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Atomic monolayer materials and their applications

Serhii Shafraniuk

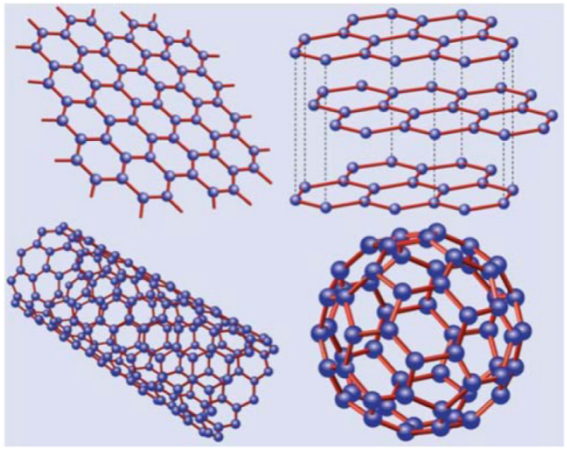
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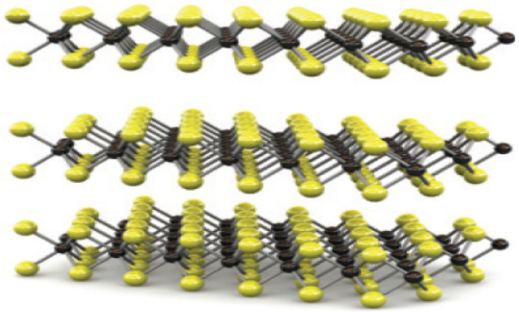
Experiment (GU):
P. Barbara, M. Rinzan,
Y. Yang

Experiment
(planned in NU):
V. Chandrasekhar,
I. Nevirkovets

Outline



- Atomic monolayer materials.
- Chirality and Klein paradox in graphene.
- Chemical, biological, d.c. magnetic, and electromagnetic sensors.
- Graphene and carbon nanotube quantum wells.

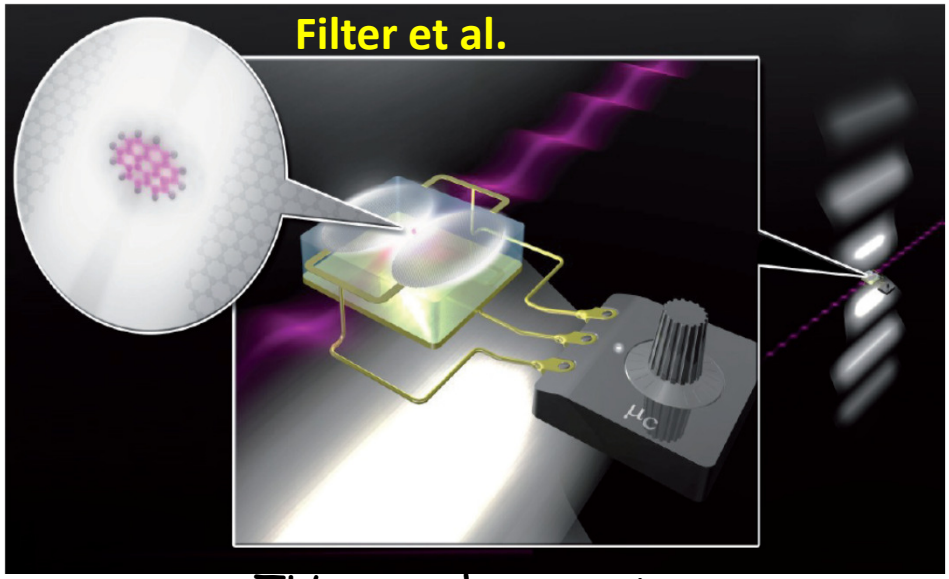


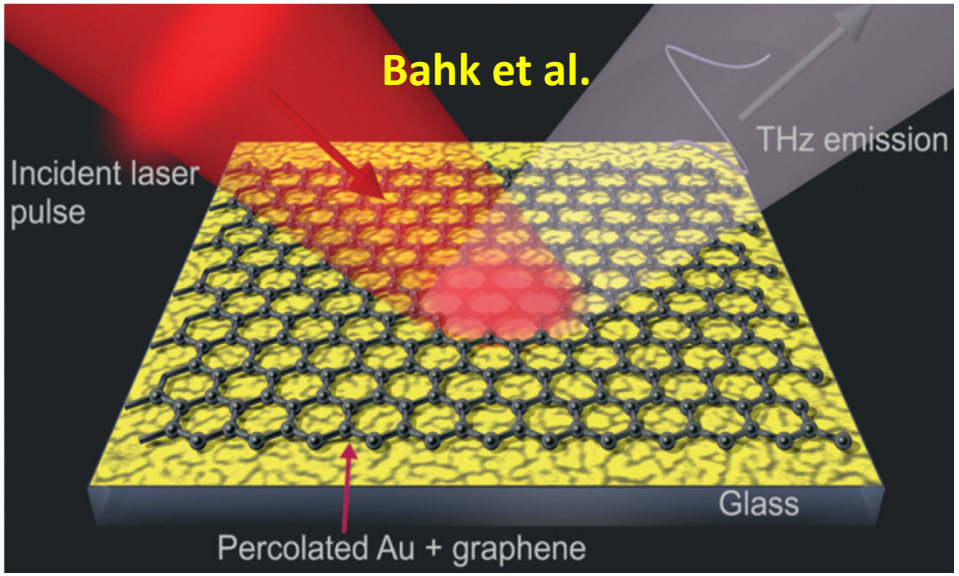
- Electron transport through the graphene and carbon nanotube junctions.

Graphene versus other AMM

	Graphene	MS_2 Atomic monolayer M=Nb,Ta	LS_2 Atomic monolayer L=Ti, Mo, W
Advantages	Intrinsic coherence due to chirality of electrons, Klein tunneling, $\Lambda \sim 10^3$ W/(m K) and $\mu > 10^6$ cm^2 /(V s) at 2 K	Metal, superconductor, no dielectric gap (Δ = 0 eV) $\Lambda \sim 10^2$–10^3 W/(m K)	Semiconductor with energy gap Δ = 1–2 eV in the electron spectrum, $\Lambda \sim 10^2$–10^3 W/(m K) $\mu \sim 10^3$ cm^2 /(V s)
Setbacks	No energy gap in electron spectrum of pristine graphene	No intrinsic coherence	No intrinsic coherence

