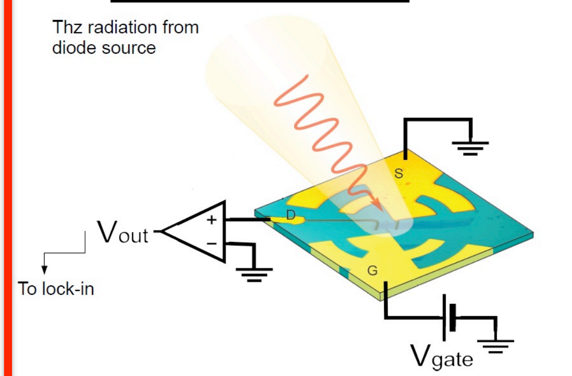
N. Papasimakis *et al*., *Light: Science & Applications* (2013) **2**, e78

THz modulation



B. Sensale-Rodriguez *et al*., Nature Commun. **3**, 780 (2012)
B. Sensale-Rodriguez *et al*., Nano Lett. **12**, pp. 4518–4522 (2012)

THz detection



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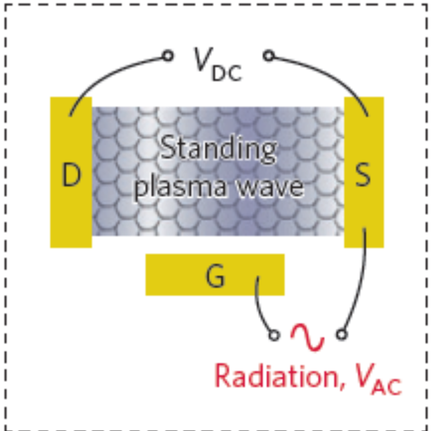
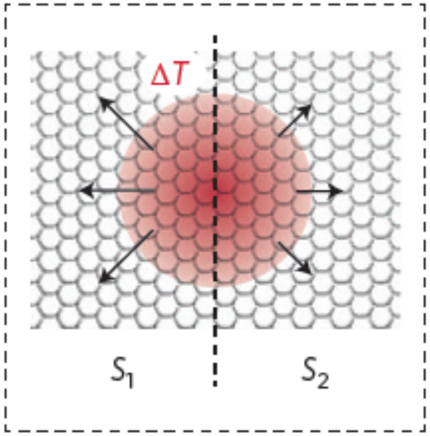
Graphene-based devices as THz detectors

Dyakonov-Shur



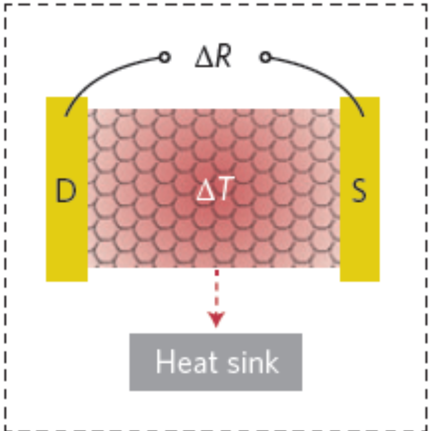
L. Vicarelli et al, Nat. Mater. **11**, 865 (2012).
D. Spirito et al, Appl. Phys. Lett. **104**, 061111 (2014).
A. Zak et al, Nano Lett. **14**, 5834 (2014).

Photo-thermoelectric



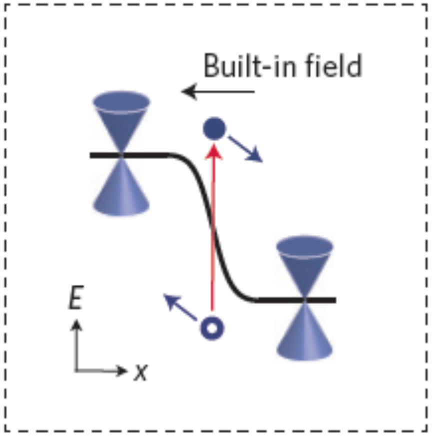
X. Cai et al., Nat. Nanotechnol. **9**, 814 (2014).

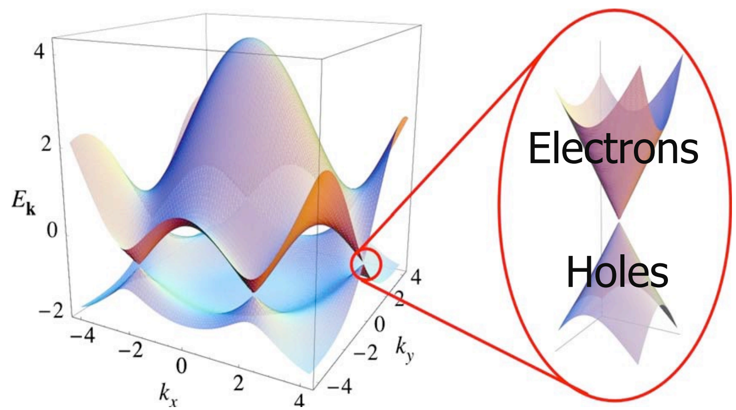
Bolometric



A. V. Muraviev et al, Appl. Phys. Lett. **103**, 181114 (2013).
M. Mittendorff et al, Appl. Phys. Lett. **103**, 021113 (2013).

