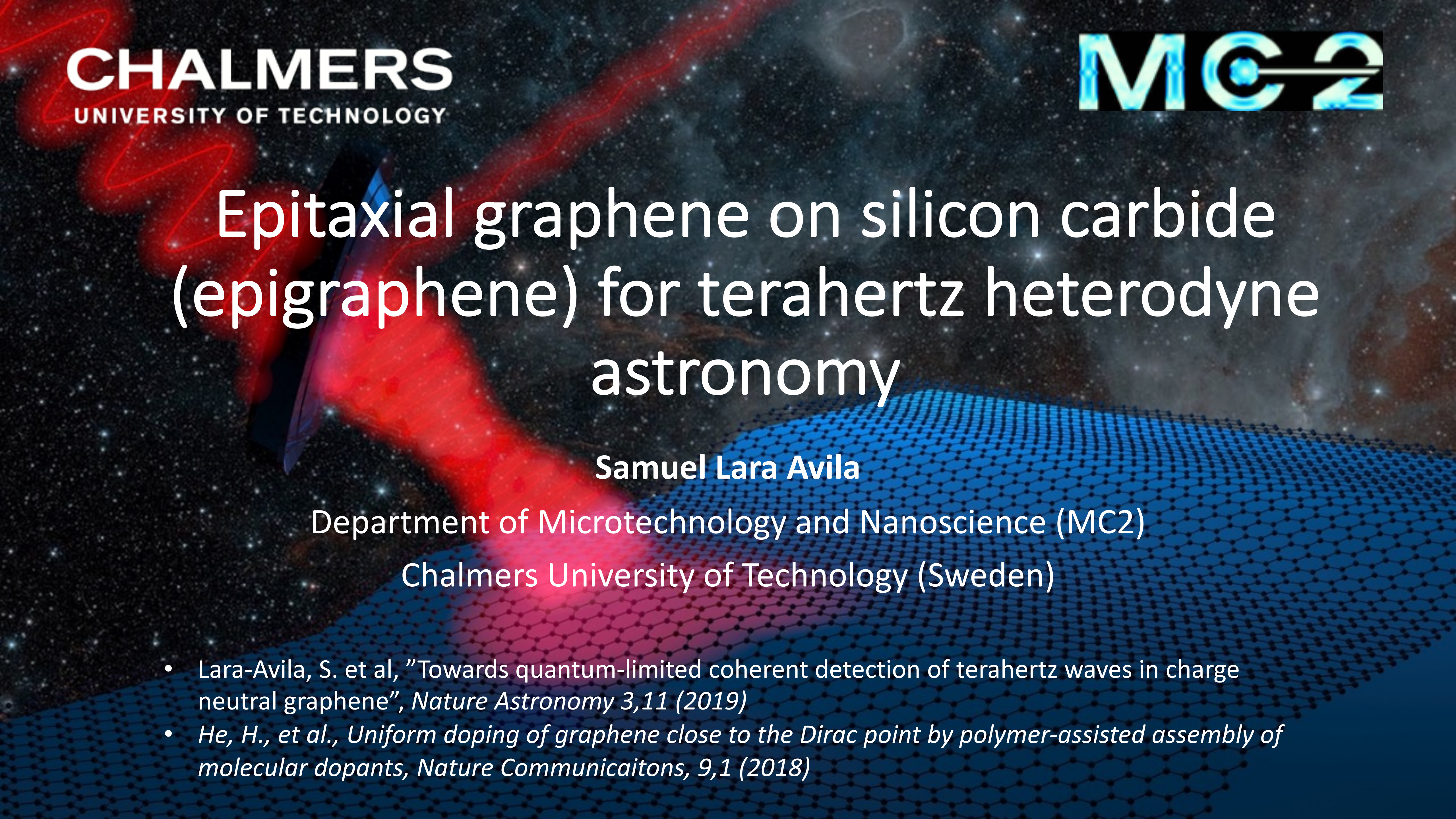

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MC2

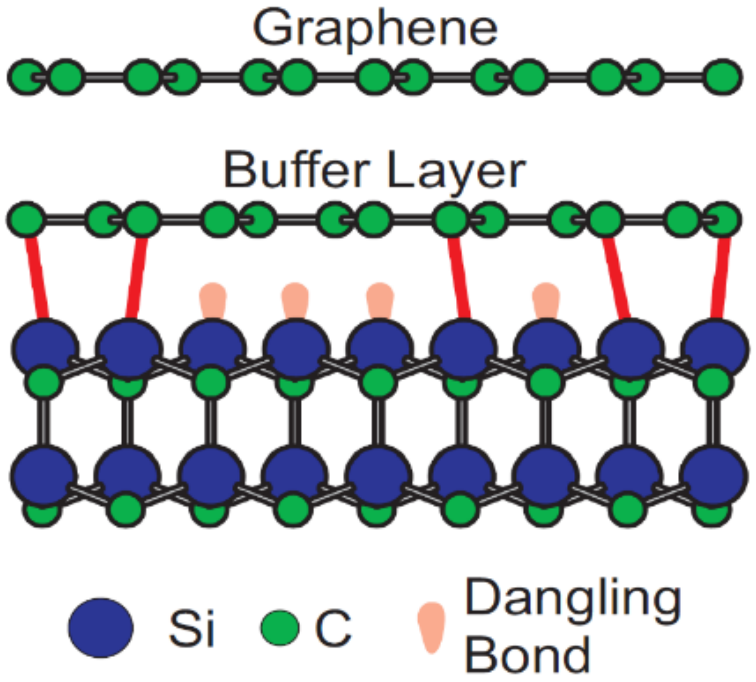
Epitaxial graphene on silicon carbide (epigraphene) for terahertz heterodyne astronomy

Samuel Lara Avila

Department of Microtechnology and Nanoscience (MC2)
Chalmers University of Technology (Sweden)

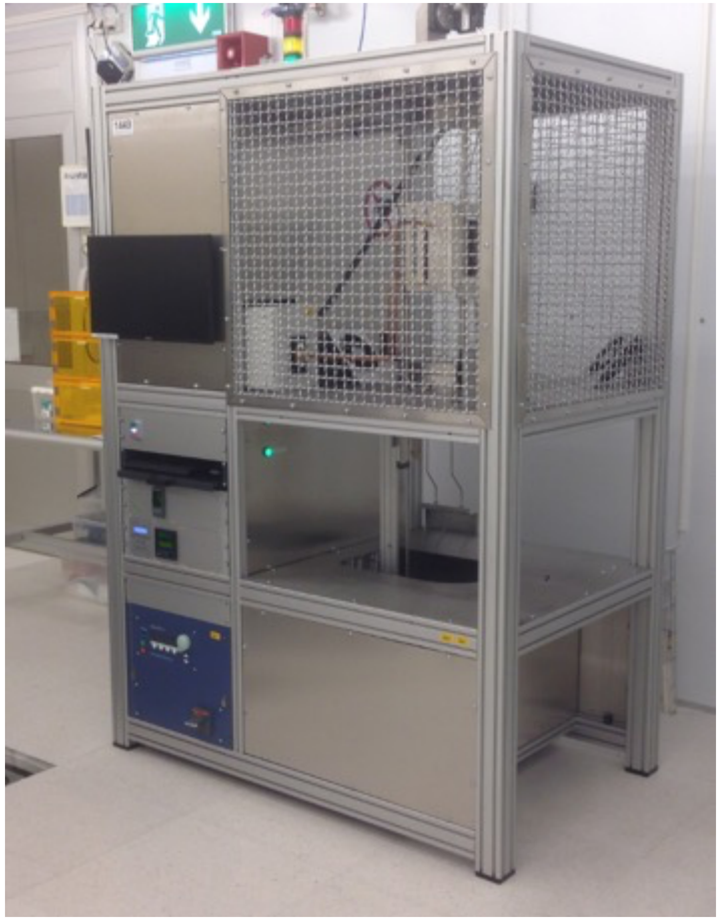
- Lara-Avila, S. et al, ”Towards quantum-limited coherent detection of terahertz waves in charge neutral graphene”, *Nature Astronomy 3,11 (2019)*
- *He, H., et al., Uniform doping of graphene close to the Dirac point by polymer-assisted assembly of molecular dopants, Nature Communicaitons, 9,1 (2018)*

Epigraphene: Epitaxial graphene on silicon carbide



Adapted from C. Riedl, PRL 103 (2008)