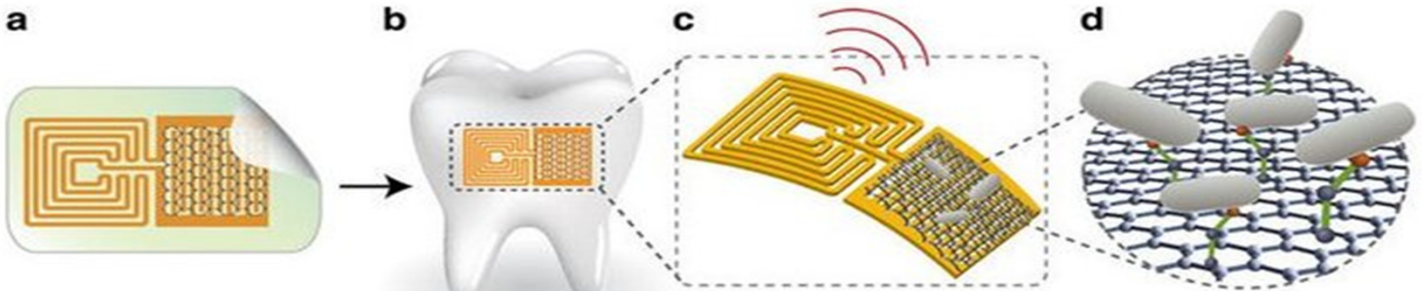
Recent graphene applications

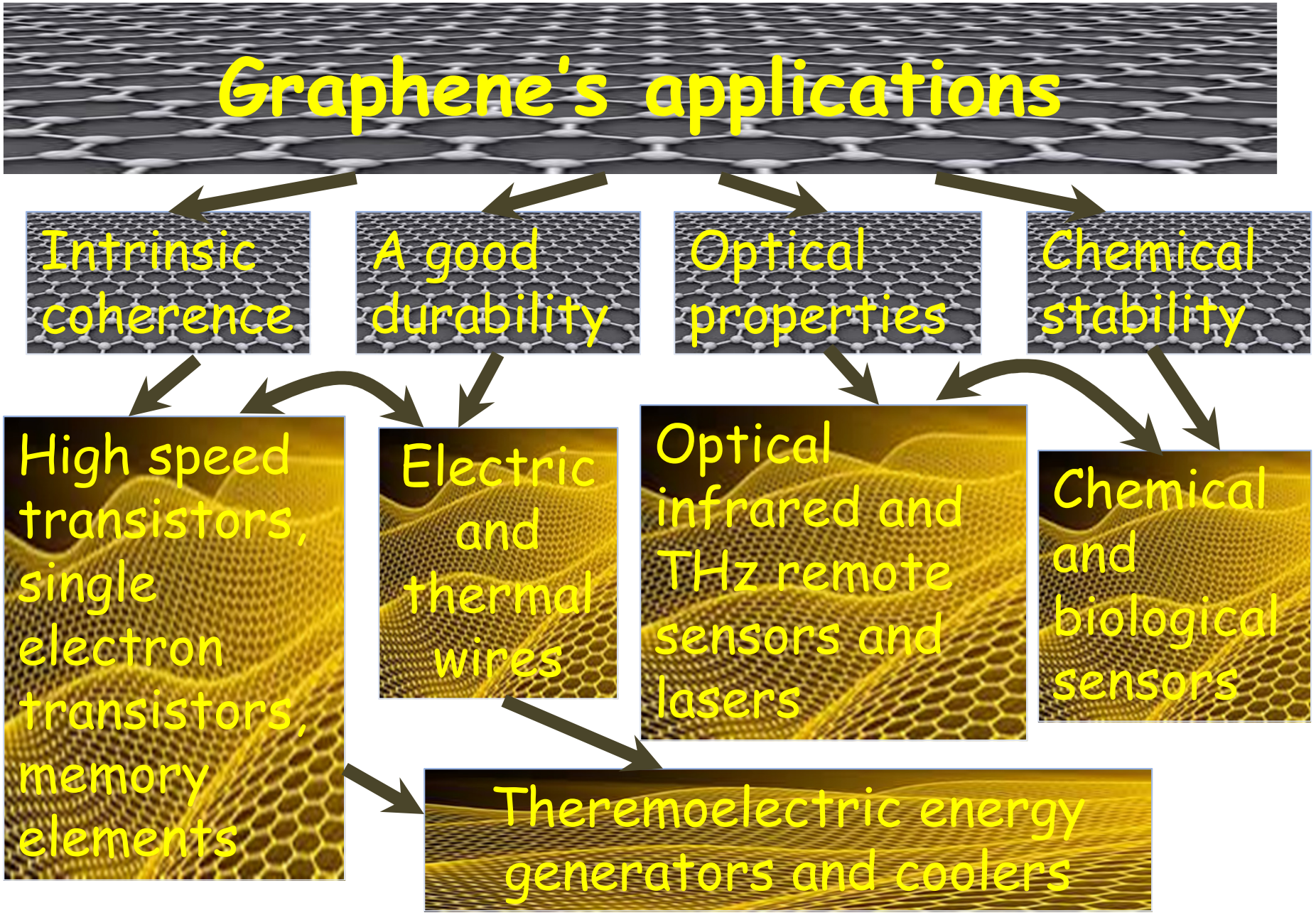




THz graphene antenna

Biotransferrable graphene wireless nanosensor, Princeton, NJ




Graphene's applications
Intrinsic coherence
A good durability
Optical properties
Chemical stability
High speed transistors, single electron transistors, memory elements
Electric and thermal wires
Optical infrared and THz remote sensors and lasers
Chemical and biological sensors
Theremoelectric energy generators and coolers

Our activity at Northwestern

- Graphene and CNT quantum dots for THz electronics (jointly with Georgetown).
- Electron and heat transport through graphene/metal or CNT/metal interfaces (I. Nevirkovets).
- Graphene and carbon nanotube thermoelectric energy generators and coolers (T. Gupta, S. Davis, and V. Chandraseckar).

Challenges

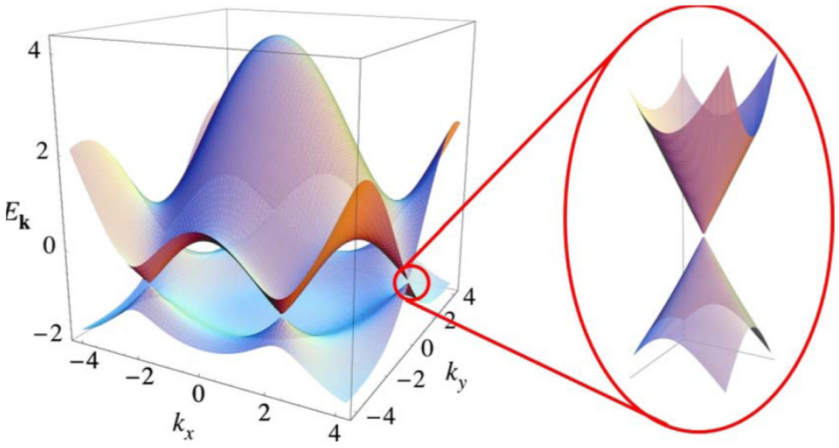
- Influence of surface (water molecules) and substrate defects.
- Forming of highly efficient local gates.
- Heat flow management.