Photovoltaic



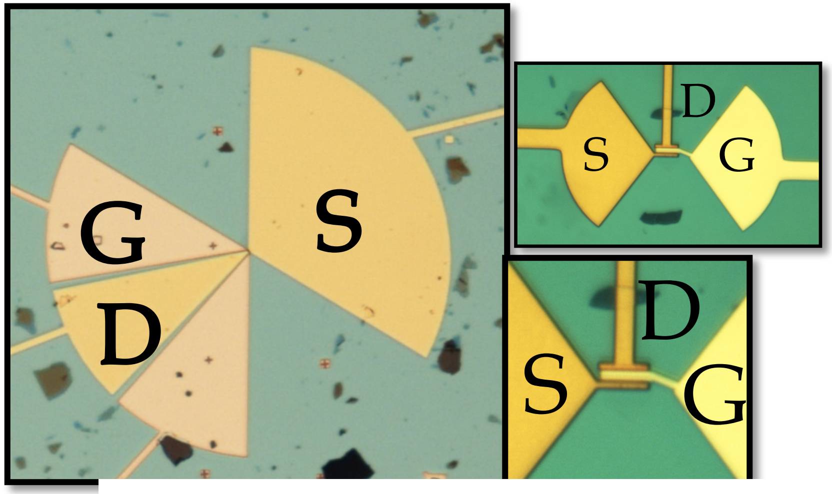


Koppens et al, **Nature Nanotechnology** 2014

Works only for Graphene in the THz Range

Antenna coupled Graphene-FET

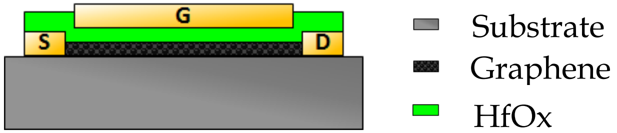
Antenna Integration



Broadband Asymmetric coupling

Device development@NEST

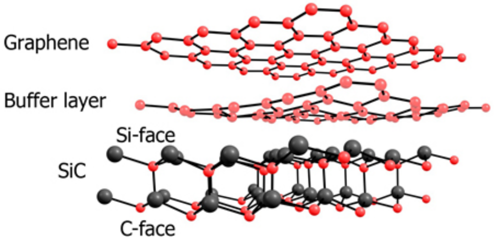
Top-gate G-FET



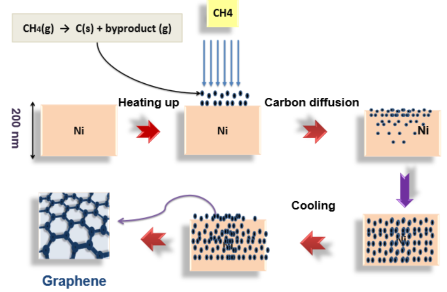
Exfoliated graphene

Epitaxial and CVD graphene

Epitaxial growth

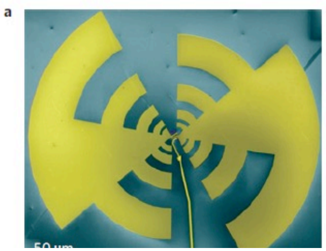


CVD growth

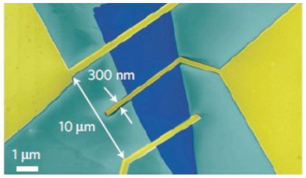


Antenna coupled Graphene-FET

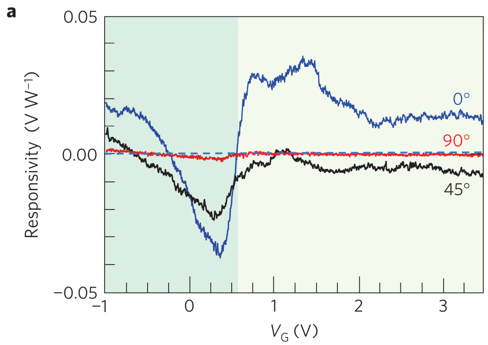
L.Vicarelli, Nat. Nano 2012

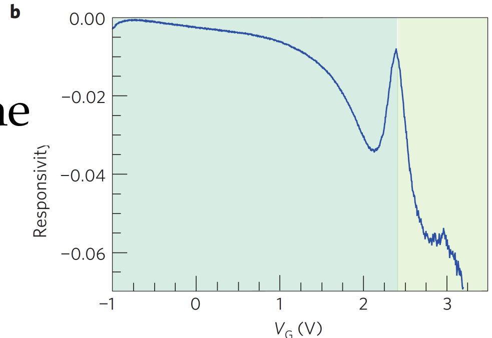


Exfoliated SL Graphene



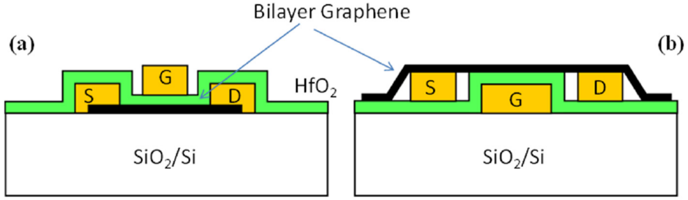
Maximum responsivity :
R = 0.05 V/W
Minimum Noise Equivalent Power:
NEP = tens of nW/$\sqrt{\text{Hz}}$



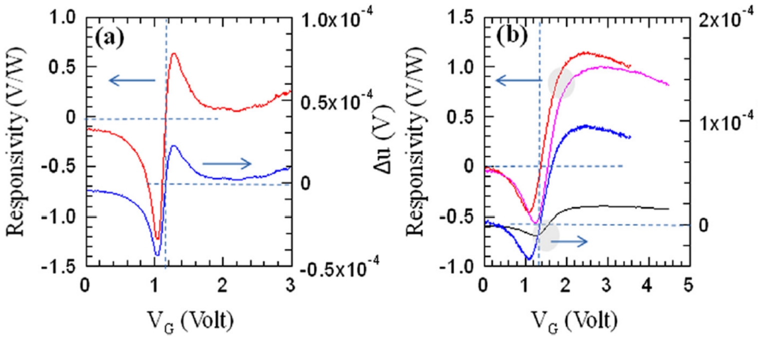


0.3 THz

D. Spirito, APL 2014



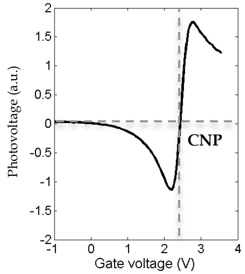
Exfoliated BL Graphene



Maximum responsivity :
R = 1.2 V/W
Minimum Noise Equivalent Power:
NEP = 2 nW/$\sqrt{\text{Hz}}$

