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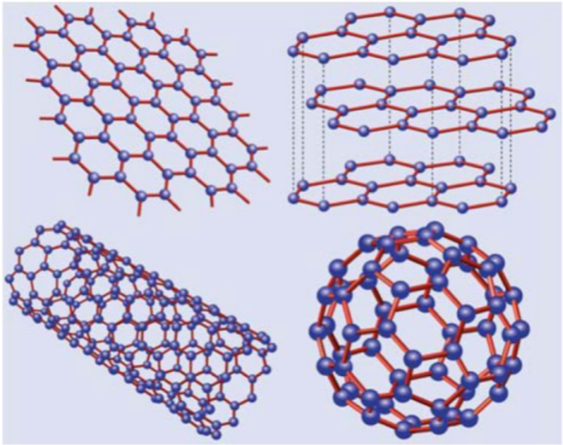
THz applications of atomic monolayer materials

Serhii Shafraniuk
Physics & Astronomy Department,
Northwestern University, 60208 Evanston IL
Ph. (847)467-2170, kyiv.phys.northwestern.edu

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

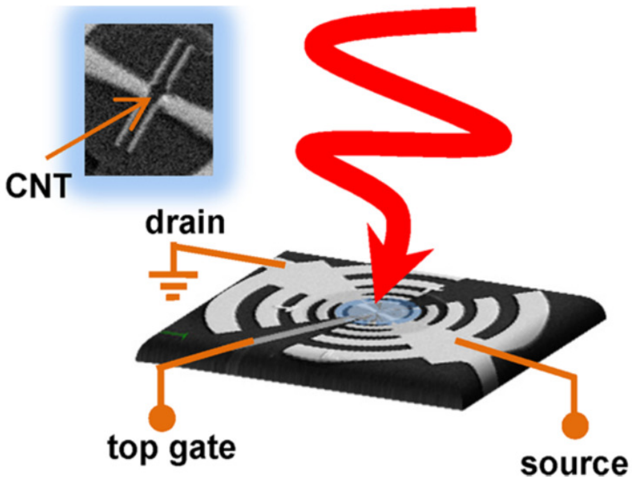
Experiment
(planned in NU):
V. Chandrasekhar,
I. Nevirkovets

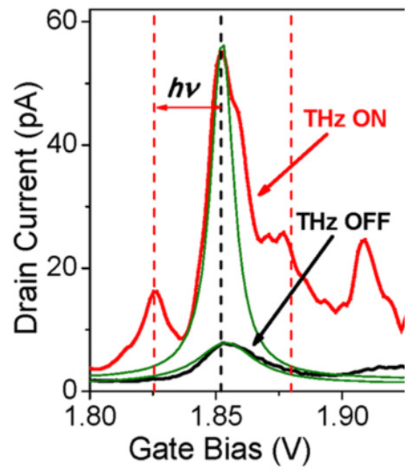
Outline



- •Atomic monolayer nanotube quantum wells.
- •A.C. transport through the graphene and carbon nanotube junctions.
- •Photon-assisted tunneling.
- •THz sensing with non-equilibrium intrinsic cooling.