Key aspects

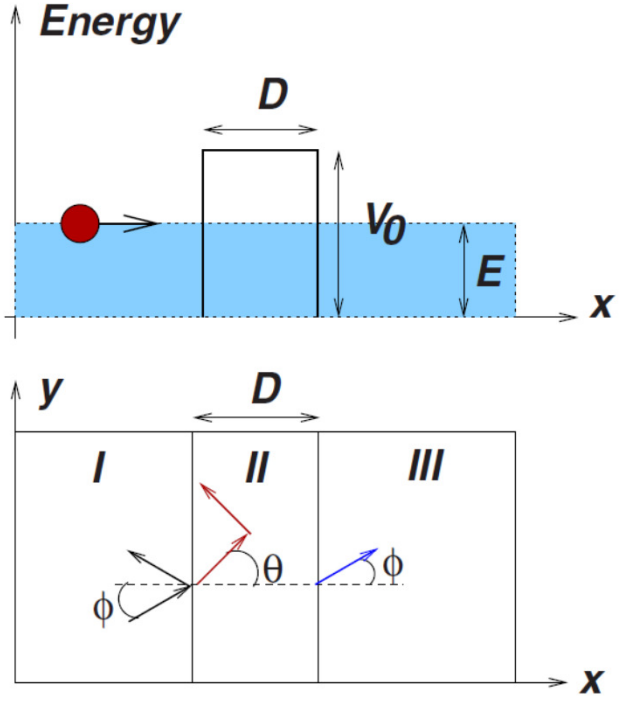
- Chirality of low-energy excitations (regular spinless quasiparticle picture is inaccurate).
- Highly transparent interfaces (tunneling Hamiltonian fails).
- Energy-dependent relaxation time with $\tau_K / \tau_{opt} \sim 10^3$.
- Multi-sectional (multi-barrier) junctions: The coherence of electron wavefunctions is preserved over multiple sections.

The electron density of states in pristine graphene

$$D(\varepsilon)=\frac{1}{S}\sum_{s,k}\delta(\varepsilon-\varepsilon_k)=\frac{|\varepsilon|}{2\pi v^2}$$

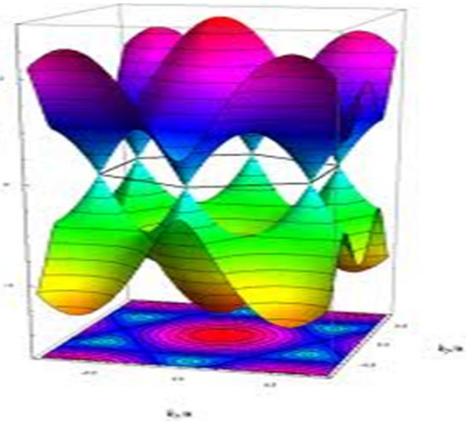


Electronic dispersion in the honeycomb lattice. Left: energy spectrum (in units of t) for finite values of t and t', with t=2.7 eV and t'=−0.2t. Right: zoom in the energy bands close to one of the Dirac points.

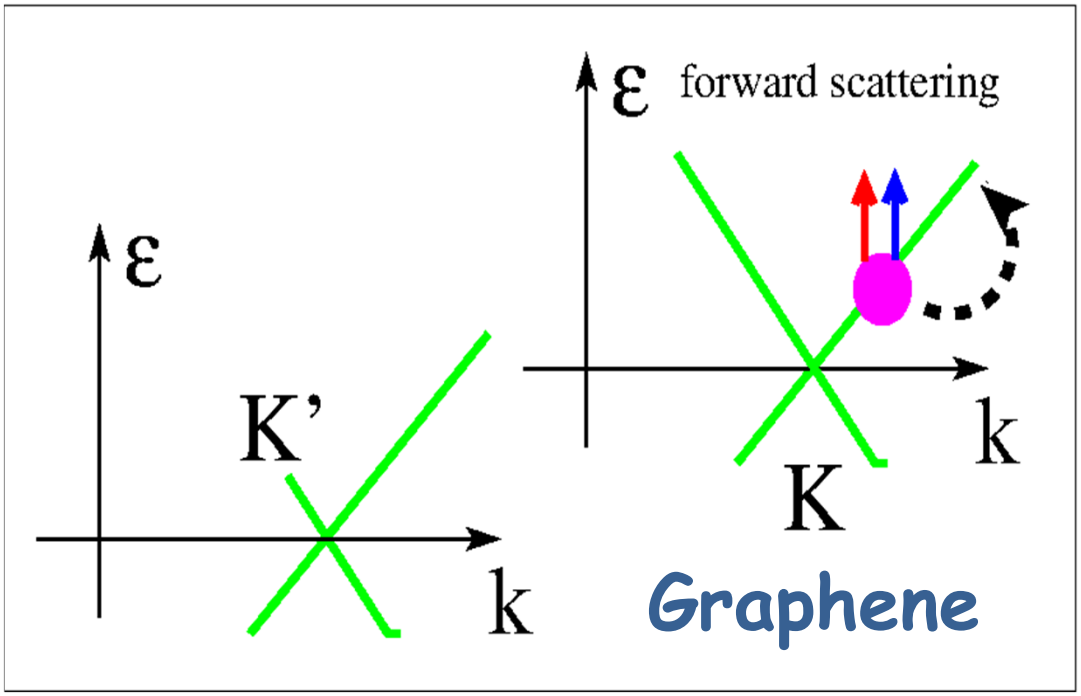


Klein tunneling in graphene. Top: scattering the Dirac electrons by a square potential. Bottom: definition of the angles ϕ and θ used in the scattering formalism in regions I, II, and III.