T = 2,000C; P= 1 atm Ar

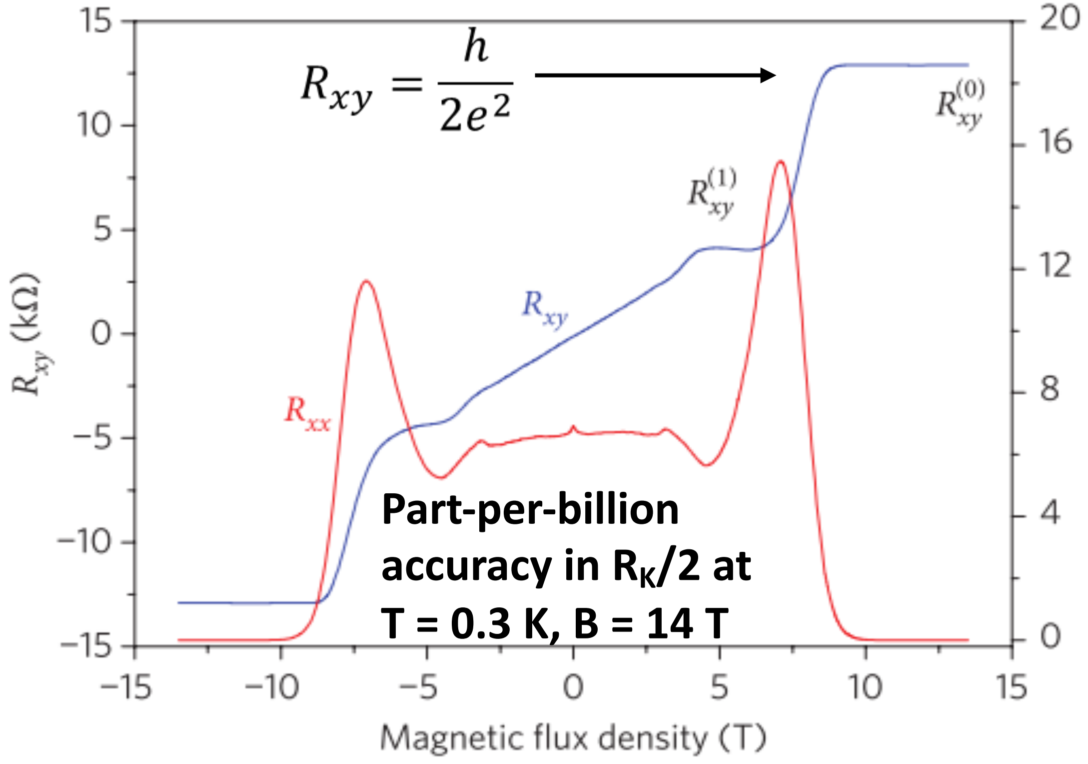


R. Yakimova. Linköping, Sweden. Phys. Rev. B (2008)

Epigraphene: Technology evolution over a decade

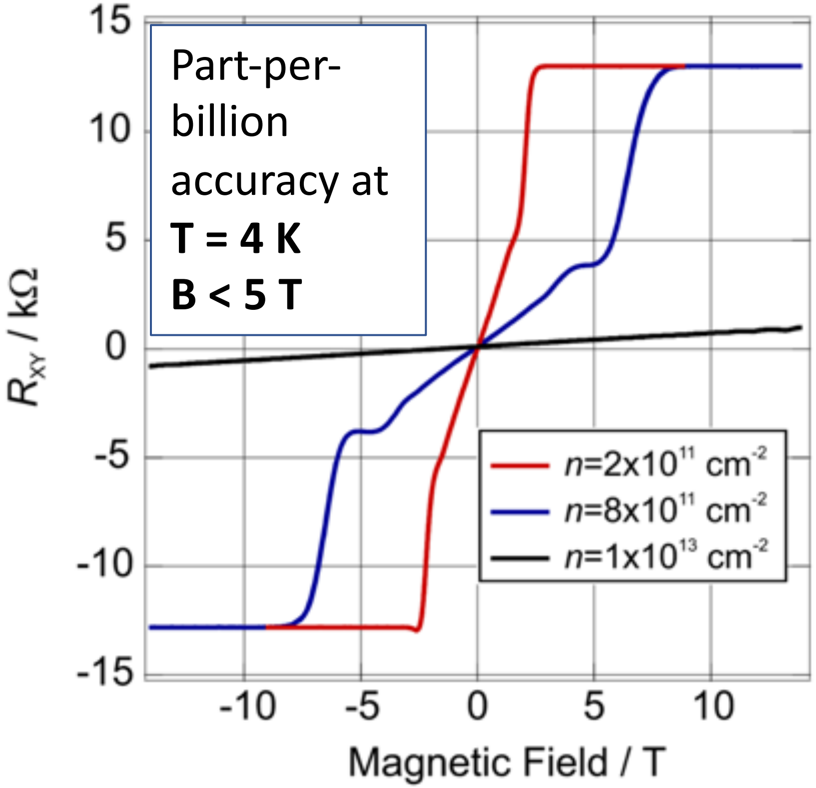
Tzalenchuk, Lara-Avila, Kubatkin, et al., Nat. Nano. **(2010):** Graphene is comparable or better than conventional GaAs technology.

Von Klitzing constant = $R_K/2 = h/2e^2$ ~ 12.9064...kΩ



Part-per-billion accuracy in $R_K/2$ at T = 0.3 K, B = 14 T

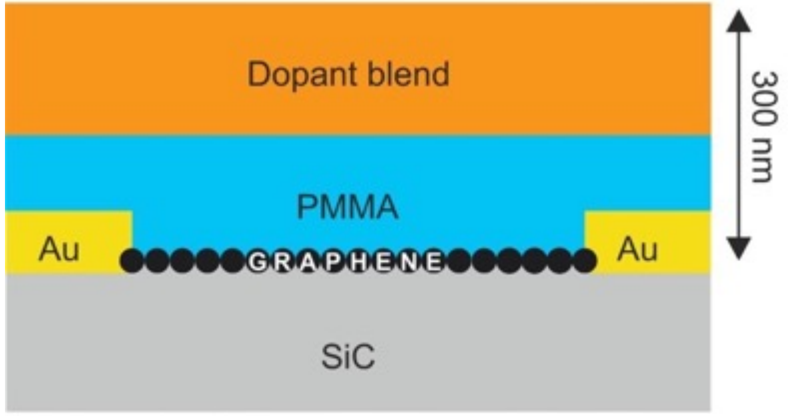
He, Lara-Avila, Kubatkin, **Metrologia (2019):** Graphene is the material of choice for quantum metrology of electronic quantities: The Ohm (**Ω**) and the kilogram **(kg)** as of May 20th, 2019.



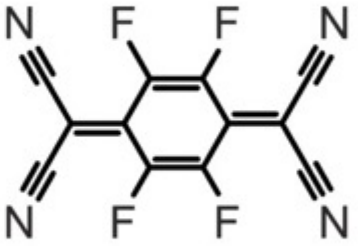
Part-per-billion accuracy at
T = 4 K
B < 5 T

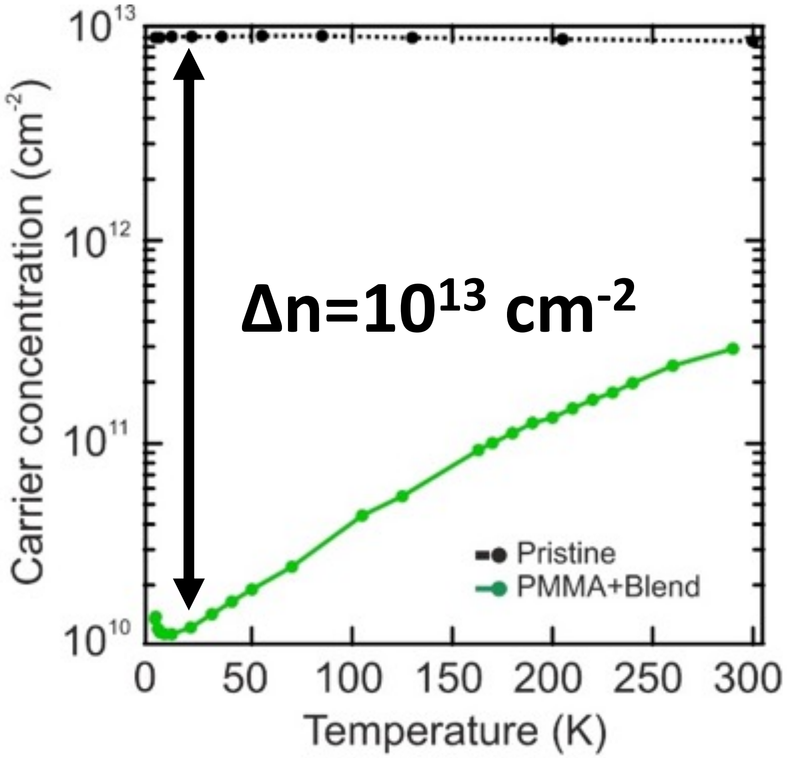
Chemical doping of epigraphene withF4TCNQ-PMMA

PMMA and Dopant blend (F4TCNQ-PMMA) spin coated on graphene



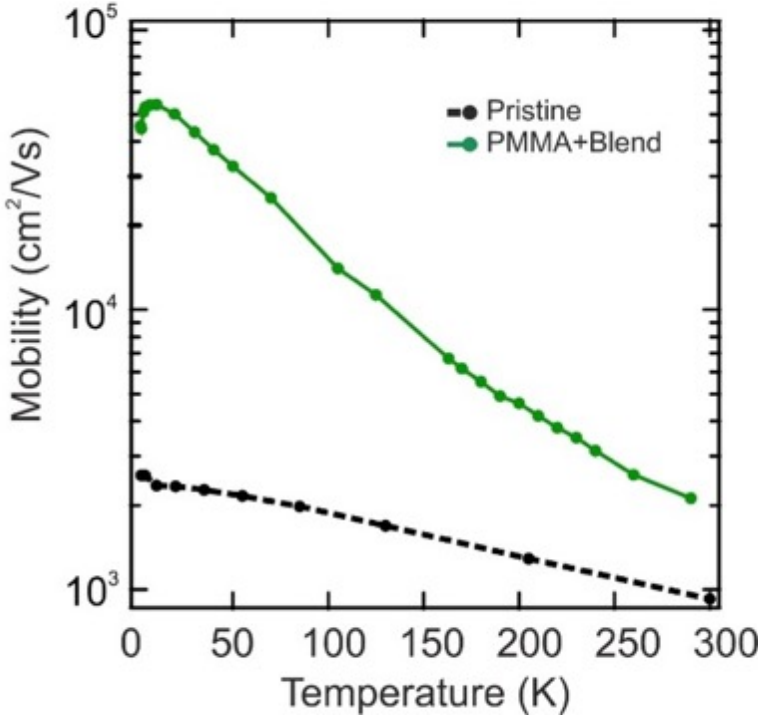
F4TCNQ





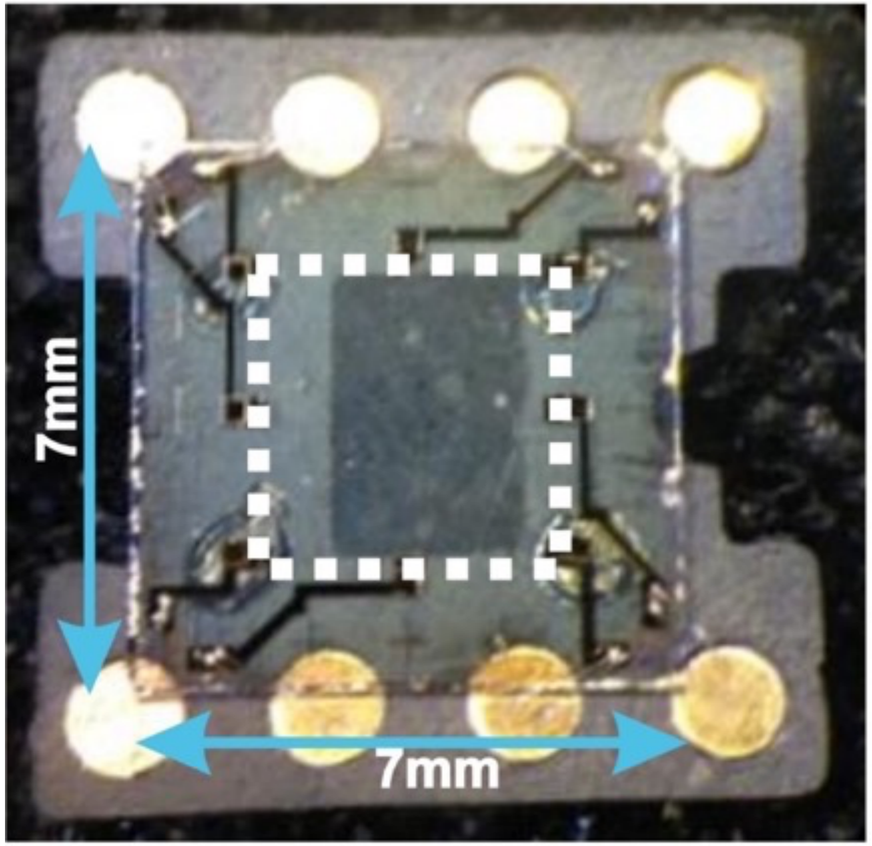
Mobility

~ 50,000 cm^2/Vs



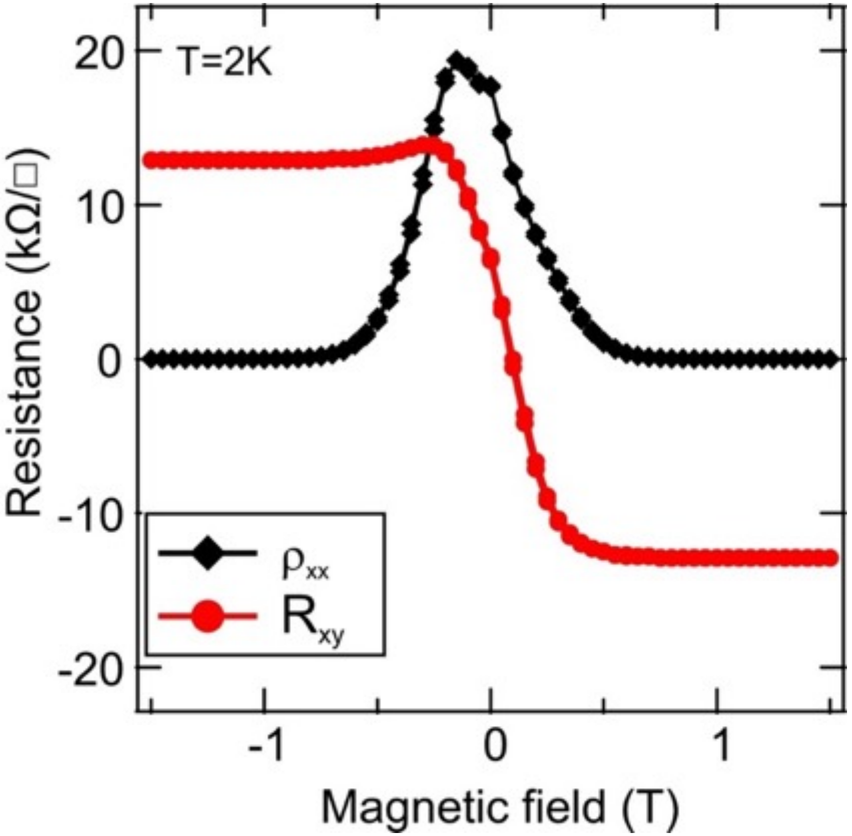
He, H., Lara-Avila, et. al, Nat. Communications 9, 3956 (2018)