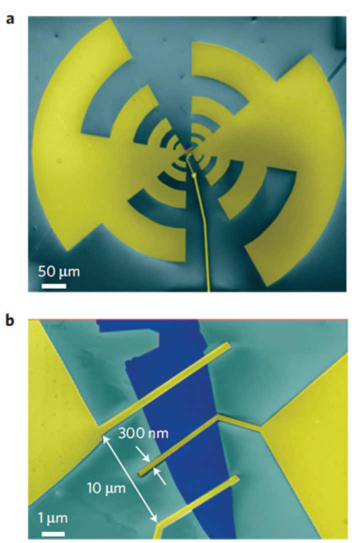
Graphene and CNT THz sensors

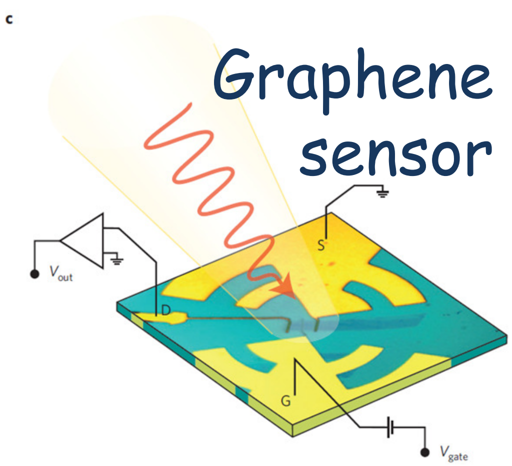




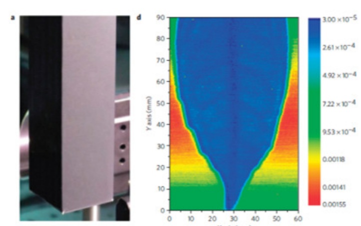
Rinzan et al, NanoLetters, 2012

Theory: Shafraniuk, 2006-12





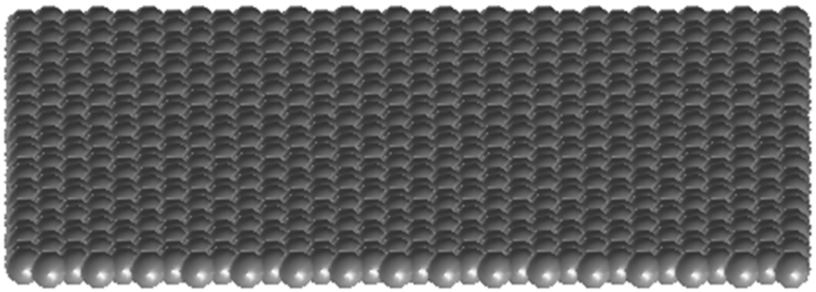
Graphene sensor

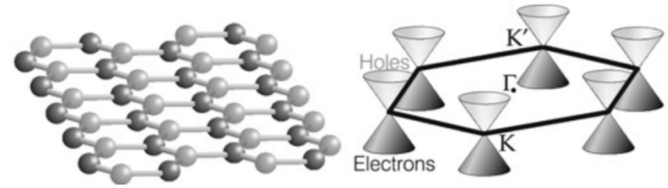


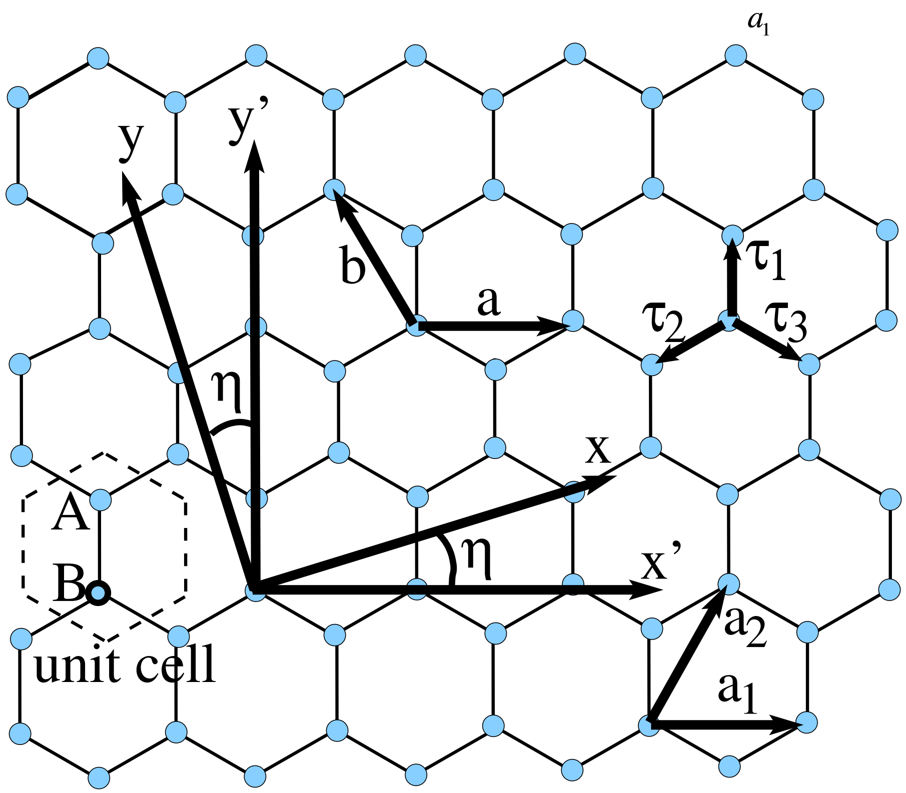
0.3 THz transmission

Vicarelli et al, Nature Materials, 2012

Graphene lattice



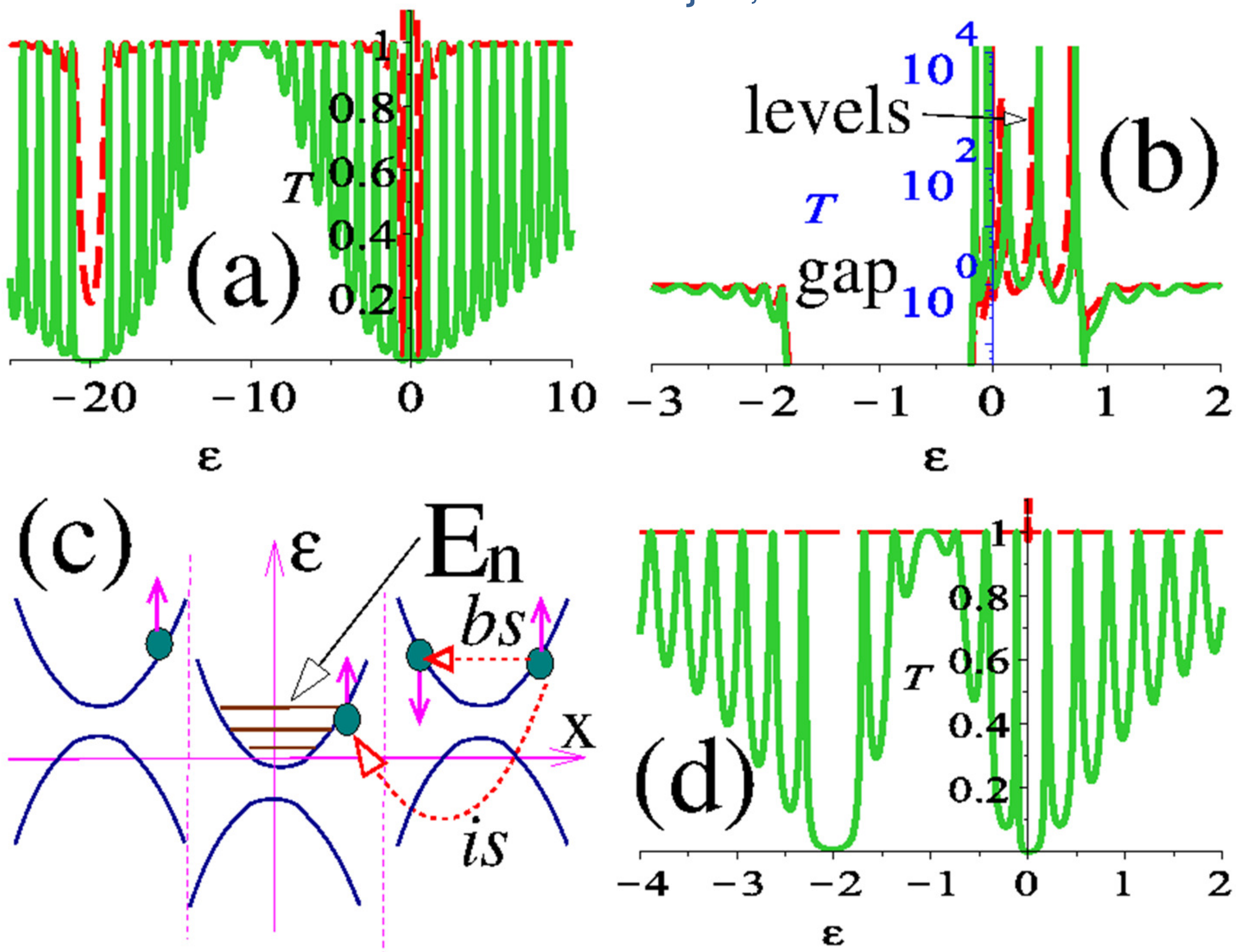




Here ***a*** and ***b*** are two primitive translation vectors. The hexagonal unit cell represented by a dashed line contains two carbon atoms denoted by A and B. Three vectors directed from a B site to nearest neighbor A sites are τ_1, τ_2, and τ_3. The coordinates and are fixed onto the graphene, x and y are along the circumference and axis, respectively, and denotes a chiral angle. Another choice of primitive translation vectors is $\boldsymbol{a}_1$ and $\boldsymbol{a}_2$.