Graphene versus other 2D AMM



At K-points m*->0



Graphene: minor scattering τ->oo

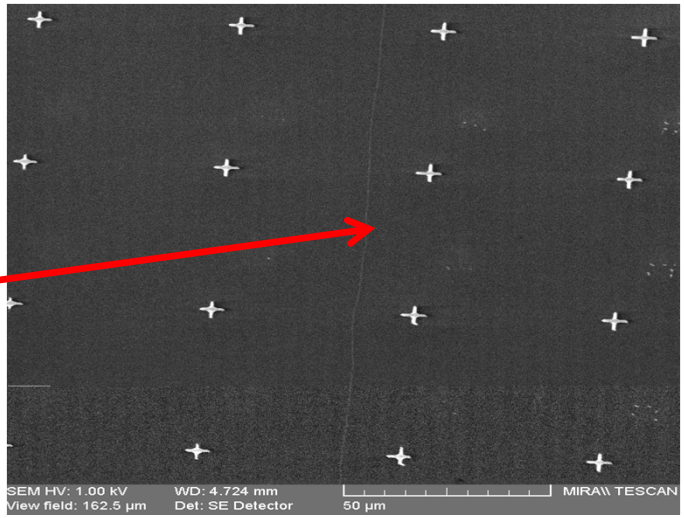
Regular SC: Strong scattering τ->finite

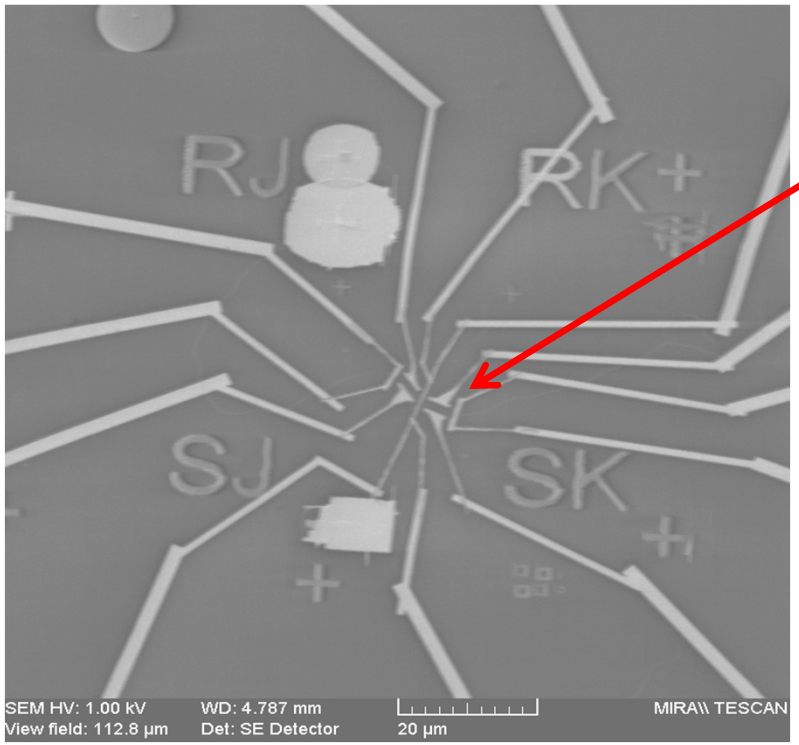
Intrinsic coherence: electrons and holes are chiral particles with 2 *pseudospins* (blue and red)

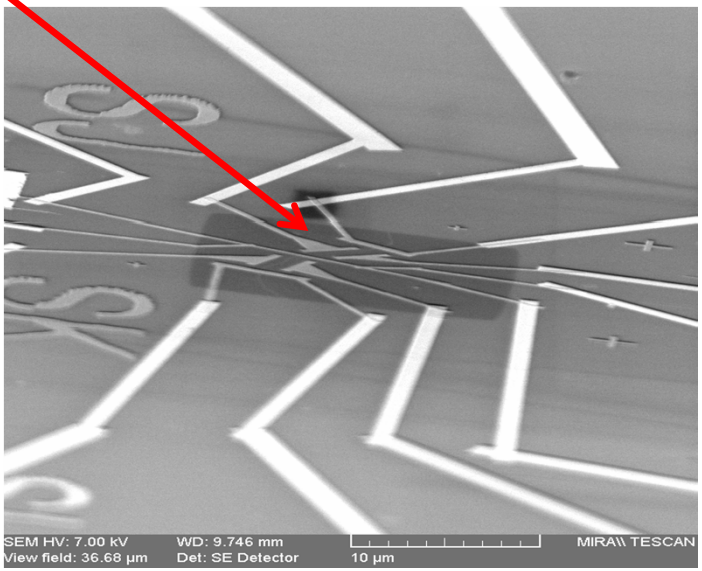
Our thermoelectric devices

T. Gupta, S. Davis, and V. Chandraseckar

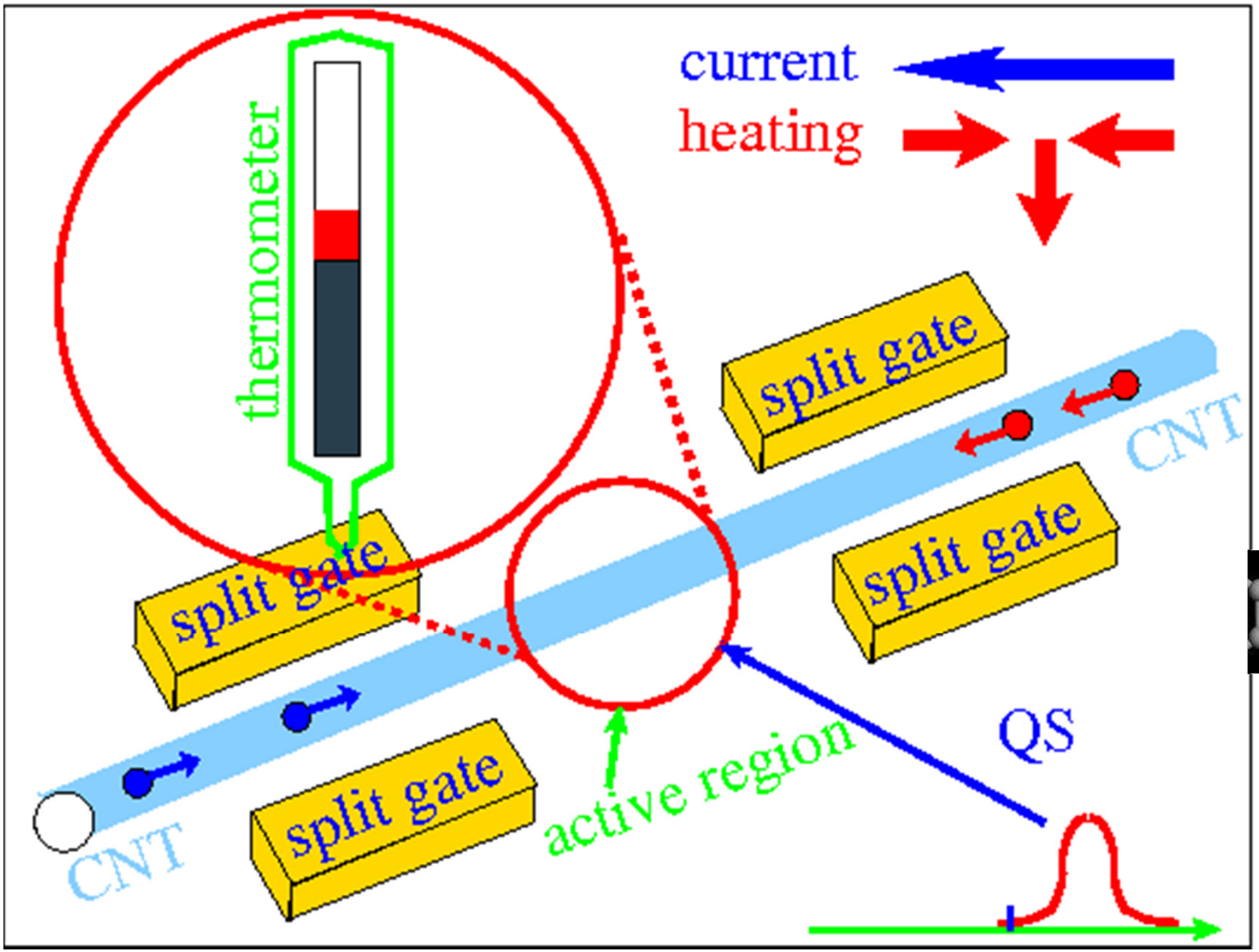
Our group has fabricated a variety of carbon nanotube PC devices with Pd, Ti, Au electrodes. The gates are side (made of Pd stripes), and back (++Si).