Broadband detection

$j = e \langle n(t) \cdot v(t) \rangle_{2\pi/\omega}$



$\Delta U = C^* \sigma^{-1} * d\sigma/dV_G$

$C \sim 10^{-4}\ V^2$
efficiency of the antenna coupling and the FET impedance

$\sigma = 1/R_{sd}$
source/drain conductance

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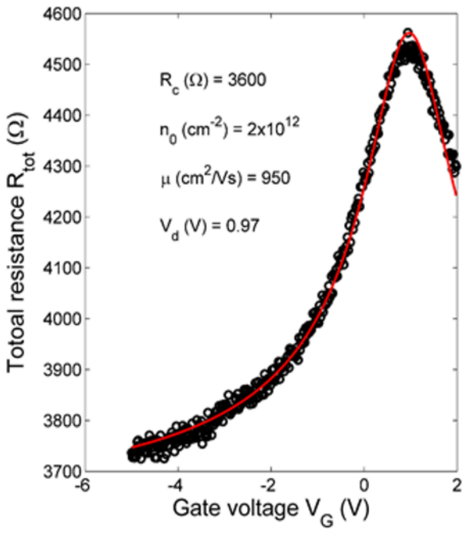
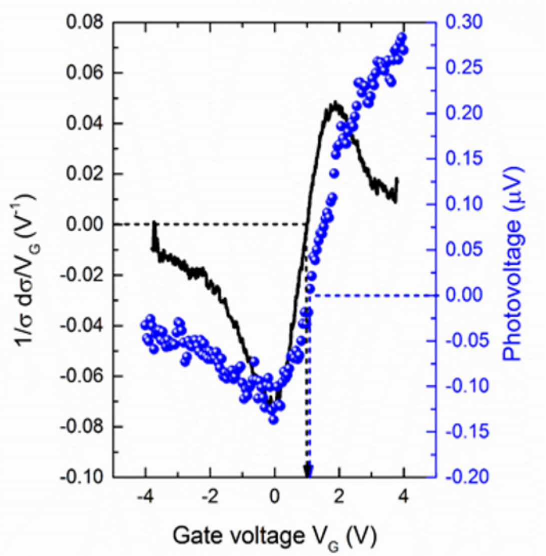
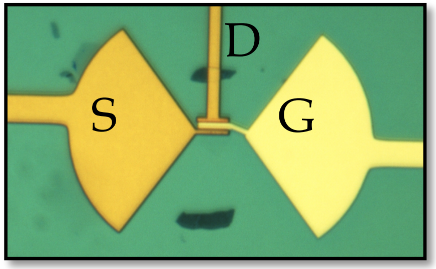
QCL radiation detection by GFETs at 3.4 THz





Non-resonant plasma wave rectification



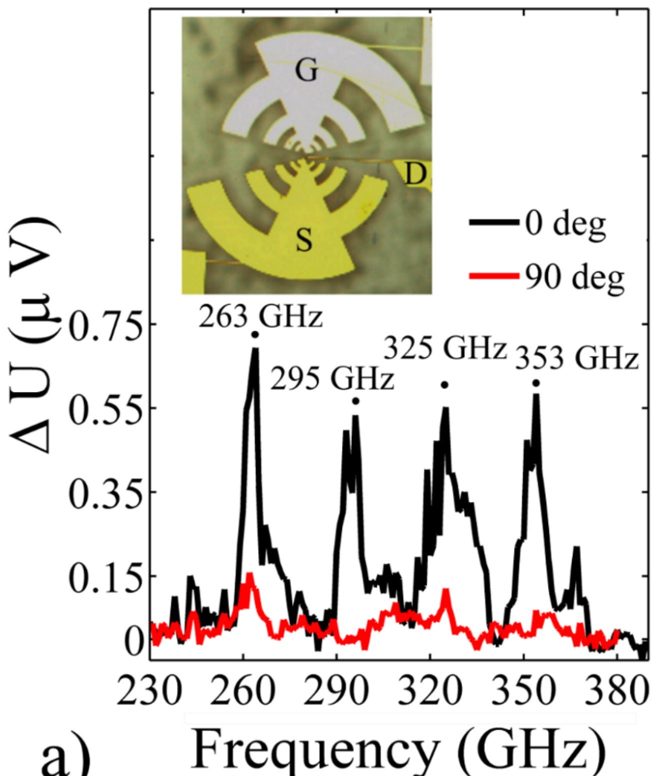
Maximum responsivity :
R = 1 V/W

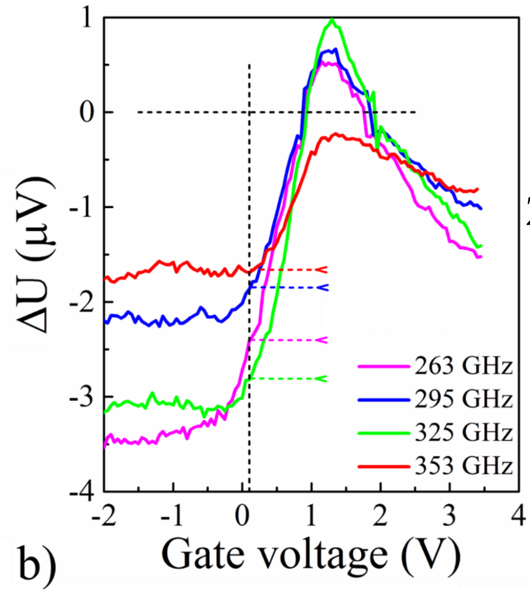
Detection speed:
250 kHz
Limit imposed by presently used experimental set up
Expected maximum speed > 1 MHz