Energy levels in the graphene/CNT quantum dot

Shafranjuk, 2010



Steady state quantized energy levels formed inside the chiral (red dashed curves) and non-chiral (green solid curves) QW made of semiconducting nanotubes

Important issues
(though largely disregarded)

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

Photon-assisted tunneling

Tien-Gordon model assumptions: (i) T<<1 and

$$\psi \exp\left(iE_p^0 t\right) \to \psi \exp\left\{iE_p^0 t + eV_{ac}\int dt \cos \omega t\right\}$$

(ii)

$$= \psi \exp\left(iE_p^0 t\right) \times \sum_n J_n\left(eV_{ac} / \hbar\omega\right) \exp\left\{in\omega t\right\}$$

then the electric current is

$$I_{TG} = \sum_{n=\infty}^{\infty} J_n^2\left(\frac{eV_{ac}}{\hbar\omega}\right) I_{dc}^0\left(eV_0 + n\hbar\omega\right) = \sum_{n=\infty}^{\infty} I_n$$

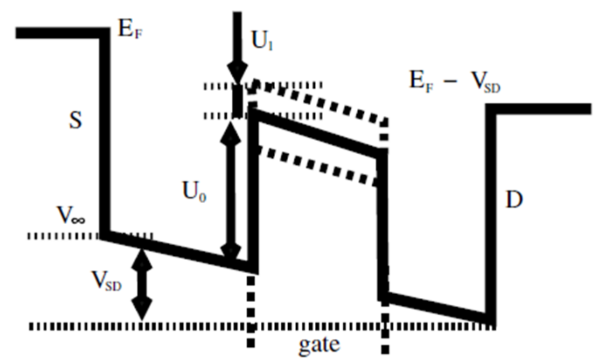
Dayem-Martin steps

For chiral tunneling (i) and (ii) fail since $T\left(\mathrm{E}_p^0\right) \square 1$