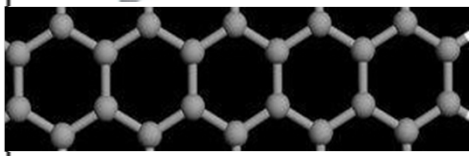




How the thing works?

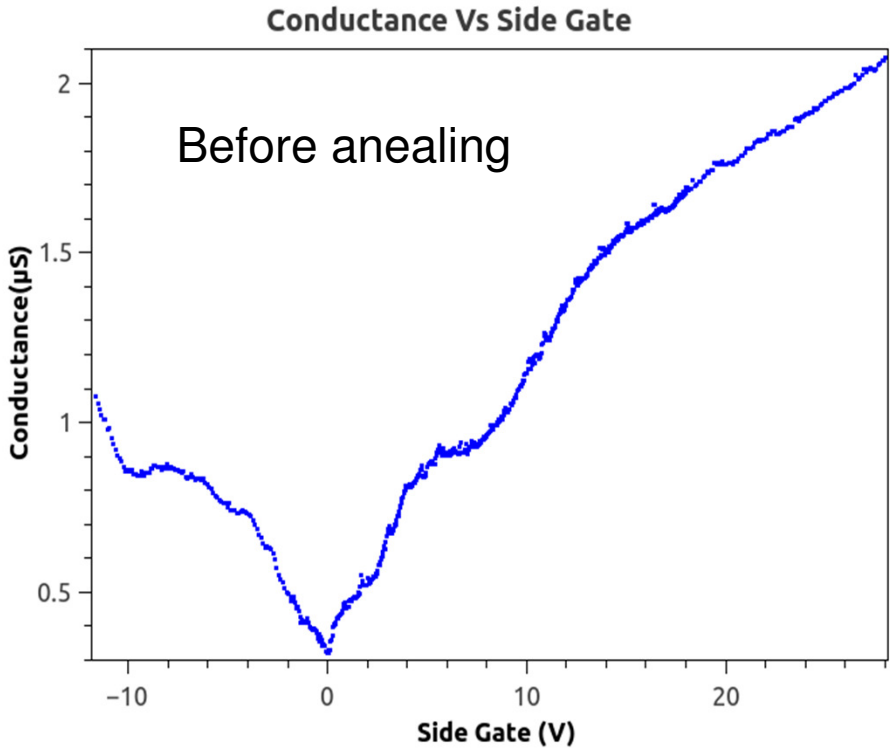


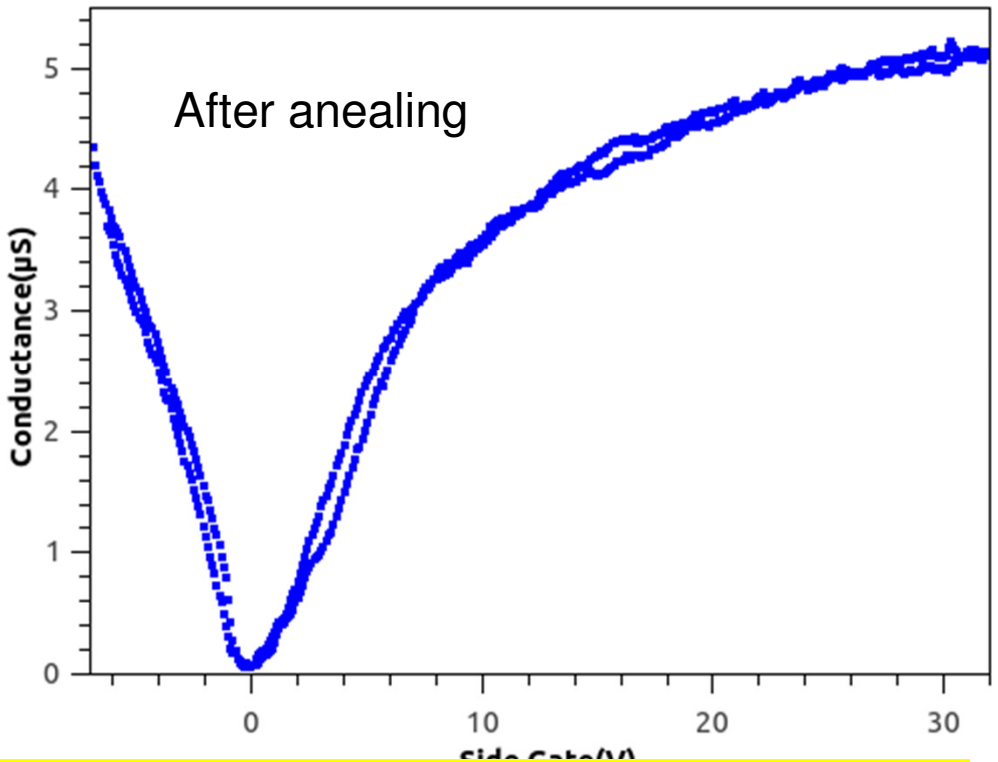




'A poor man' thermometer

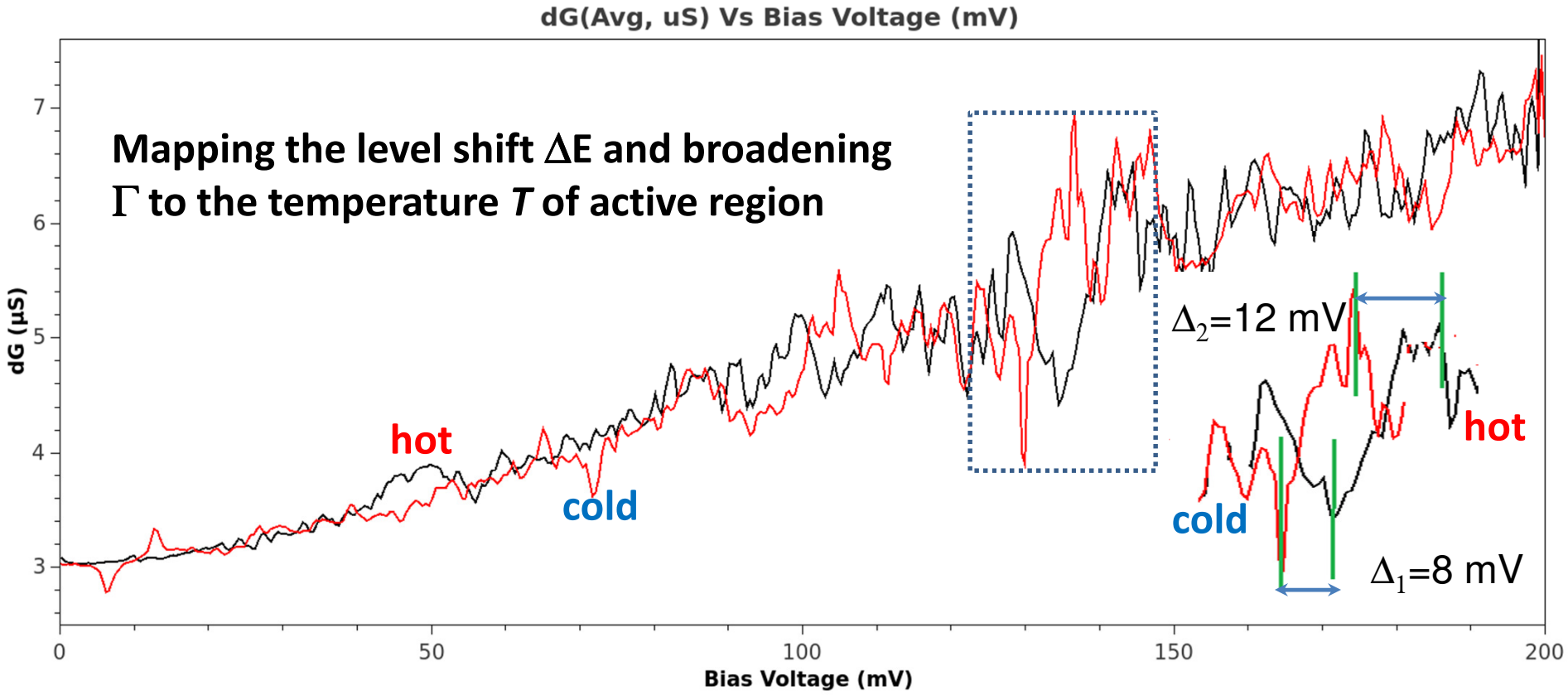
CNT FET with Ti contacts





<u>Remaining issues</u>: We are still about an order of magnitude below the maximum of cooling power. We need the cooling power increase