Minimum Noise Equivalent Power:
NEP = 10 $nW/Hz^{-1/2}$

Epitaxial graphene FET

F. Bianco, APL 2015

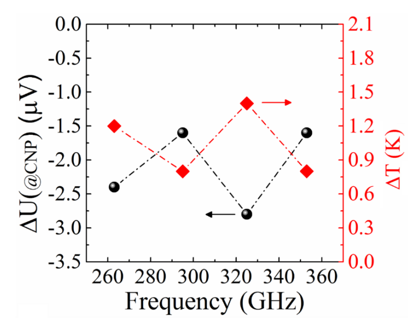


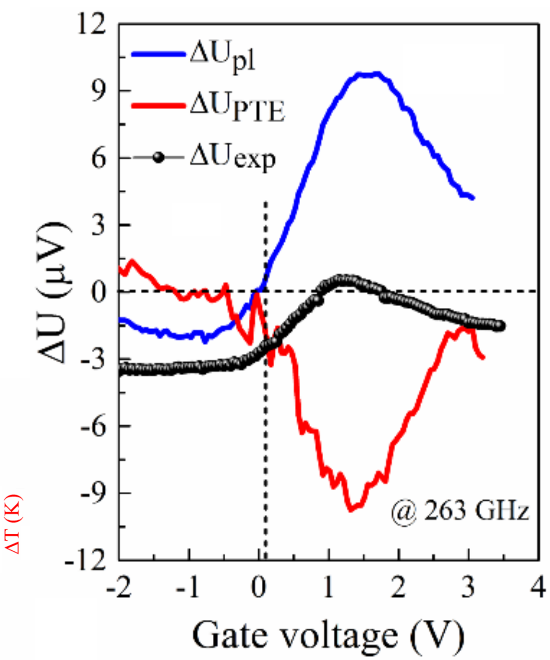


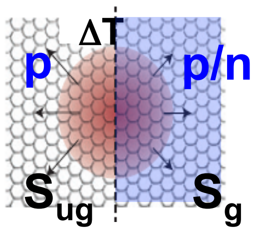
Max responsivity R = 0.25 V/W

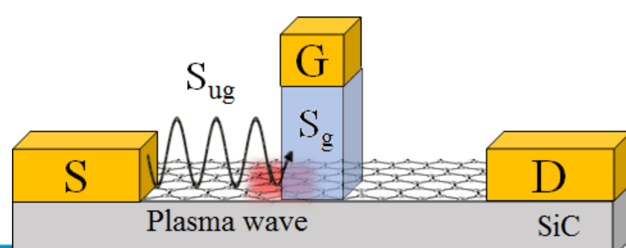
NEP = 80 nW/√Hz

2 Competing detection mechanism





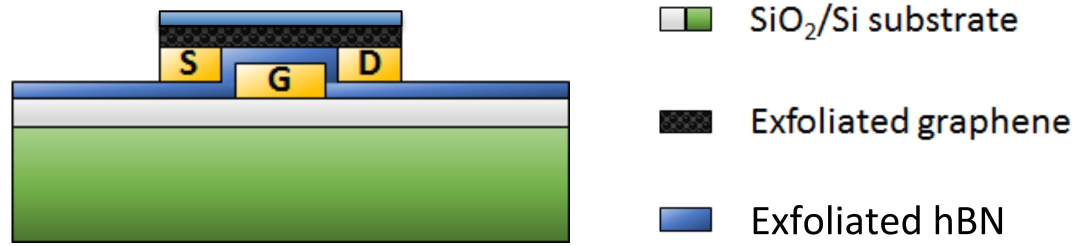




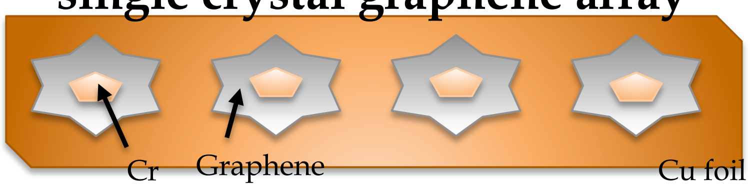
Resonant Detectors (work in progress)

Encapsulated graphene

Large scattering time, High mobility

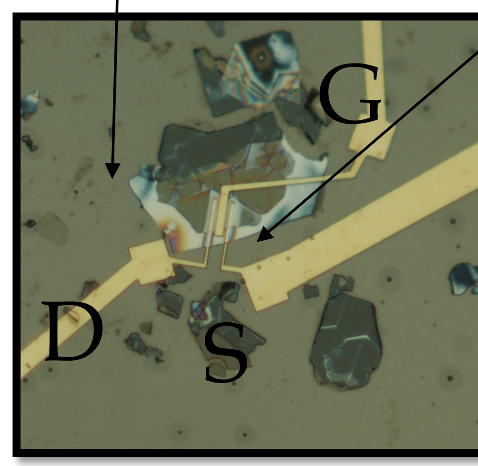


Cr-seeded CVD grown single crystal graphene array

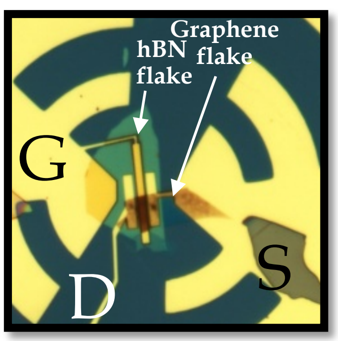


Graphene on hBN

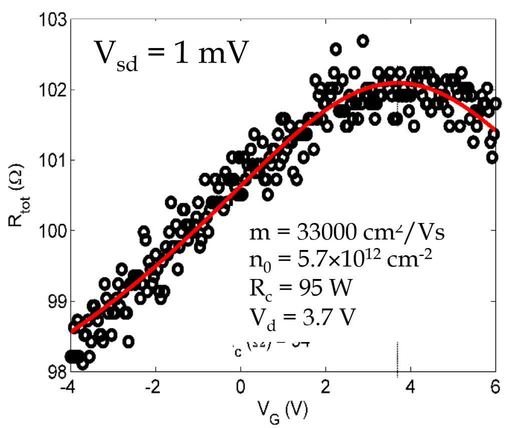
Top hBN



45 nm-thick hBN f

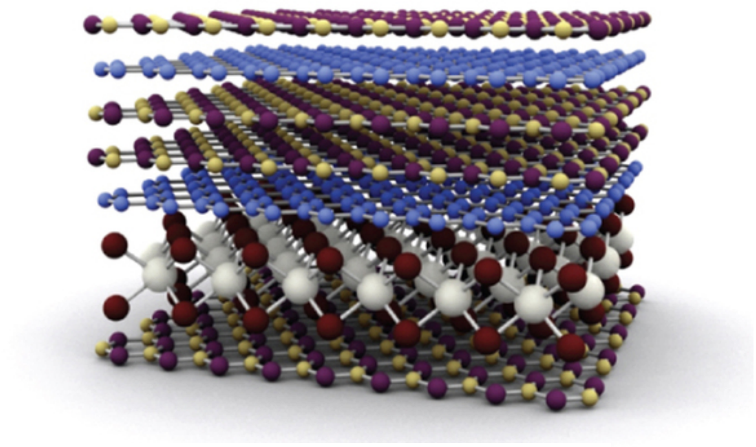


15 nm-thick hBN flake



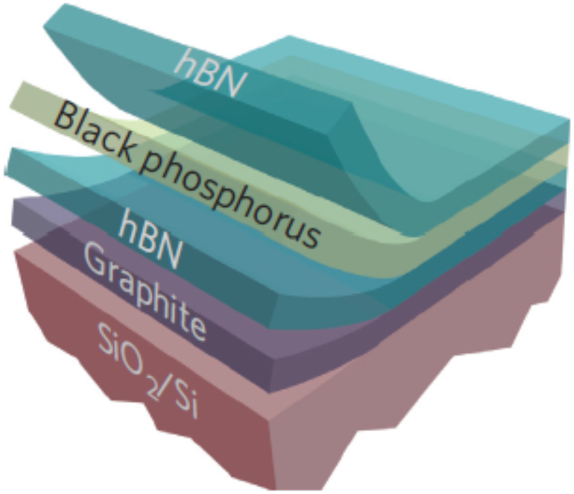
NEST

Van Der Waals Heterostructures: the Flat Land



Improved material properties by creating the «ideal» environment

BORON NITRIDE is a promising candidate:
- Impervious to water and oxygen
- High k dielectric
- No dangling Bonds