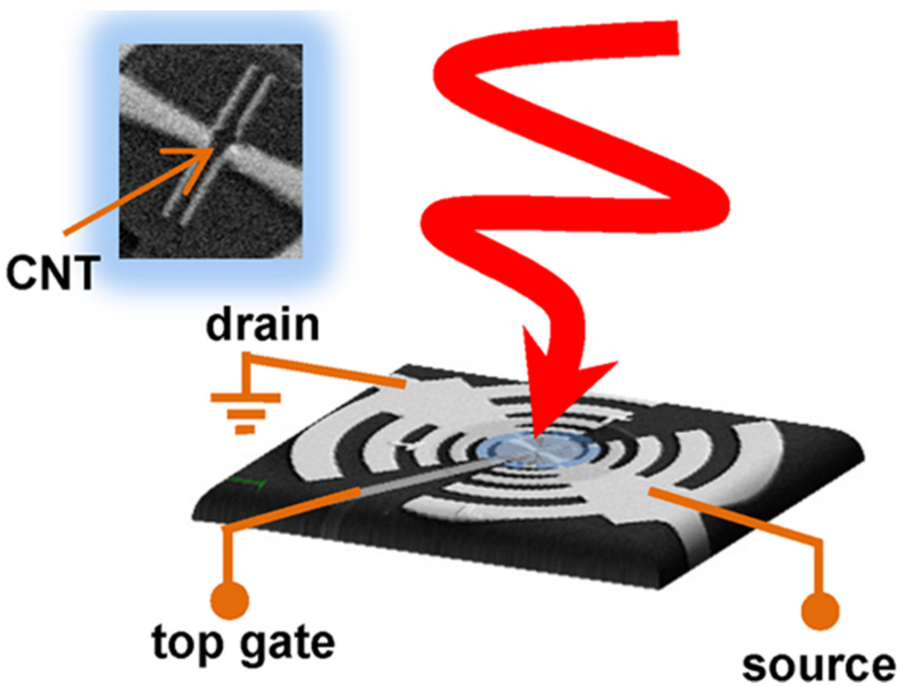
and the normal electron momentum

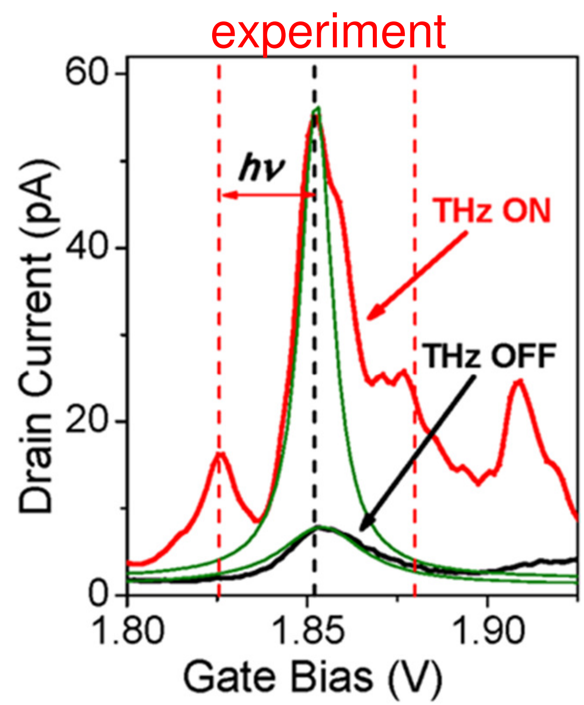
$$k(t) = \sqrt{\left(E_p^0 - V_G(t)\right)^2 / (\hbar v)^2 - q_n^2}$$

In a confined sample



THz wave sensing

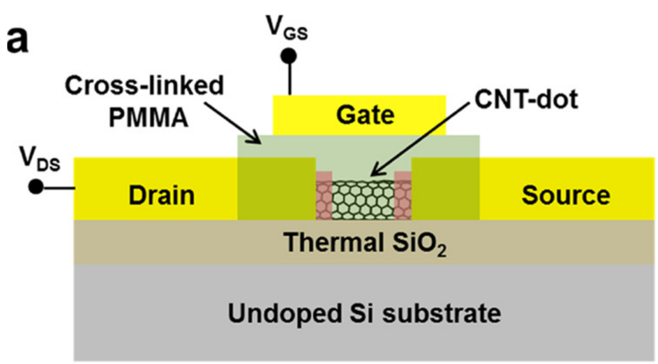




Georgetown University (M. Rinzan, P. Barbara group, 2010-11)
THz sensing with the single-electron tunneling in carbon tube junctions

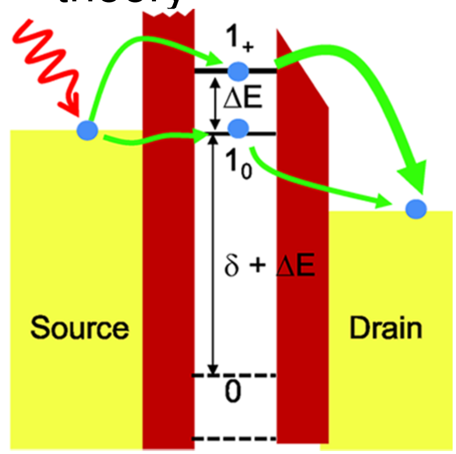
Theory (Shafraniuk, 2011)