Chemical doping is homogeneous over chip scale

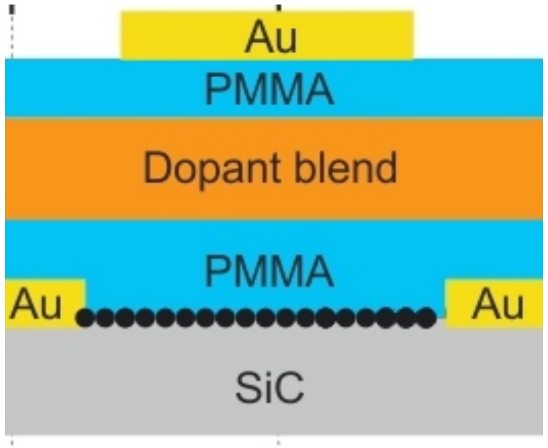


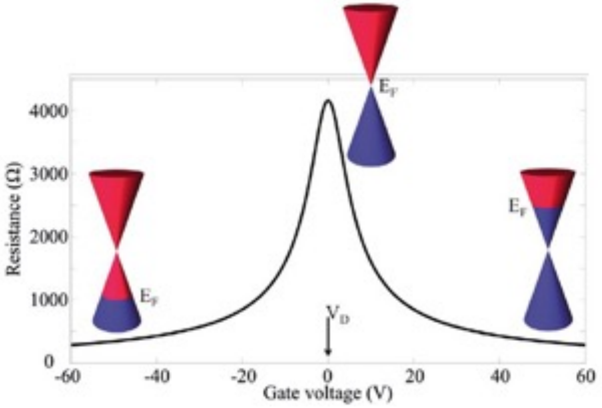
QHE in 5x5 mm2 substrate

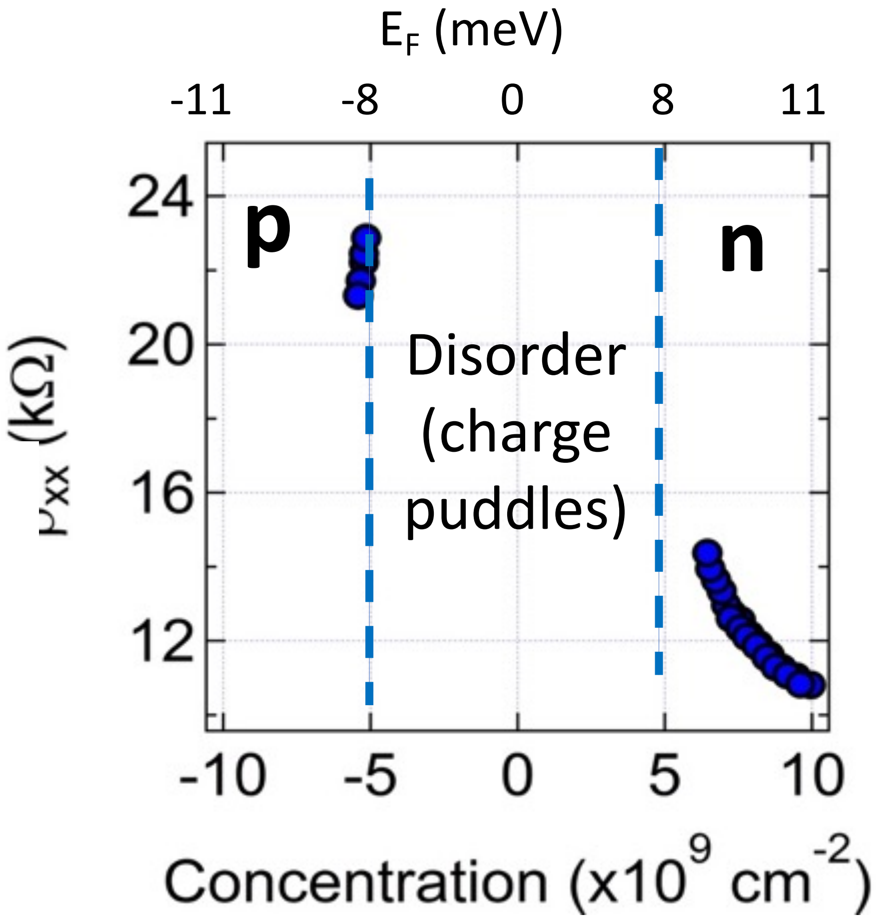
μ = 39,000 cm^2/Vs, p = 9x10^9 cm^{-2} (holes)



Very close to Dirac point by chemical doping



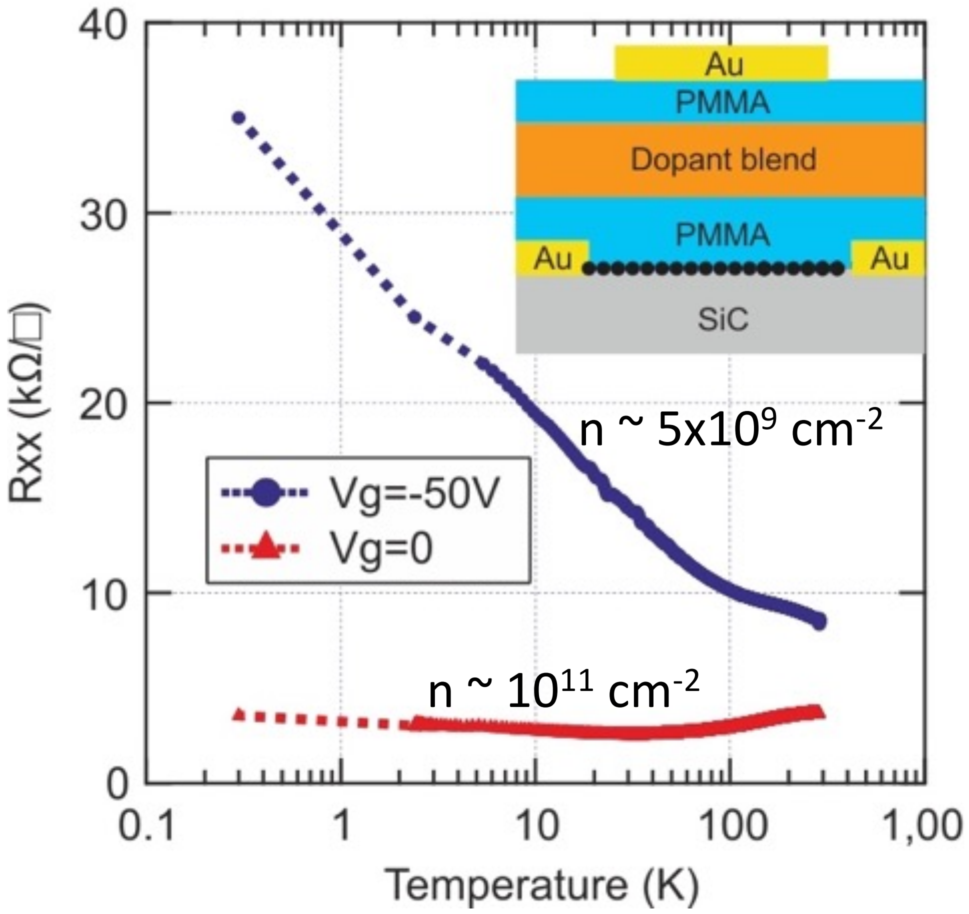




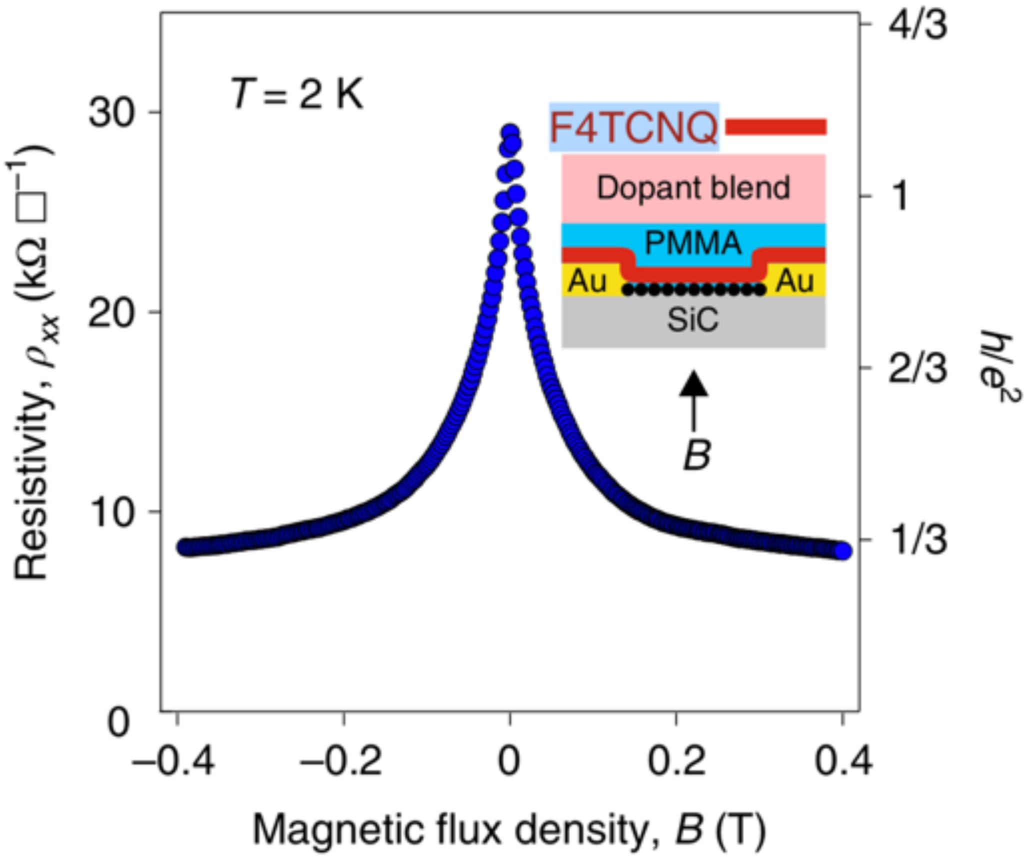
Suspended graphene (Mayorov et al.)	1 meV
Exfoliated Graphene/hBN (S.C. Martin et al.)	5 meV
SiC/G (this work)	**8 meV**
Flakes on SiO_2 (Y. Zang et al.)	20-50 meV