Examples:

hBN/Graphene/hBN samples

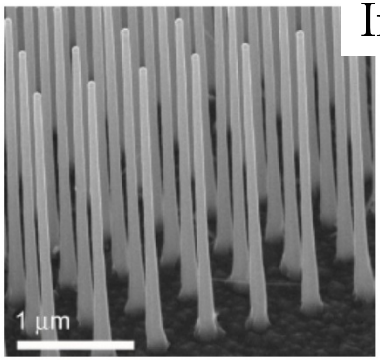
$\mu > 10^5\ cm^2/Vs$

hBN/BP/hBN Heterostructure

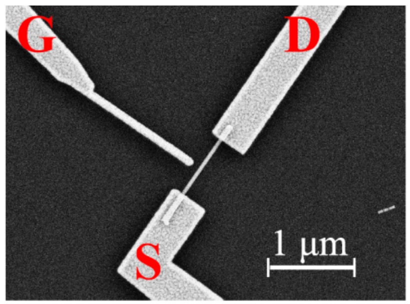
High Mobility
High Stability
[L.Viti, Adv. Mater. 2016]

THz Detection in nanostructures: Nanowire-FETs

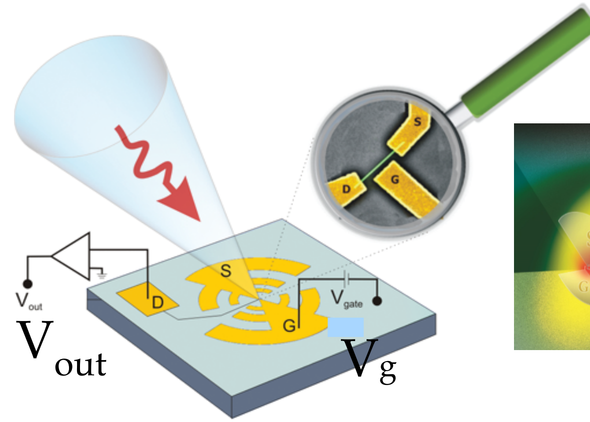
InAs NanoWires-FETs

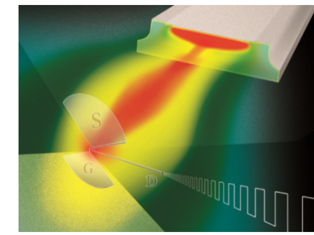


Viti et al., Nanoscale Research Letters ***7****, 159 (2012)*



Vitiello et al., Nano Letters ***12****, 96 (2012)*

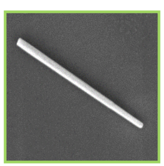


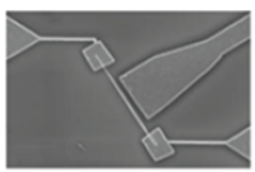


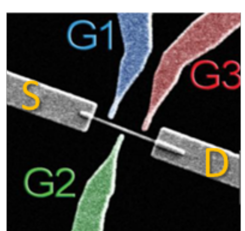
Room temperature
THz detectors
0.3 – 3.5 THz range

Optimization: materials, device design, antenna (*Vitiello M.S., APL Materials 2015*)

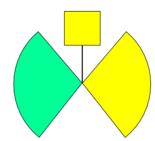
Homogeneous and Gradient-doped tapered InAs NWs



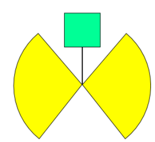




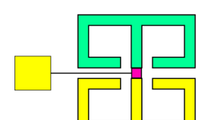
Asymm. Broad Band



Symm. Broad Band



Asymm. Narrow Band



300 GHz

$$R = 100\ \frac{\text{V}}{\text{W}}$$

$$\text{NEP} = 100\ \text{pW}/\sqrt{\text{Hz}}$$

National Enterprise for nanoScience and nanoTechnology

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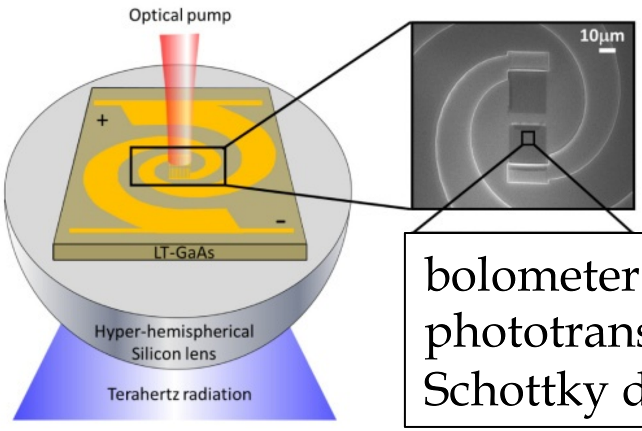
Sensing single photons at THz

Detector Scheme for free-space THz beams: quasi optical approach

Used also Photo-Conductive Antenna generators

- THz beam is focused, collected and converted by the antenna
- THz field is confined in a sub-wavelength region hosting the sensing element



bolometer
phototransistor
Schottky diode

•for certain applications an ultimately high sensitivity reaching a photon-counting level is required (direct detection of dark matter in a region of the parameters space difficult to reach with different techniques)

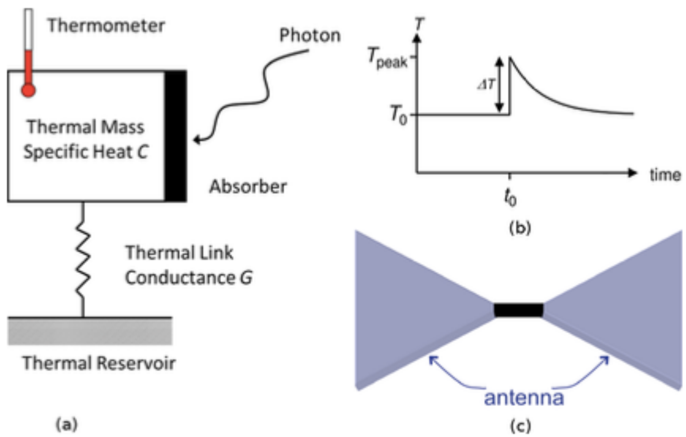
• in THz range E< 124 meV, λ> 10 μm: the single-photon detection is not trivial