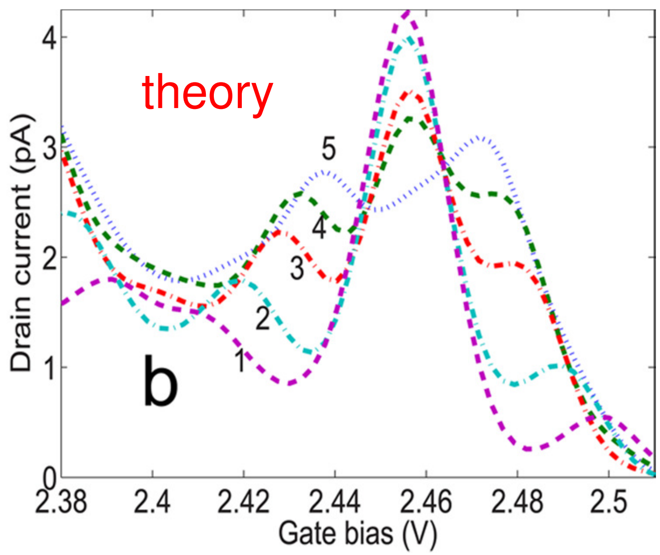
setup



THz photon-assisted tunneling through the double barrier quantum dot

theory



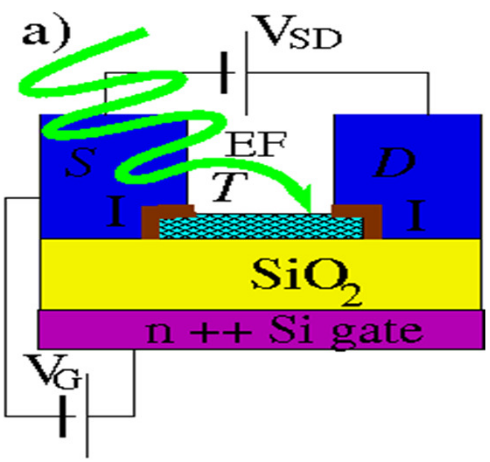


Splitting the single electron tunneling peak of the drain current through the CNT quantum dot at different frequencies the external THz field *hf* = 7.31, 6.33, 4.67, 3.31, and 3.02 meV

Graphene FET quantum dot with single electron tunneling

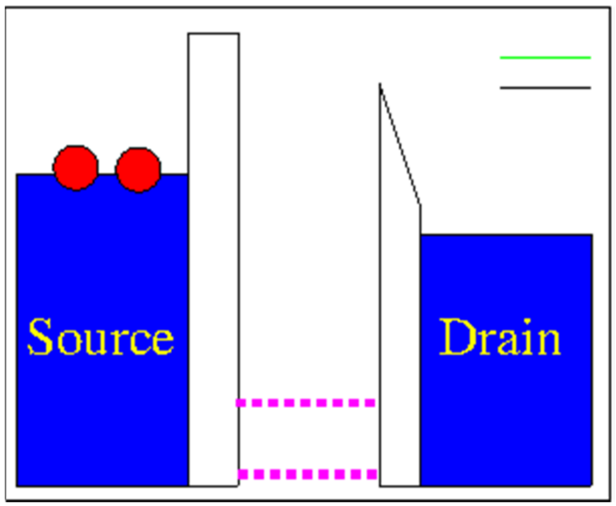
<u>Concept:</u> *Photon-assisted single electron tunneling* (PASET) into the graphene quantum dot (S. Shafraniuk, 2008-12).

<u>Dot setup:</u>



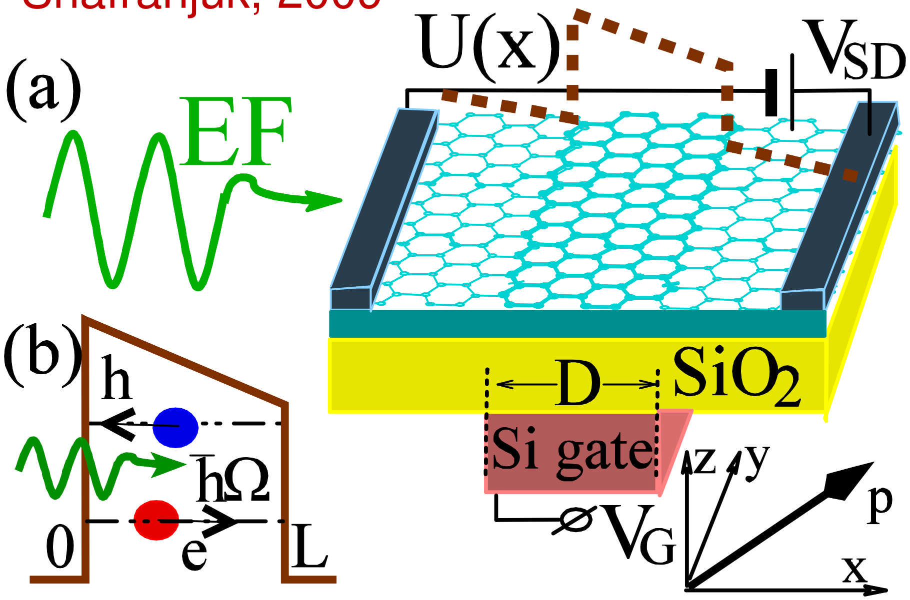
Photon-assisted single electron tunneling = (energy quantization) X (charge quantization)