He, H., Lara-Avila, et. al, Nat. Communications 9, 3956 (2018)

Logarithmic temperature dependence of resistance at low doping



n ~ $5x10^9$ cm^{-2}

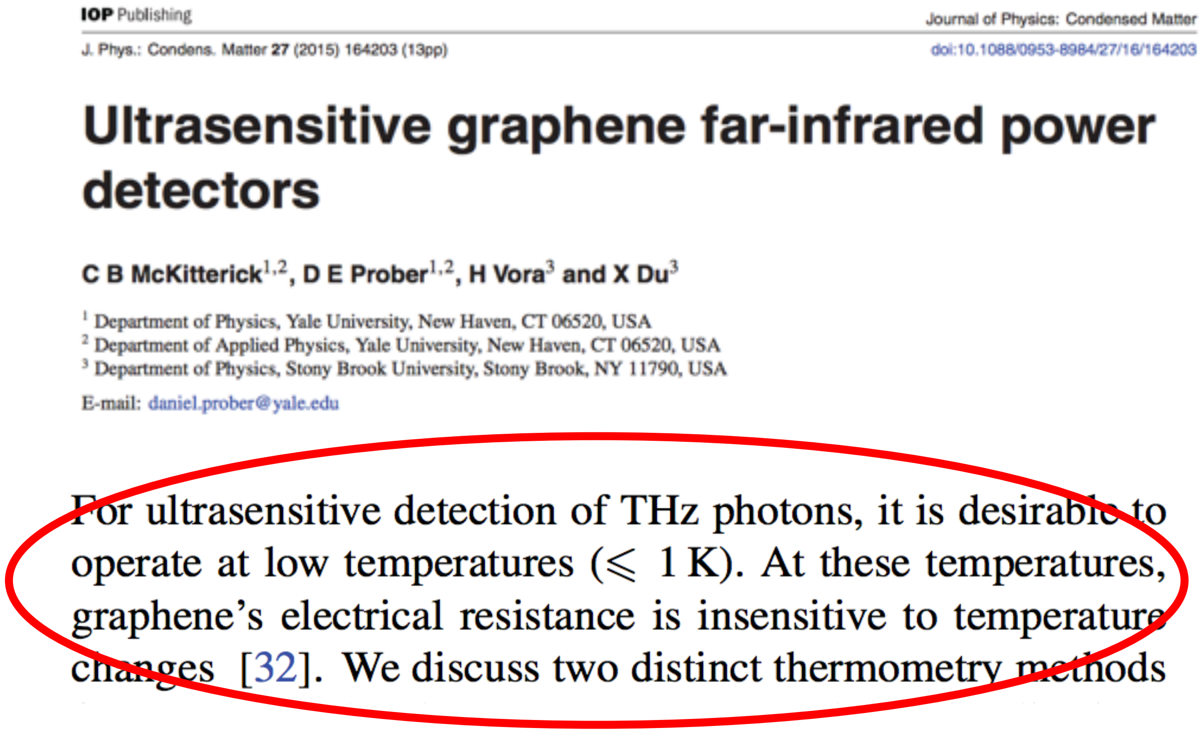


Quantum interference effects leads to weak localization (negative magnetoresistance)

Lara-Avila, et. al. Phys. Rev. Lett. **115** (2015)

Lara-Avila, et. al, Phys. Rev. Lett. **107** (2011)

…but graphene was known to have dR/dT~0 at low temperatures



IOP Publishing
Journal of Physics: Condensed Matter
J. Phys.: Condens. Matter **27** (2015) 164203 (13pp)
doi:10.1088/0953-8984/27/16/164203

Ultrasensitive graphene far-infrared power detectors

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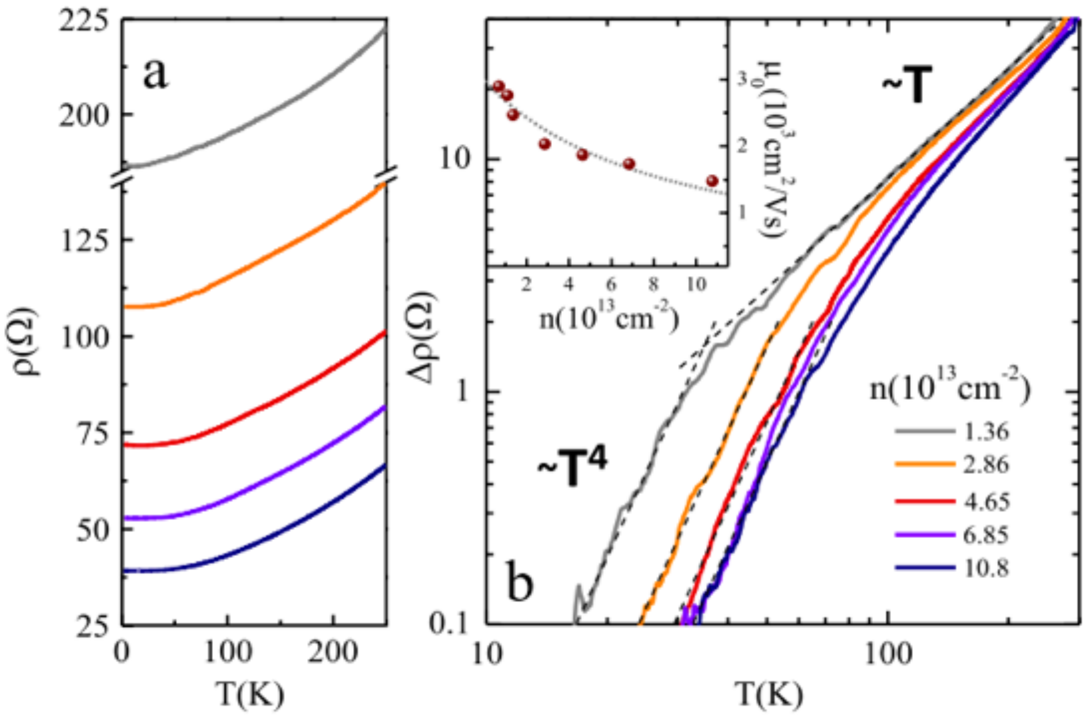
[3] Department of Physics, Stony Brook University, Stony Brook, NY 11790, USA

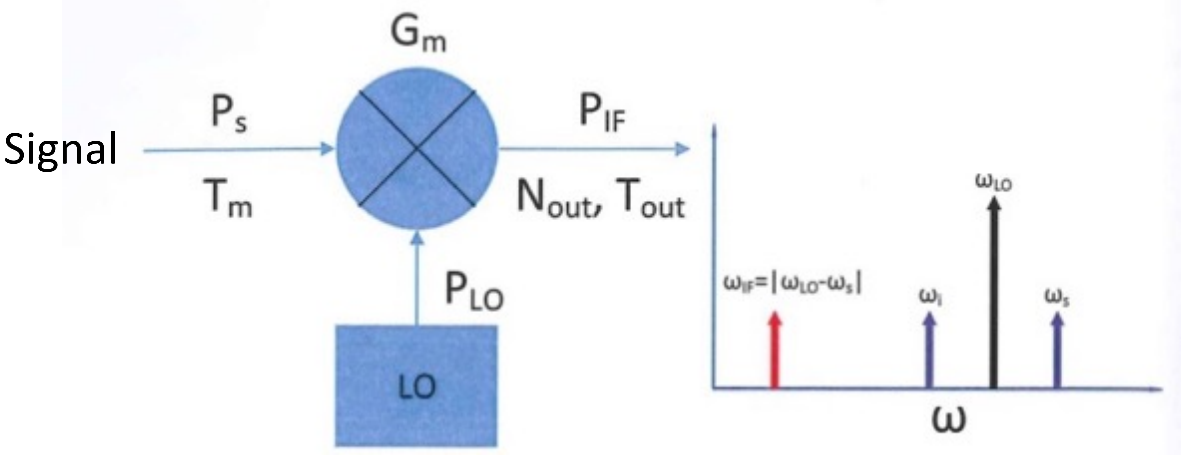
E-mail: daniel.prober@yale.edu

For ultrasensitive detection of THz photons, it is desirable to operate at low temperatures ($\lesssim$ 1 K). At these temperatures, graphene's electrical resistance is insensitive to temperature changes [32]. We discuss two distinct thermometry methods



PRL **105,** 256805 (2010)

Principle and implementation of heterodyne detection

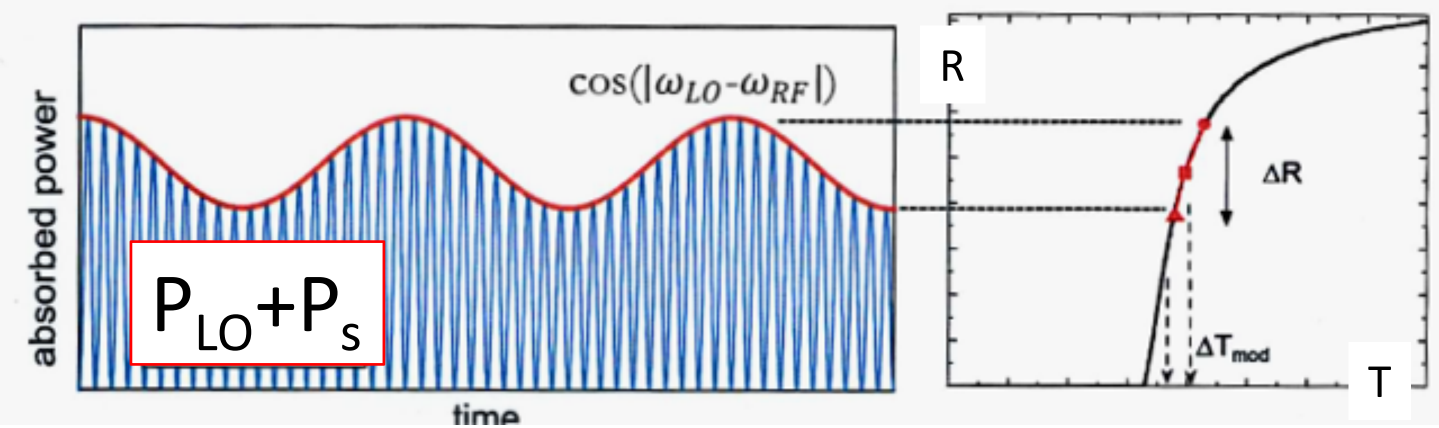

Mixer (multiplier), with gain G_M

Local Oscillator (LO)

$$sin(\omega_1 t)sin(\omega_2 t) = \frac{1}{2}[cos(\omega_1 - \omega_2)t)] - \frac{1}{2}[cos(\omega_1 + \omega_2)t)]$$