in our PC. We address it by selecting of best CNT/metal contacts from a variety of different contacts. So far we are testing CNT/Pd-Au, CNT/Pd-Ti, CNT/Ti, CNT/Au, and CNT/Cr contacts.

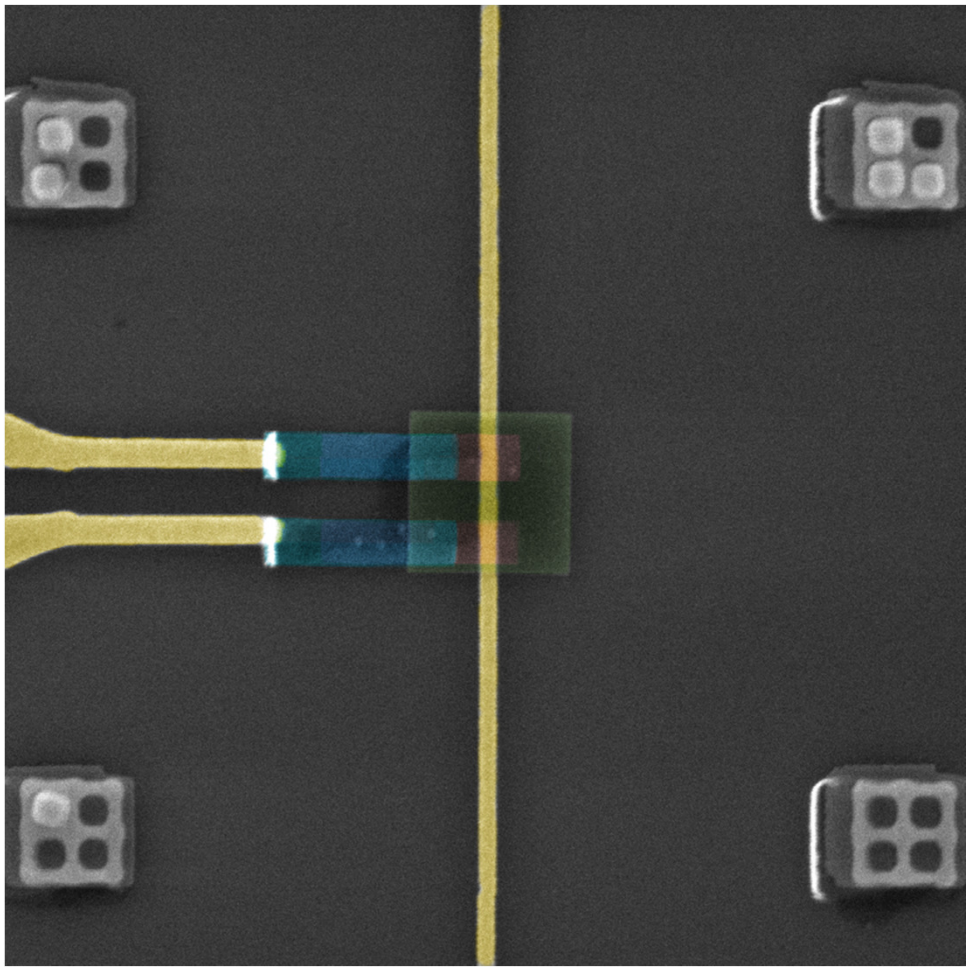
‘A poor man’ thermometer for CNT



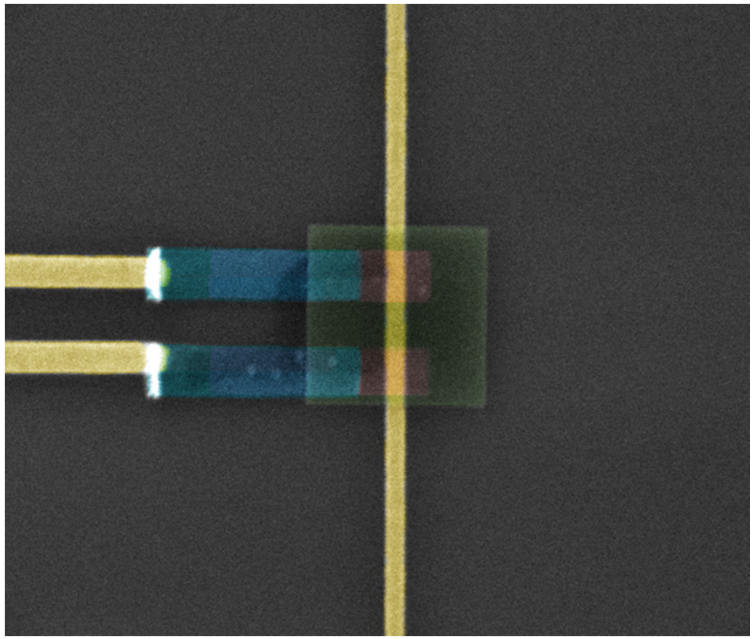
Δ_1=8 **mV just outside the active region**
Δ_2=12 **mV inside the active region**