With the available detector technologies, attainable sensitivities are currently far below the level of single-photon detection

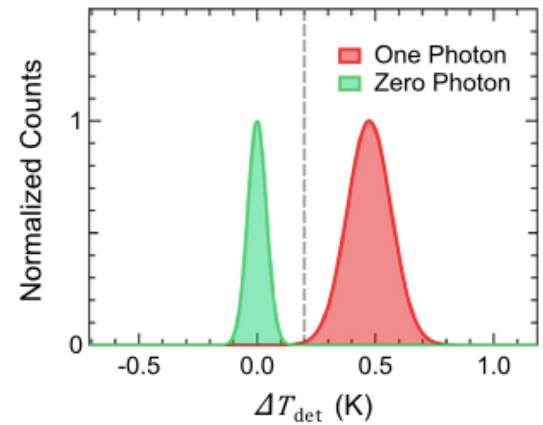
Graphene Bolometers

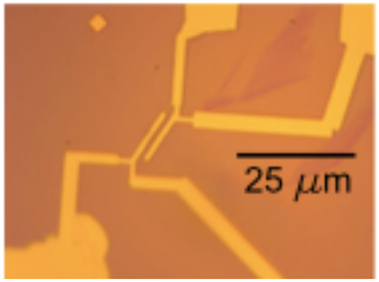
Key points:

•strong light-matter interaction and collective effects (plasma waves in the 2DEG)
•Transport dominated by Hot-Carrier
•Study on the thermal properties indicated the possibility to reach very high sensitivity as both a bolometer and as a calorimeter



T increase:
4 μm^2 channel,
100mK,
Superconding contatcts, el-phonon coupling very weak
…



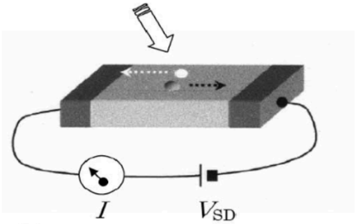


General Advantages
•Low Noise, Broadband absorption
•*Challenge: material purity, fabrication; many device contraints*

Nanostructured systems for THz Photon Counting

quantum devices based on nanostructured semiconductors have demonstrated single-photon detection capabilities in the THz range

Classical photodetector



(a)

$\mathrm{Isig}=G_{pc}{*}e{*}(\eta P_{in}/h\nu)$, $G_{pc}<1$ (gain)

$R= I_{sig}/P_{in} = 8\ A/W$

1photon – 1 electron, E=124 meV

Responsivity is limited, some Gain enhancement is needed

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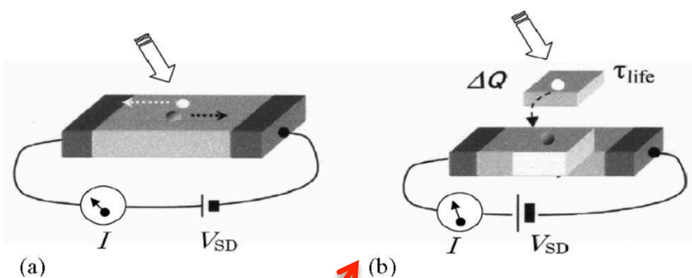
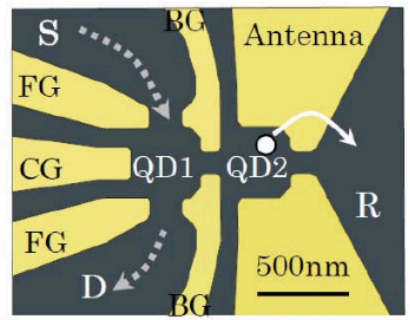
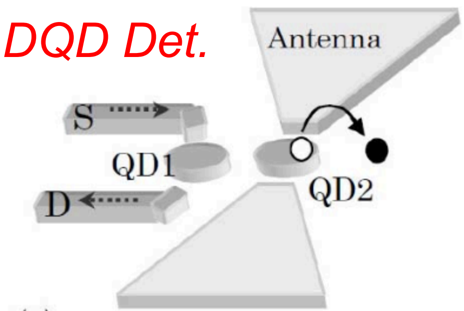


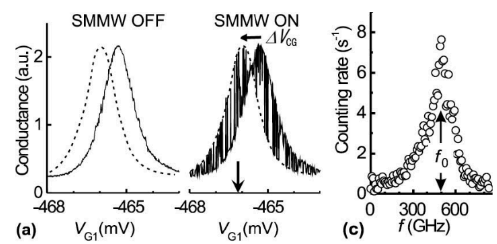
Novel nanostructure-based detector



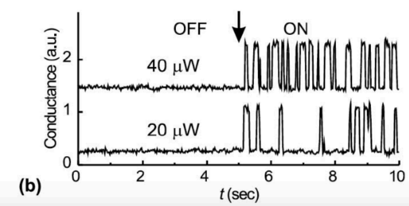
DQD Det.



1-QD charging by 1-photon abs
2-sensing the 1QD via conductance in QPC or SET



Komiama, IEEE JSTQE 2011,
See also F. Gatti talk

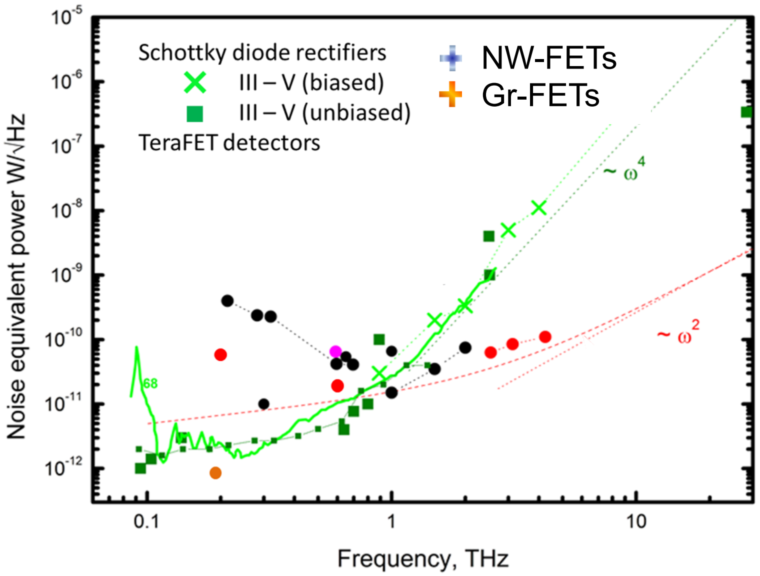


P_{in} 10^{-18}W
every skip is single photon!
Dark count 10^{-2} s^{-1}

Robust and reliable metrologies for single-THz photons are still lacking
Why not to implement device concepts on QD+new materials?