IF = Intermediate frequency = abs $(\omega_1-\omega_2)$

Implementation with e.g. superconductors

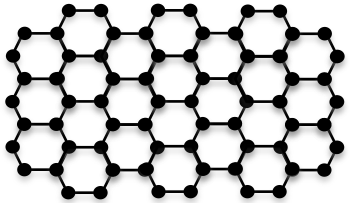


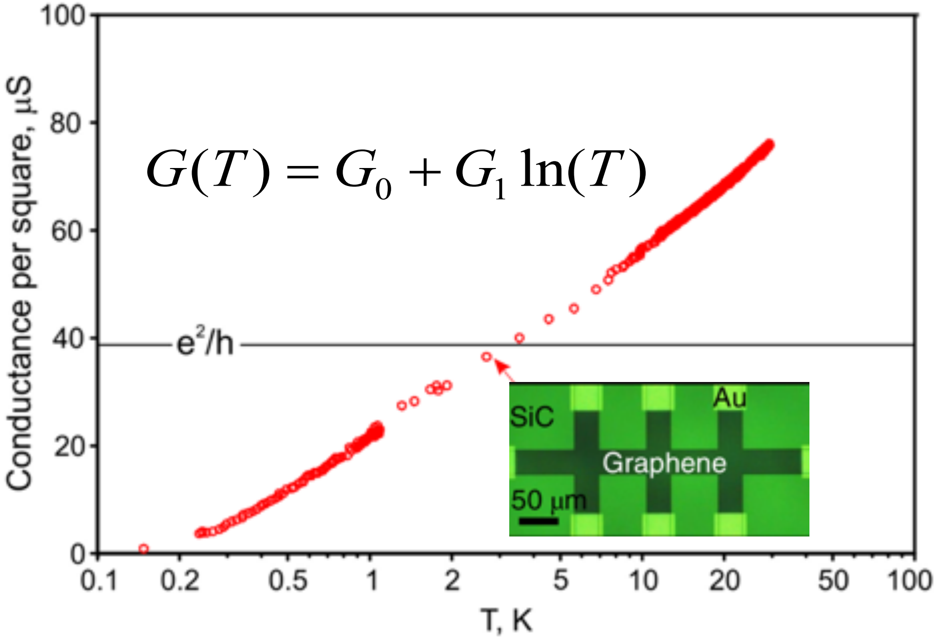
THz astronomy has been dominated by **superconducting NbN** and other hot electron bolometers

- Limited bandwidth – electron-phonon interaction is weak
- Relatively high heterodyne power – at least for for high speed devices (MgB_2) - prohibiting making arrays of sensors
- Sensitivity is 10 times the quantum limit

Can graphene help?

Charge neutral epigraphene for bolometric-type of detectors

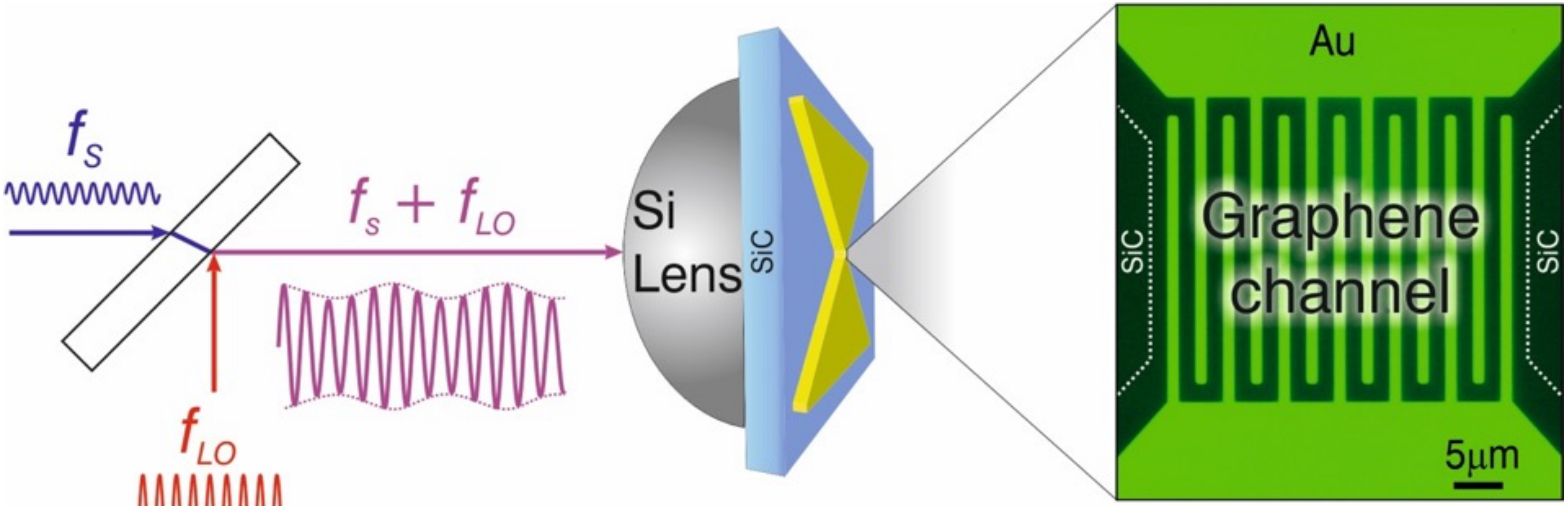




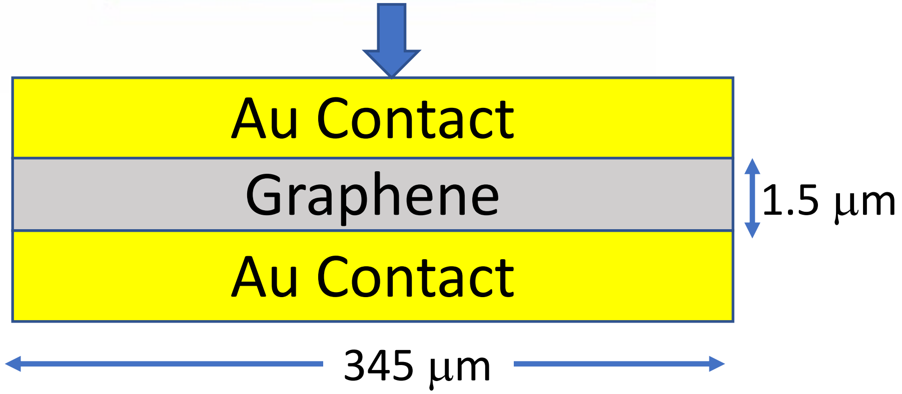
1. **Logarithmic temperature** -> diverging sensitivity of the resistive readout d*R*/d*T* ~ $T^{-1} ln^{-2}(T)$ at low Temp.
2. **Low heat capacity of graphene** -> fast operation
3. **But, electron–phonon cooling time τ_{e-ph} ~ $n^{-0.5}T^{-2}$ diverges at charge neutrality and low Temp** ->slow operation.
4. **Other cooling pathways:** electron diffusion cooling.

$$\tau_D = L^2/(\pi^2 D)$$

Experimental setup in a nutshell



Equivalent
Geometry



Au Contact

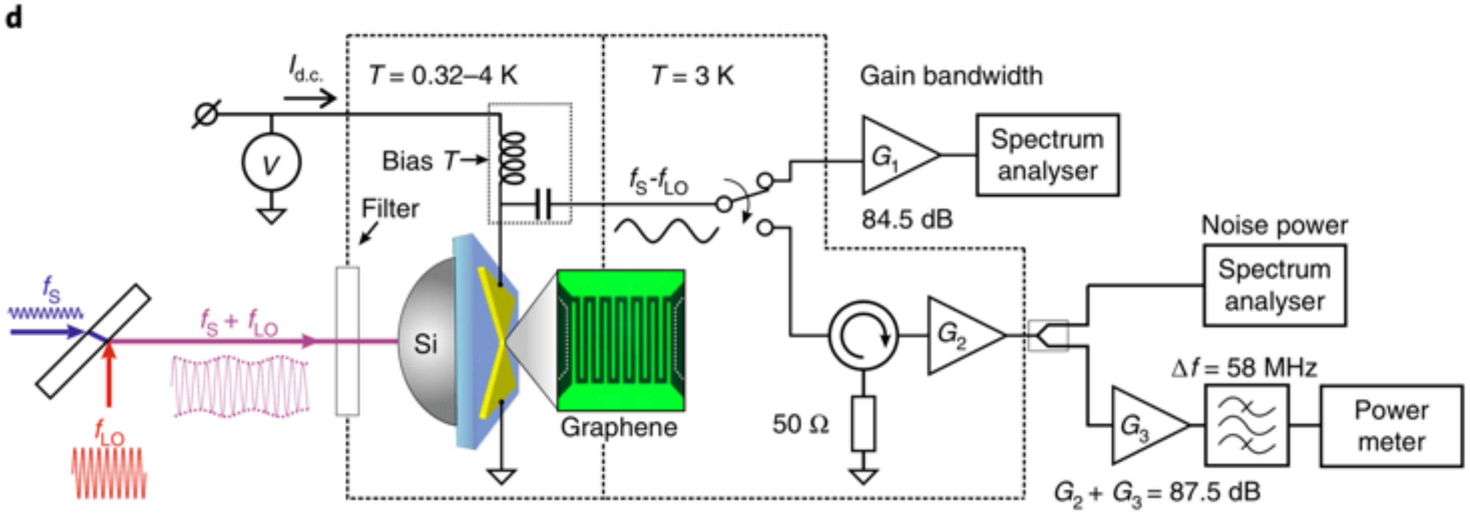
Graphene

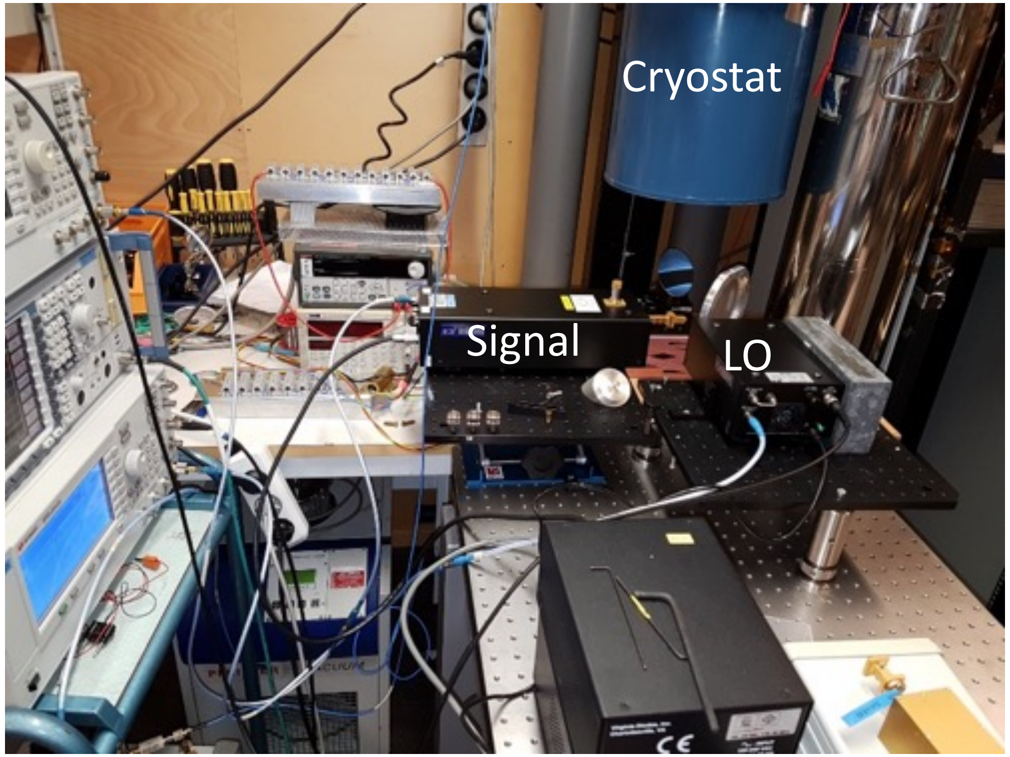
Au Contact

1.5 μm

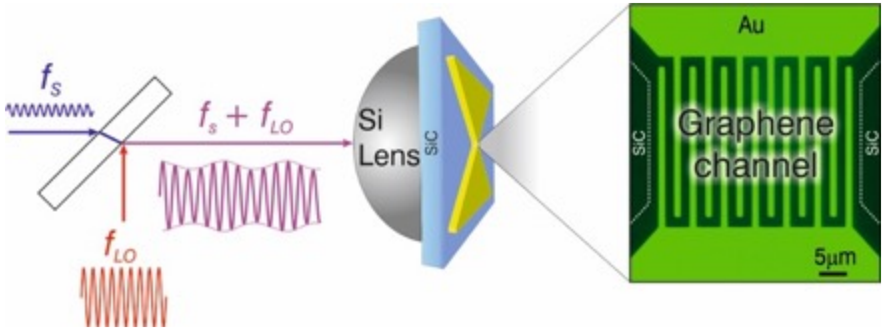
345 μm

Experimental setup in more detail





AC characterization: The device is faster than NbN!