$T_{hot}-T_{cold}$~140 **K**

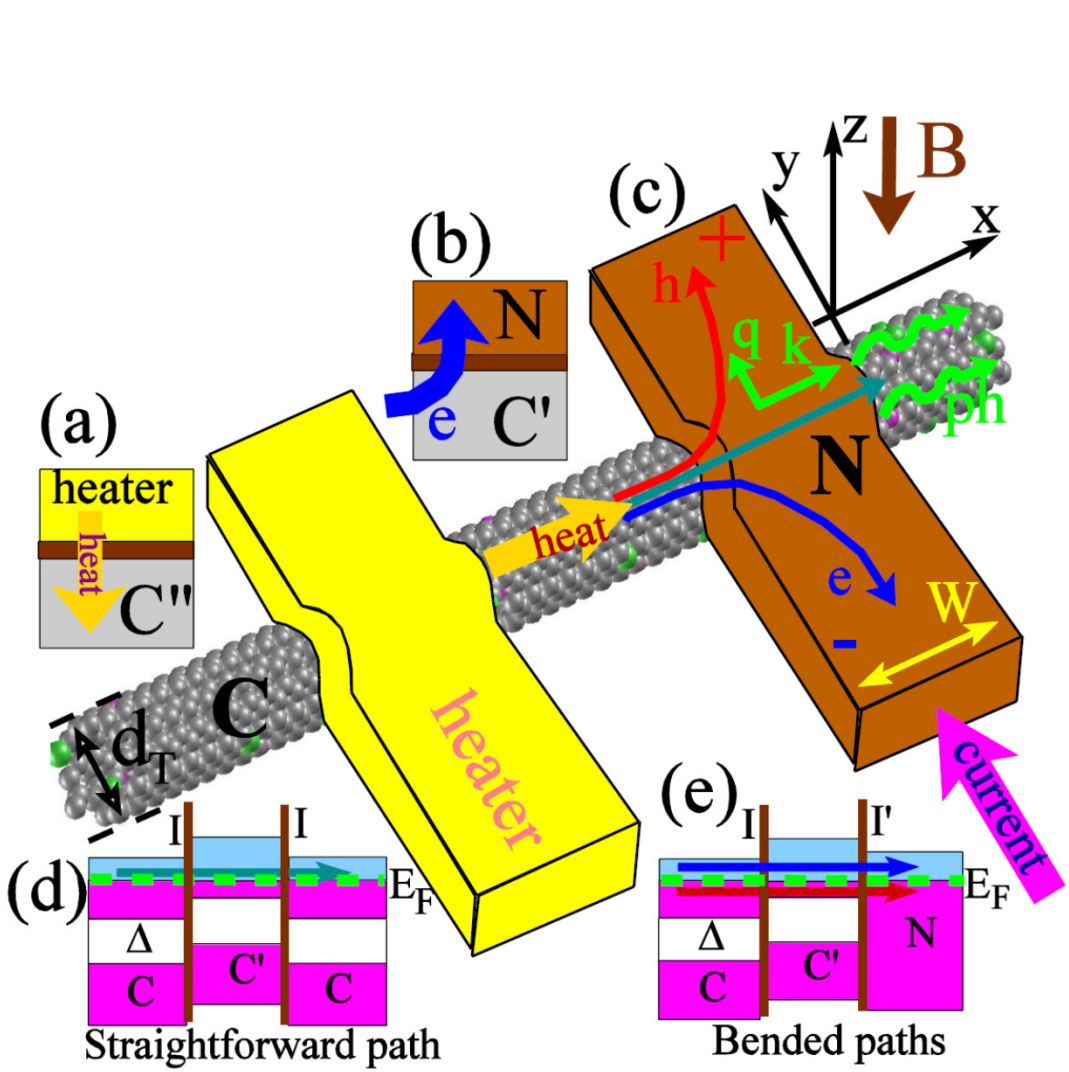
Molecular thermometer

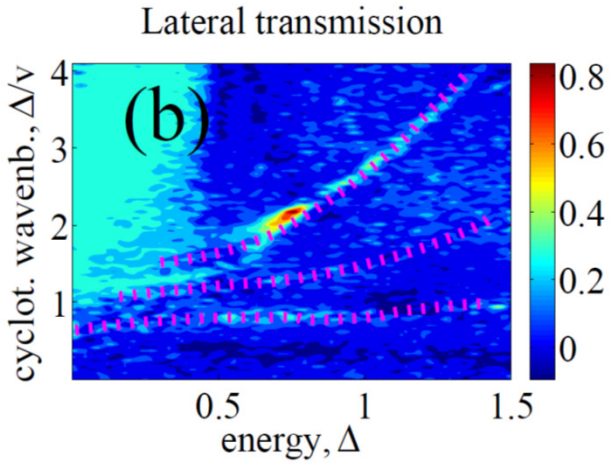


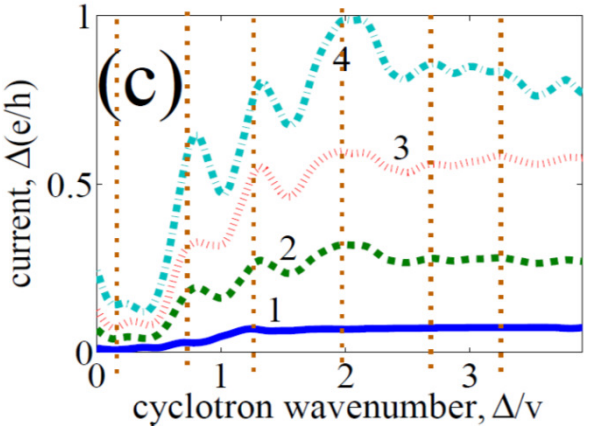
Scott Meyle, 2014



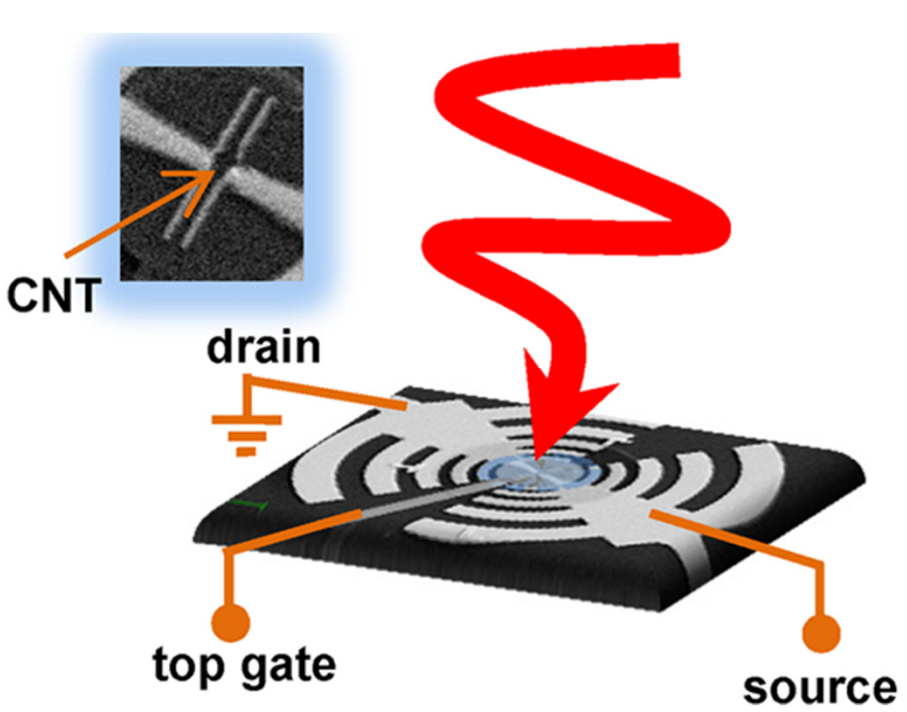
Thermal quantum Hall

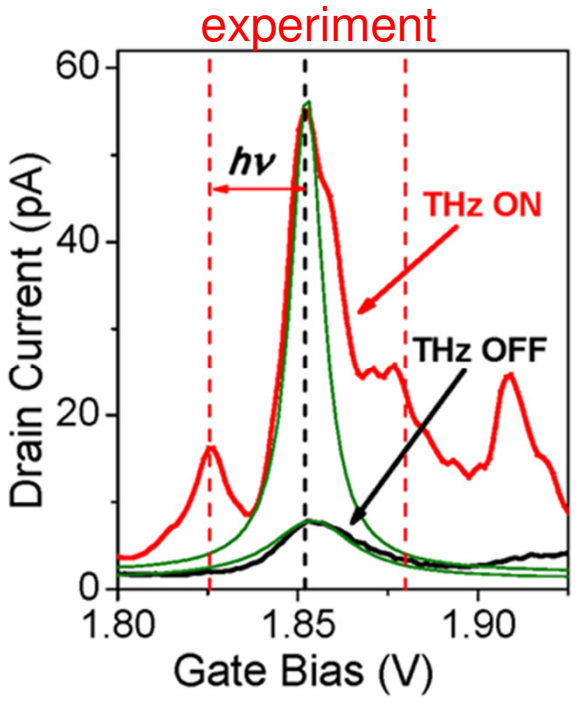






THz wave sensing

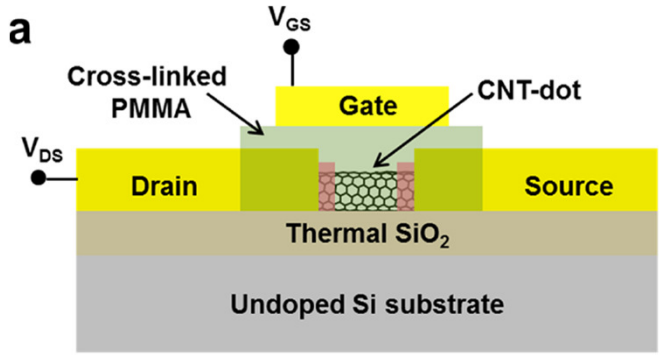




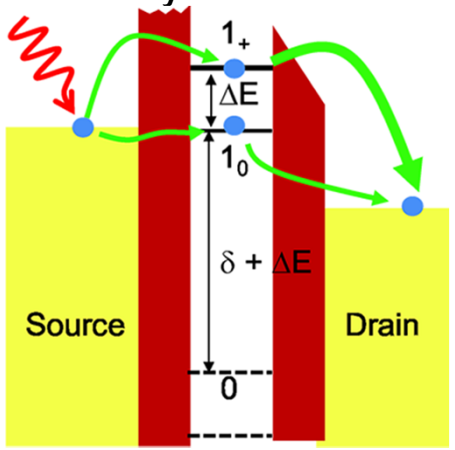
Georgetown University (M. Rinzan, P. Barbara group, 2010-11)
THz sensing with the single-electron tunneling in carbon tube junctions, Nano Letters, 2012

Theory (Shafraniuk, Nano Letters 2012)

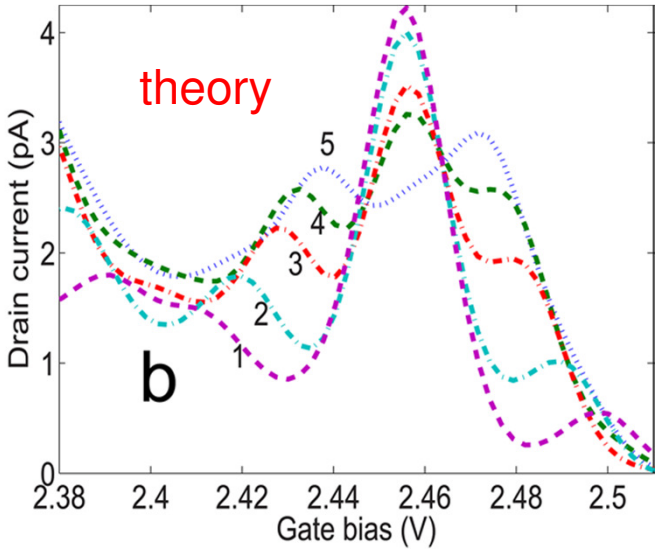
setup



theory



THz photon-assisted tunneling through the double barrier quantum dot



Splitting the single electron tunneling peak of the drain current through the CNT quantum dot at different frequencies the external THz field hf = 7.31, 6.33, 4.67, 3.31, and 3.02 meV

Conclusions

- Physics of photon-assisted chiral tunneling in graphene and carbon nanotube quantum dots along with the intrinsic coherence, high mobility, and low dimensionality is very important.
- Using the Klein tunneling in graphene and in CNT opens new exciting opportunities to improving of the a.c. electron transport.

Recent publications

- S. E. Shafraniuk, Electromagnetic properties of graphene junctions, European Physical Journal, B 80, 379-393 (2011).
- S. Shafranjuk, Graphene and Carbon Nanotube Quantum Dot Sensors of the THz Waves, In: 'Nanotechnology', Studium Press LLC, USA, Vol. 10: Nanosensing (2012).
- S. E. M. Rinzan, G. Jenkins, H. D. Drew, S. Shafranjuk, and P. Barbara , Carbon Nanotube Quantum Dots As Highly Sensitive Terahertz-Cooled Spectrometers, Nano Lett.,2012, 12(6),pp 3097-3100; DOI: 10.1021/nl300975h

Future plans

- Interpretation of experimental data.
- Scaling up to large arrays of nanosensors.

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