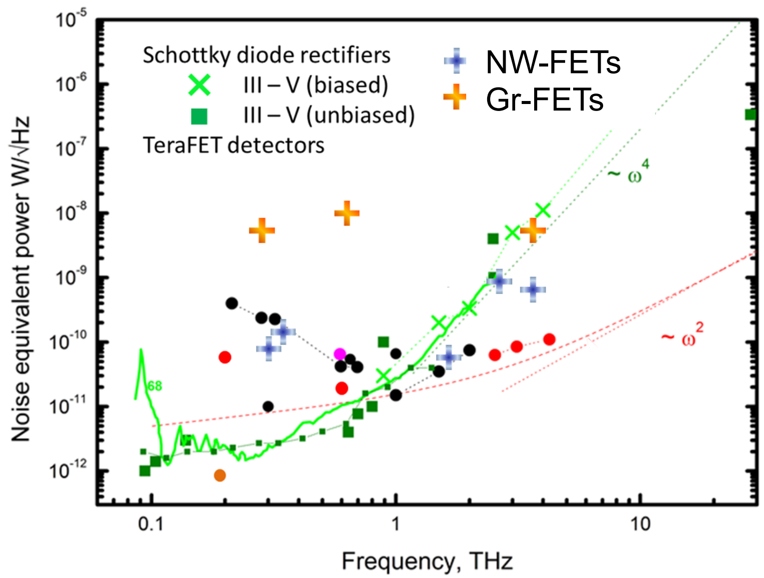
Conclusion

- Detection demonstrated from 0.2 THz up to 3.4 THz in Semiconductor Nanostructures (2D systems, Graphene, Nanowires)



Conclusion

- Detection demonstrated from 0.2 THz up to 3.5 THz in Semiconductor Nanostructures (2D systems, Graphene, Nanowires)



Conclusion

- Detection demonstrated from 0.2 THz up to 3.5 THz in Semiconductor Nanostructures (2D systems, Graphene, Nanowires)
- Detection signals related to plasma wave effects in the 2D electronic system, but also other contributions
- Antenna, device design and material are degrees of freedom for detectors optimization
- Present-days performances enabled most of room-T applications
- Quantum confinement in nanostrucutured and/or intrinsic low-dimensional materials is a potential playground for photon counters in the terahertz range

Aknowledgments

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- Tredicucci's Group@NEST, Federica Bianco

- Miriam Vitiello, Leonardo Viti, THz Group@NEST
- Camilla Coletti, Graphene Group@IIT NEST

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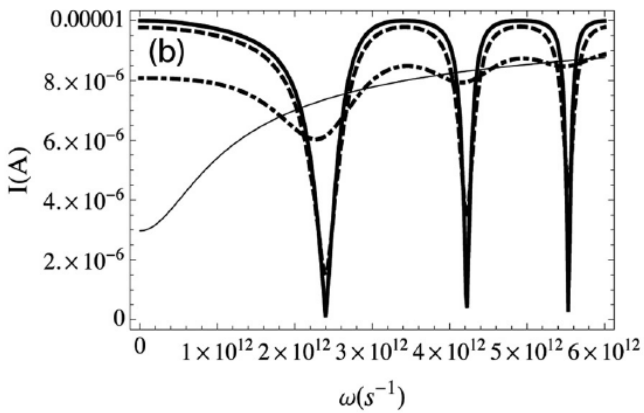
High mobility AlGaAs/GaAs heterostructure



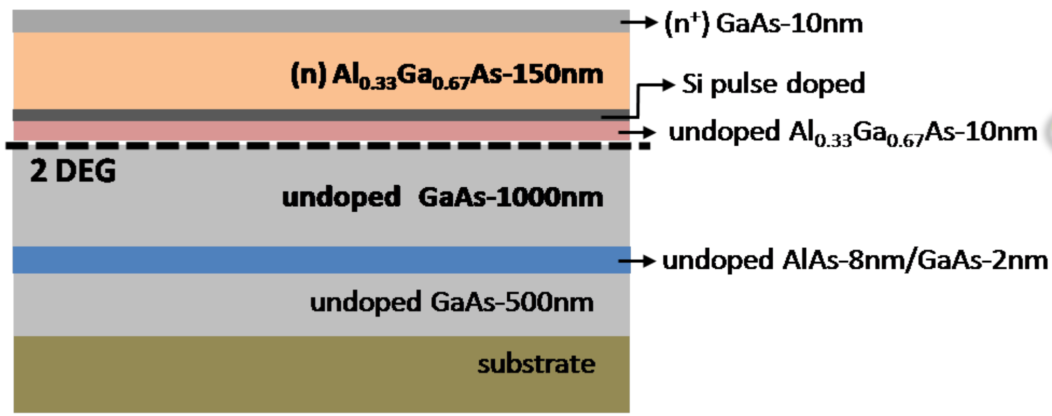
$\mu = 10^3 cm^2 / Vs$

$\mu = 10^4 cm^2 / Vs$

$\mu = 10^5 cm^2 / Vs$

$\mu = 10^{10} cm^2 / Vs$

with $L = 1\mu m$, $n_0 = 10^{11} cm^{-2}$, $\varepsilon = 12.6$



$$\mu(T = 10K) \approx 300.000 cm^2 / Vs$$

$$\tau_{transit} = L_{cav} / s = 5 ps$$

$$\tau_{damp} = \frac{\mu m^*}{e} = 9 ps$$

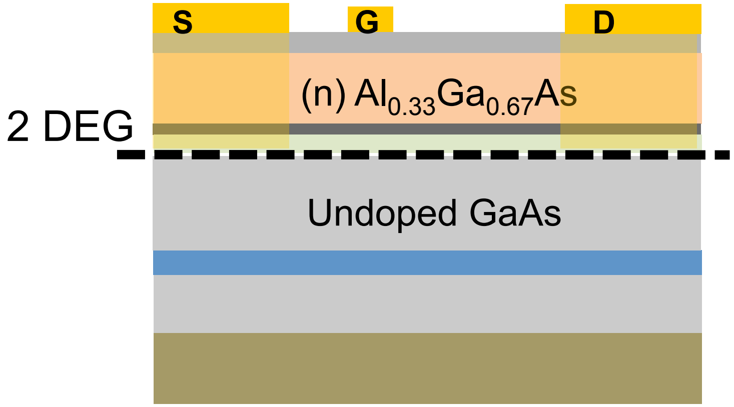
$$\tau_{transit} / \tau_{damp} \approx 0.5$$

$$\omega\tau_{damp} = 10 \div 20 @ 200 GHz$$

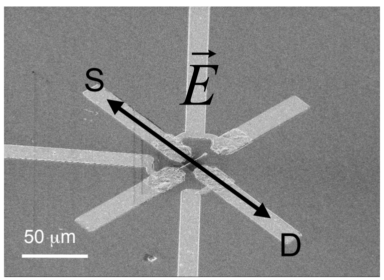
Resonant plasmons: reduced electron-phonon scattering suppresses the plasmon-phonon decay channel