Shafranjuk, 2008

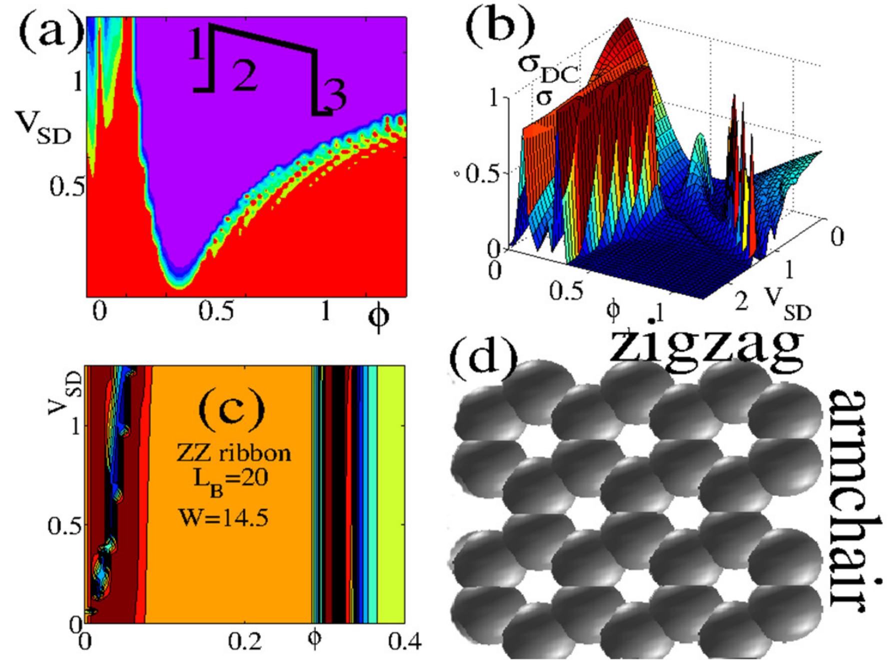


Graphene quantum dot THz sensor

Shafranjuk, 2009

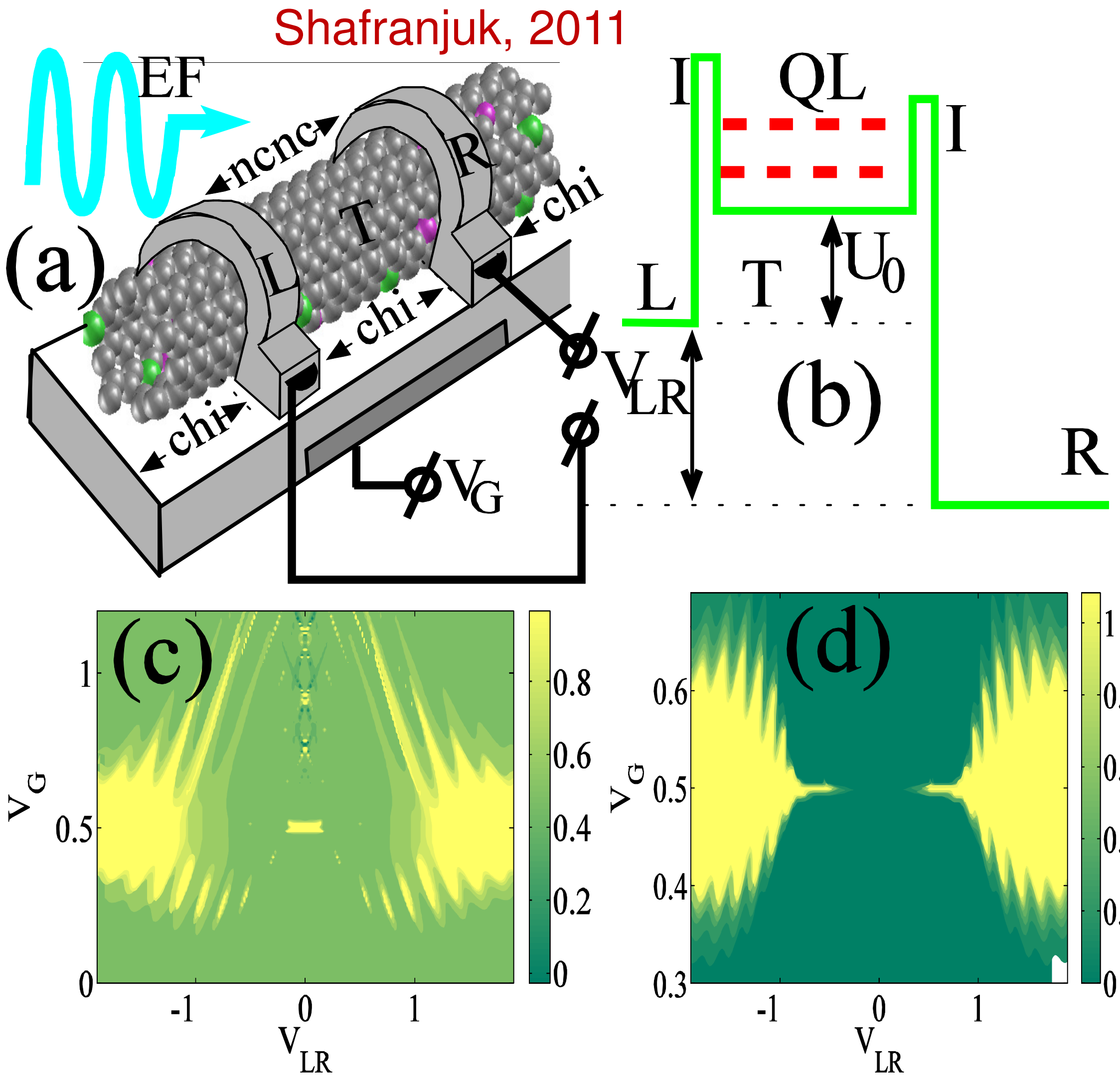


(a) The graphene quantum dot exposed to THz field and controlled by the gate voltage VG. The chiral barrier region is denoted by darker hexagons.