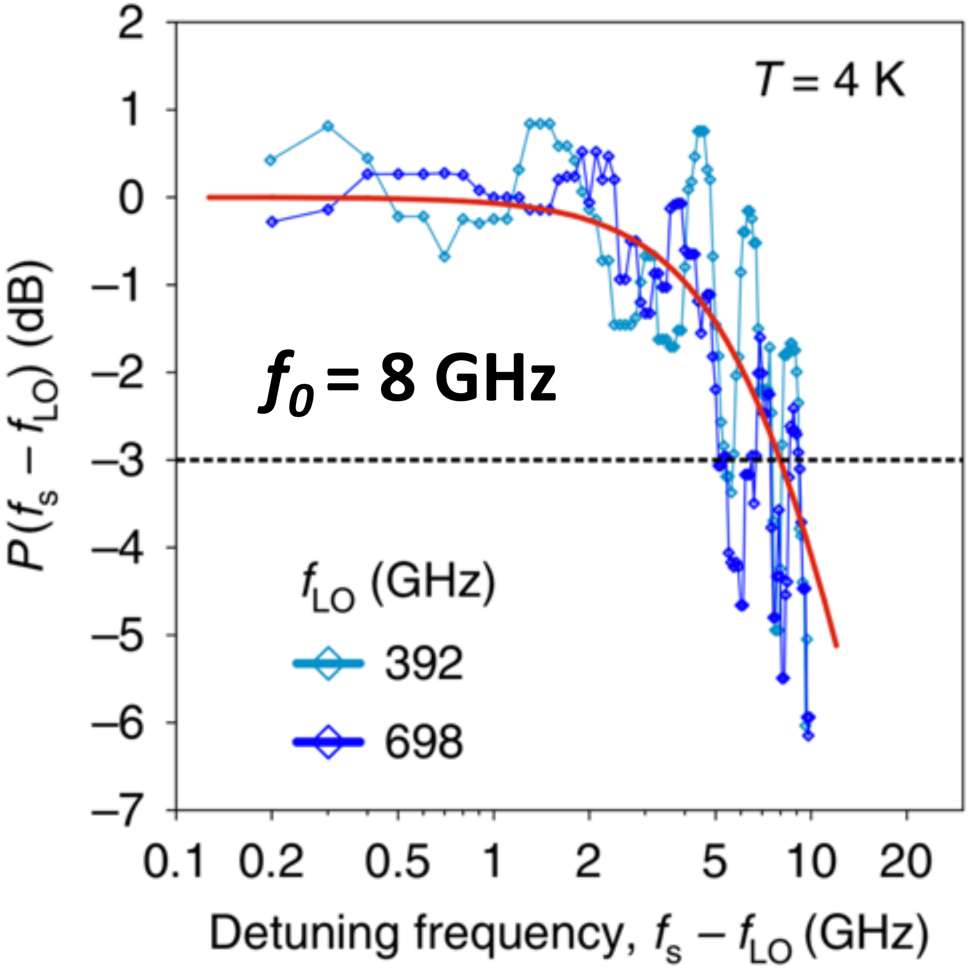


Time constant: $1/(2\pi f_0) = 20\,\mathrm{ps}$

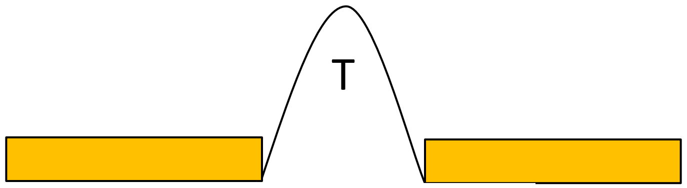
From diffusion cooling:

$$\tau_D = (1.5\mu m)^2/(\pi^2 0.01 m^2/s)) \approx 15ps$$

For **NbN, *f_0* < 5 GHz** (see e.g. Astron.Astrophys. 5218, L6 (2010) and IEEE Trans. Terahertz Sci. Technolo. 8. (2018))



Diffusion cooling model (Dima Golubev @Aalto University)



$$G(T) = G_0 + G_1 \ln(T)$$

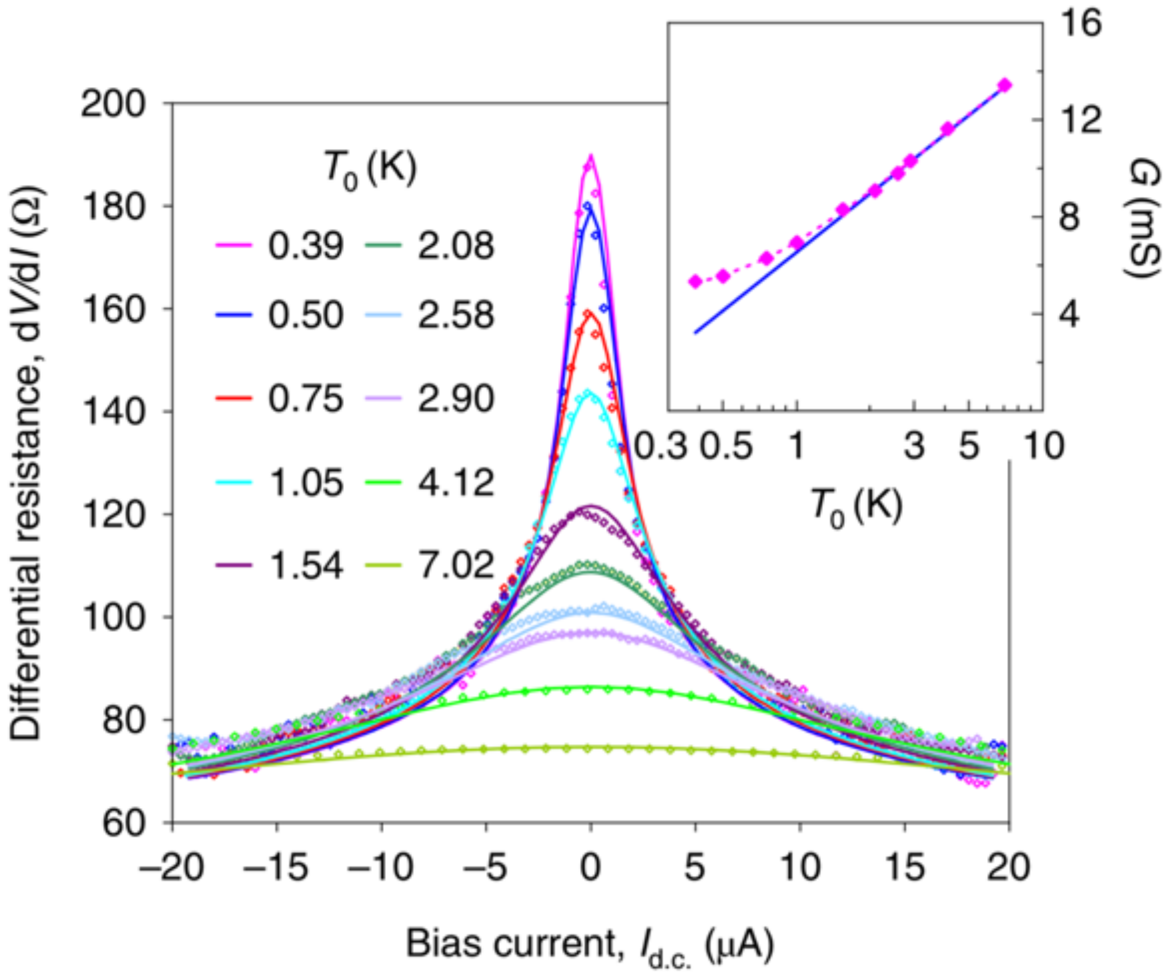
Joule heating balanced by diffusive cooling: charge carriers dissipate heat in the metallic leads

$$I(V) = G(T_0)V + G_1 V\left(\frac{\sqrt{1+u^2}}{u}\left(\sqrt{1+u^2}+u\right) - 1\right)$$

$$u = \frac{1}{V_{\mathrm{T}}}\sqrt{V^2 + \frac{V}{I}P_{\mathrm{ac}}} \qquad V_{\mathrm{T}} = \sqrt{\mathcal{L}} \times T_0.$$

P_{ac}= Optical power that couples to graphene

Differential resistance with THz source OFF



Fitting parameters:

Lorenz number, L=3.1X10^{-8}

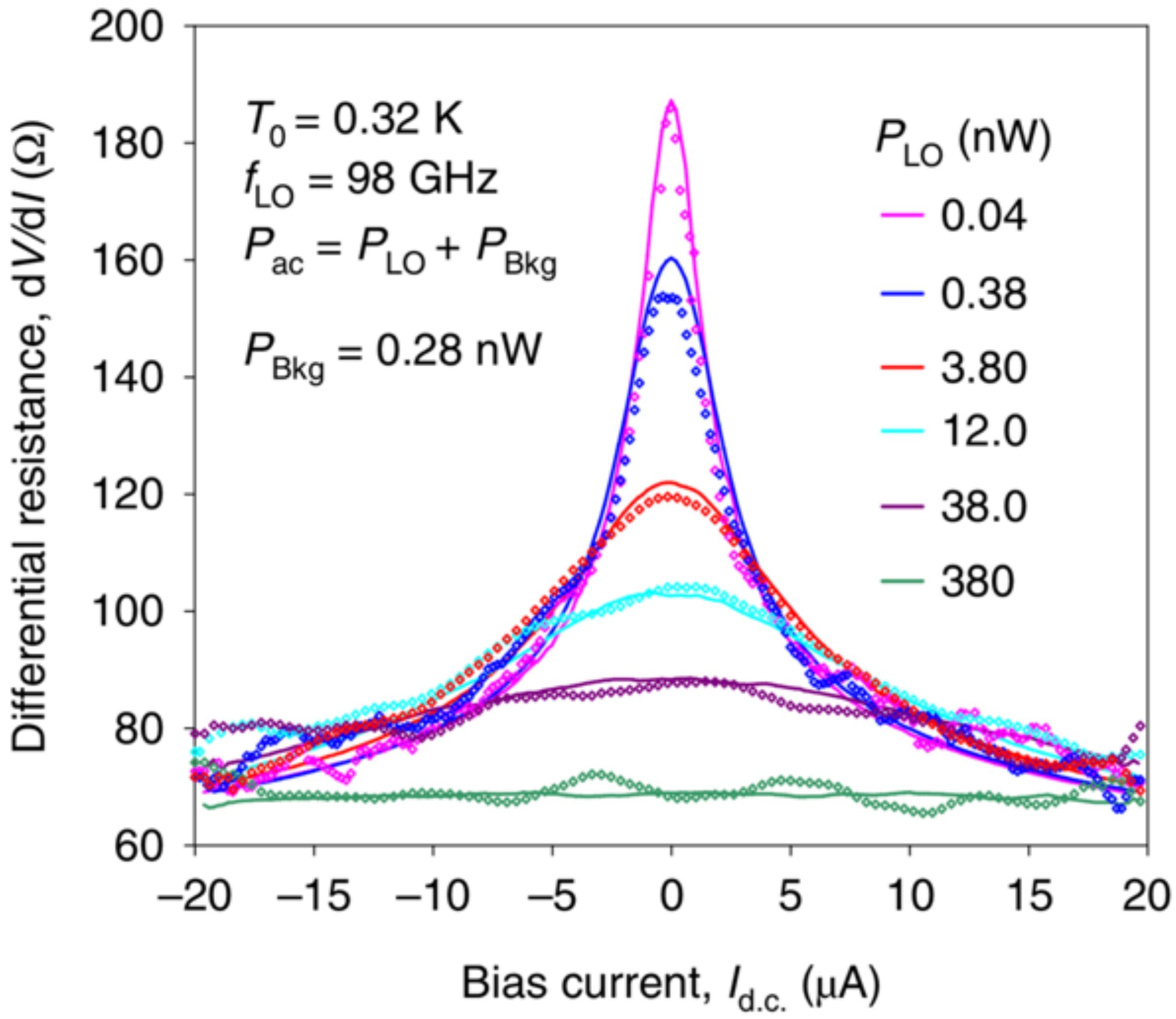
$$\mathcal{L} = \pi^2/3(k_B/e)^2 \approx 2.44\times 10^{-8}\ \mathrm{W\Omega K^{-2}}.$$

Background power (heat leak)

$$P_{ac} \neq 0\ ;$$

$$P_{ac} = P_{Bkg} = 0.28nW$$

Device response to radiation (98 GHz, dots)



Solid lines are model prediction

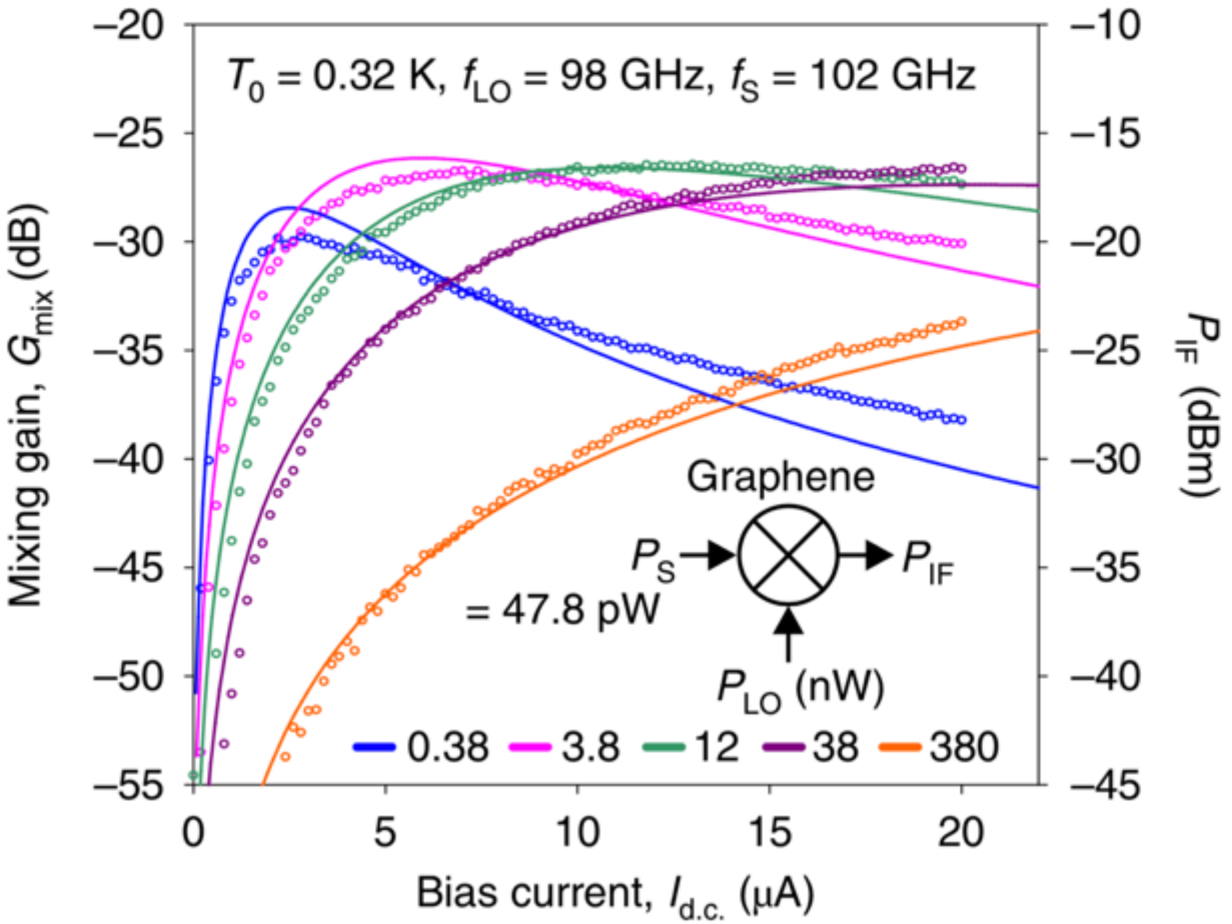
Using:

$L=3.1X10^{-8}$ $W\Omega/K^2$

P_{Bkg}=0.28 nW

i.e. solid lines are not a fit!

Bolometric mixer performance: Mixing gain $G_{mix} = P_{IF}/P_S$



$$G = \frac{1}{2}\frac{P_{LO}}{P_{DC}}\frac{50\Omega}{V/I}\left[\frac{1-\frac{V}{I}\frac{dI}{dV}}{1+50\Omega\frac{dI}{dV}}\right]^2$$

H. Ekström et al., *IEEE Trans. Microw. Theory Tech.* **43**, 938, (1995).

Maximum $\boldsymbol{G_{mix}}$ **= −27 dB** ($P_{IF}/P_S = 0.2\%$)
at P_{LO}=3.8nW, $I_{d.c.}$=5μA

Only Johnson noise in graphene bolometric mixer

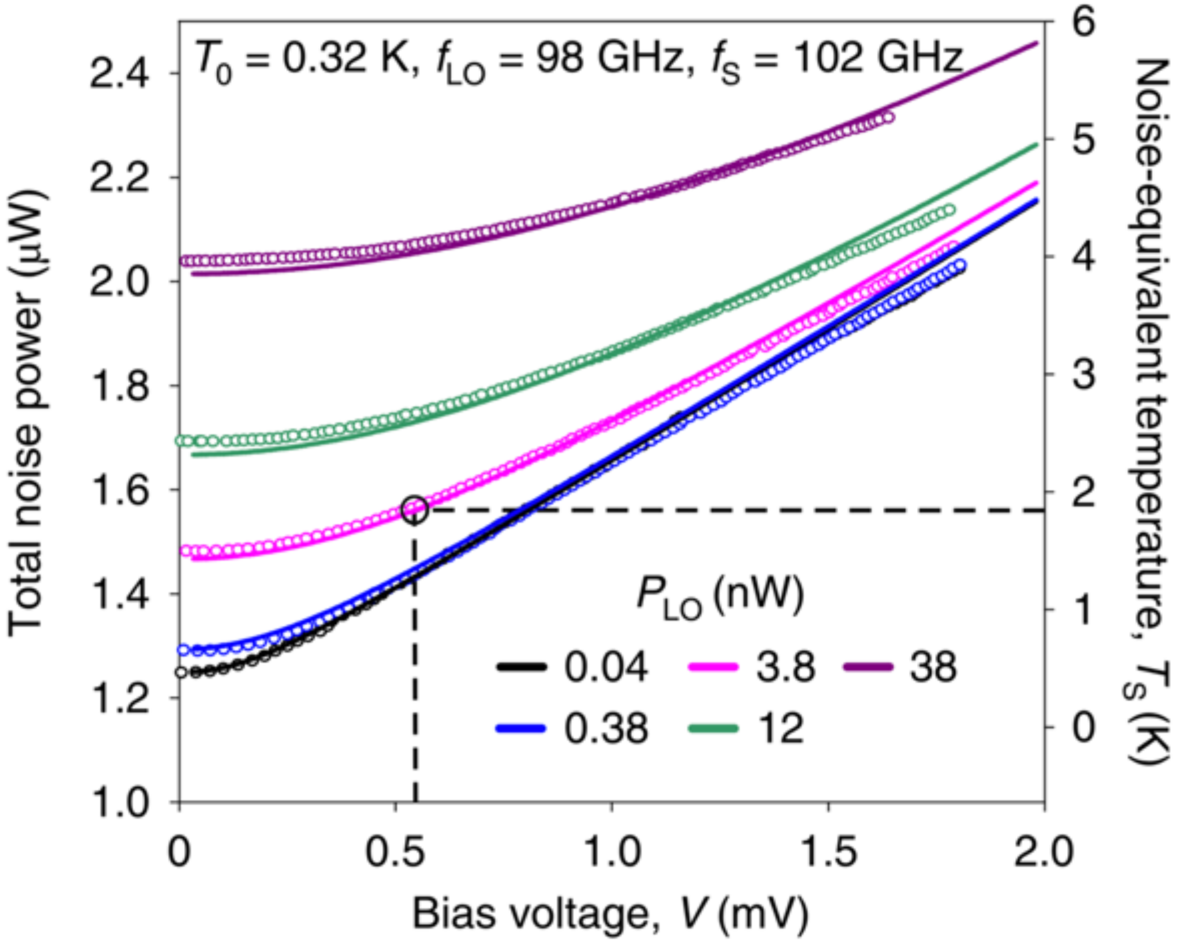
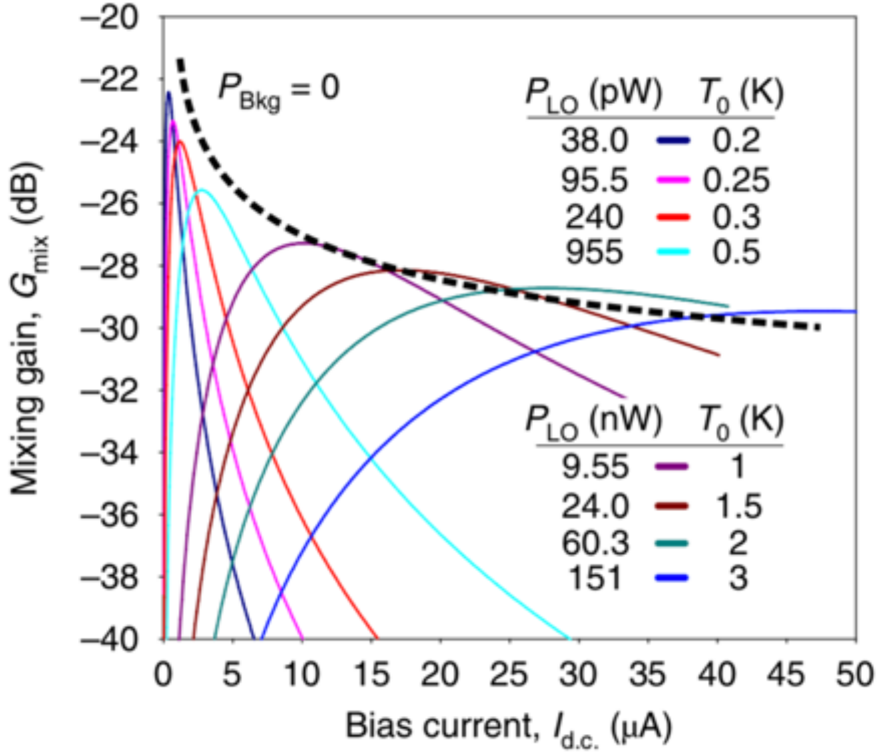