Heterostructure provided by CNR-IOM, Trieste, Italy

Antenna integrated-HFET



- **Ohmic contact**: evaporation of metal (Ge/Au/Ni multilayer) and Rapid Thermal Annealing
- **Electrical isolation of devices**: ion implantation
- **Gate contact**: evaporation of Ti/Au

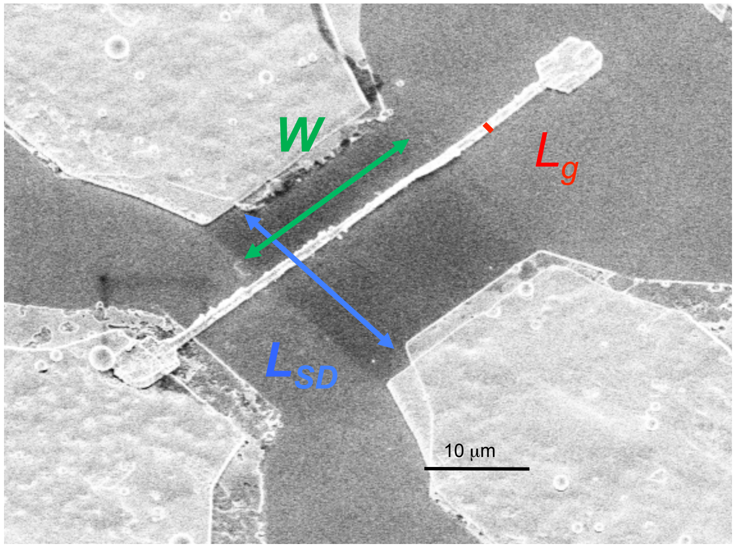


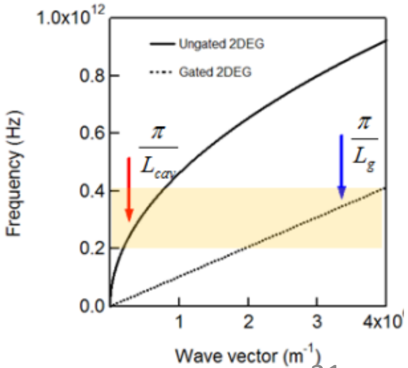
Two perpendicolar linear dipole antenna: one connected to the **source and drain terminals**, and the other connected to the **source and gate terminals**.

L_{SD}=10μm
L_{SG}=2.5μm
L_{GD}=7μm
L_g=500nm
W=10μm

THz excitation of a "2DEG diode"

- Two-terminal device with asymmetric design
- Hydrodinamic regime of the ungated 2DEG in the investigated spectral range

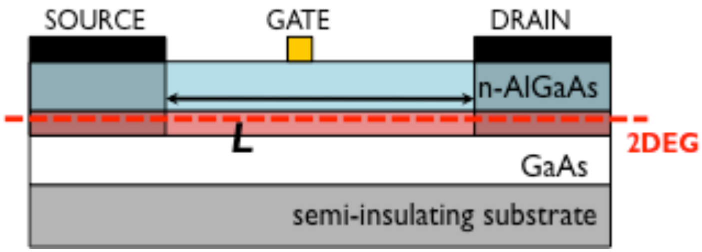


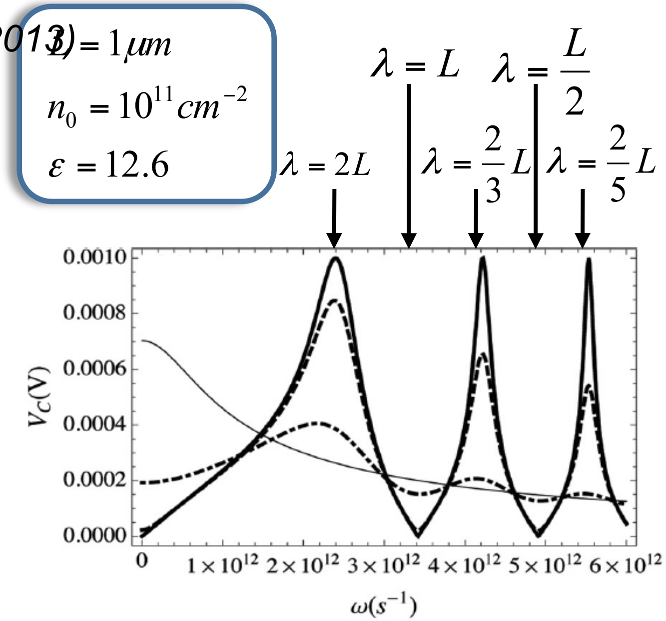


Plasma wave devices

Electrodynamics equations for the 2DEG

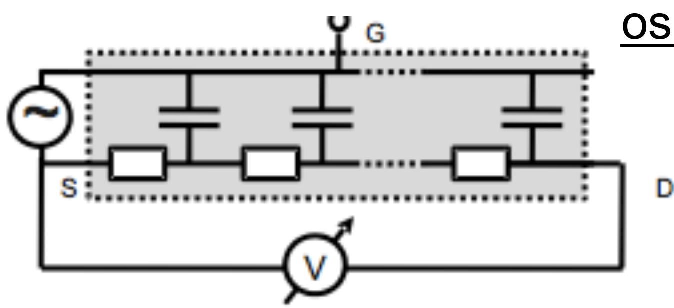
F. Evangelisti, *Journal of Applied Physics 114, 124506 (2013)*





$$Z_{2DEG} = \frac{-i\beta}{\varepsilon\omega kW}\left(\frac{1-\cos kL}{\sin kL}\right)$$

Equivalent Circuit:



<u>The 2DEG impedance oscillates as function of frequency</u>