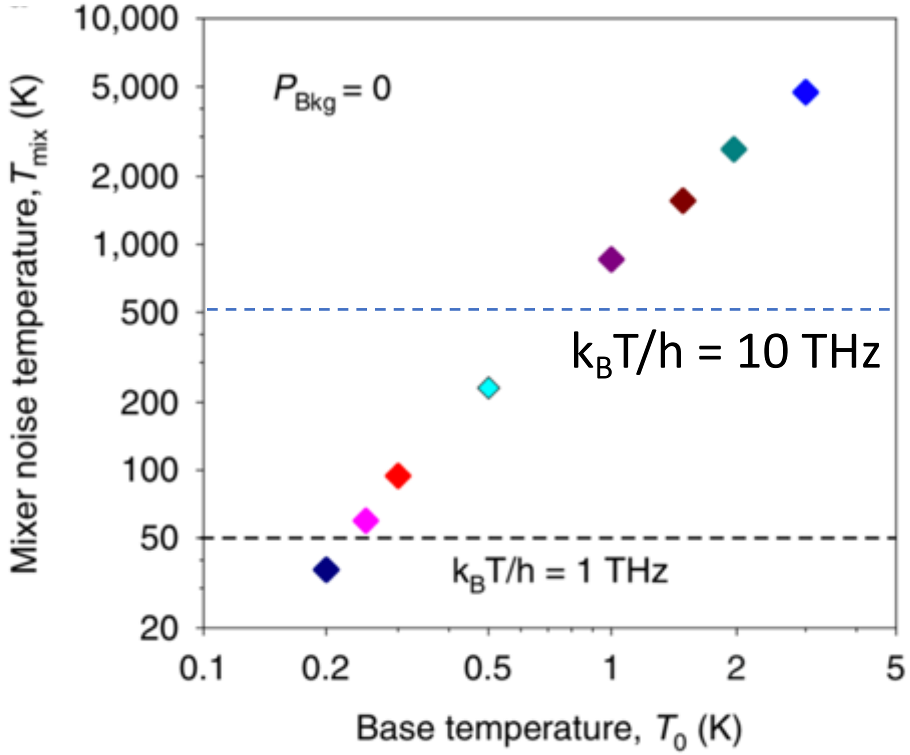
Figure of merit: Mixing temperature

$T_{mix} = T_{noise}/2G_{mix}$ = 1.9 K/(2*.002) = **475 K**

The measured perfomance of our mixer (T_{mix} = 475 K) is **limited by experimental setup**: sample is overheated to 1.9 K due to background radiate power P_{Bkg}

Prediction of device performance on a space mission (no background power, $P_{Bkg} = 0$)

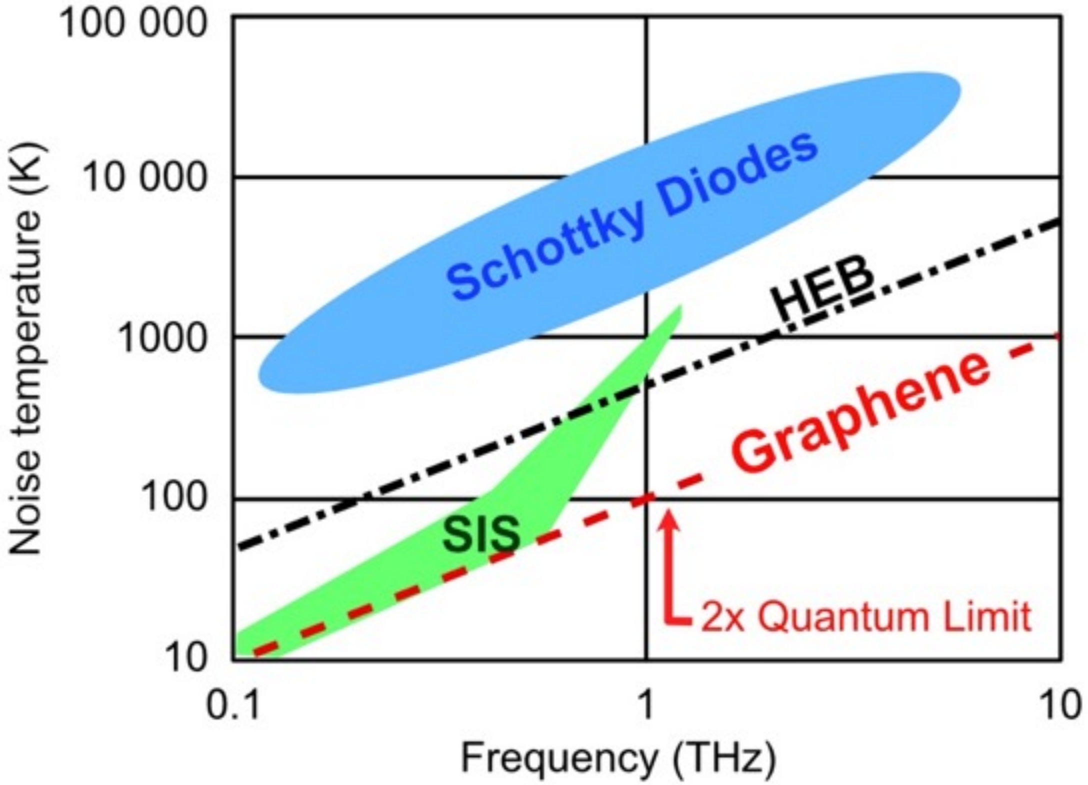




At T_0= 0.2 K, T_{mix}= 36 K, the detector is quantum-limited above 0.75 THz

Summary

- Bolometric mixing of THz signals in epigraphene doped to Dirac point, where sample resistance is dominated by quantum localization, and thermal relaxation is governed by diffusion cooling of carriers.
- At sub-Kelvin temperatures, T_{mix} = 36 K in an optimized setup (or space operation), implying quantum-limited detection for f > 0.75 THz
- Response of 8 GHz in 1.5um device, could be increased to 20 GHz in 0.8-1um long device
- Scalability of material and low Local Oscillator power requirements <100pW: attractive to envision large arrays of quantum–limited detectors a >1THz

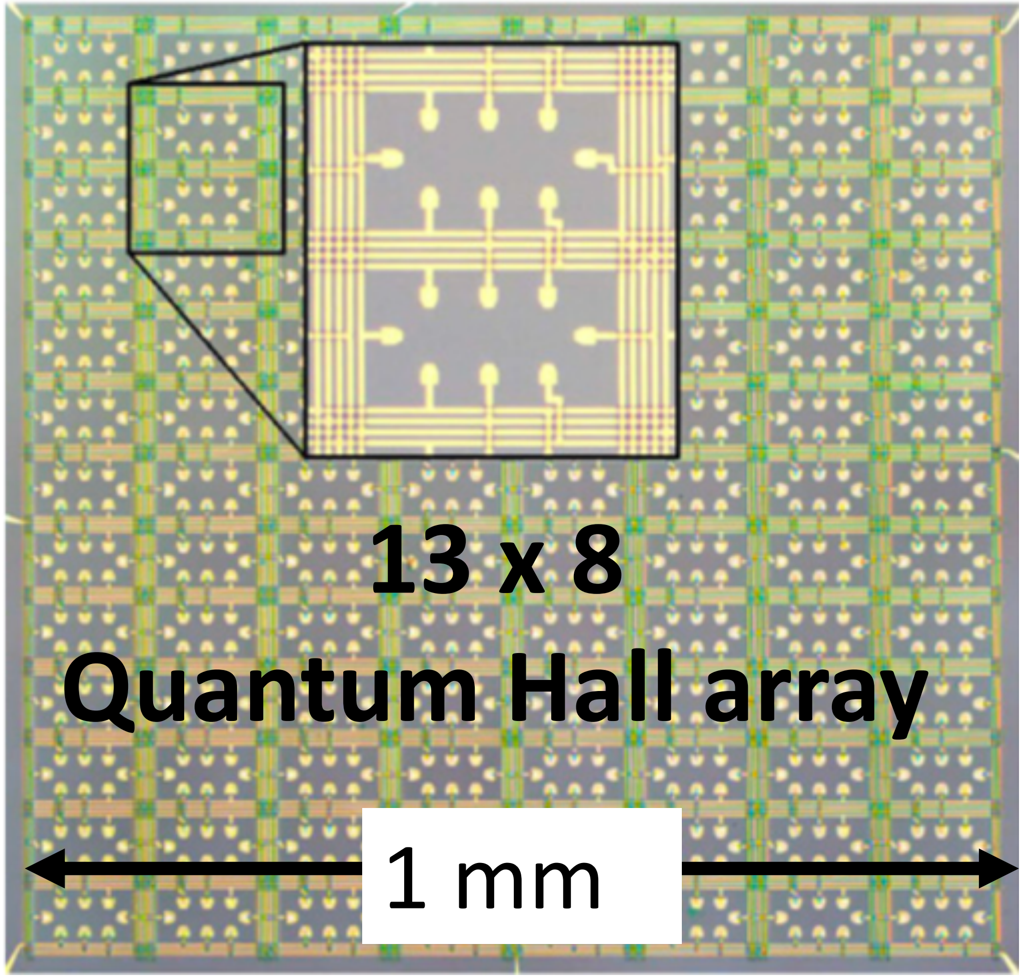


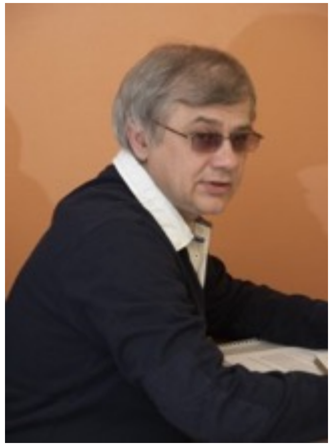
Outlook

Long term vision: Imaging at THz frequencies with graphene-based multi-pixel THz detector arrays

- 1-3 years: Refine single pixel detector
- 5 years: small scale arrays (~10 pixels)

Currently, 3 proposals under evaluation at the KAW foundation (Sweden), and under Horizon 2020 (Europe level together with DLR , Delft TU)




Andrey Danilov


Dmitry Golubev


Hans He


Kyung Ho Kim


Rositsa Yakimova


Floriana Lombardi


Thilo Bauch


Sergey Cherednichenko


Sergey Kubatkin

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