(b) Quantum e-h interference inside the chiral barrier.



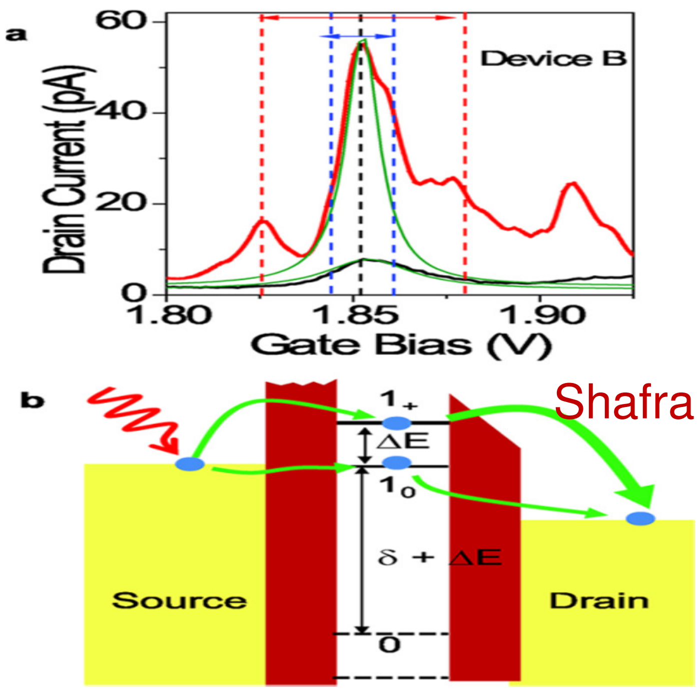
(a) The steady state differential conductivity *versus source draine voltage and azimuthal angle. (b) The 3D plot of the same. (c) The same for a ribbon* with zigzag edges,shown in *(d).*

CNT field effect transistor

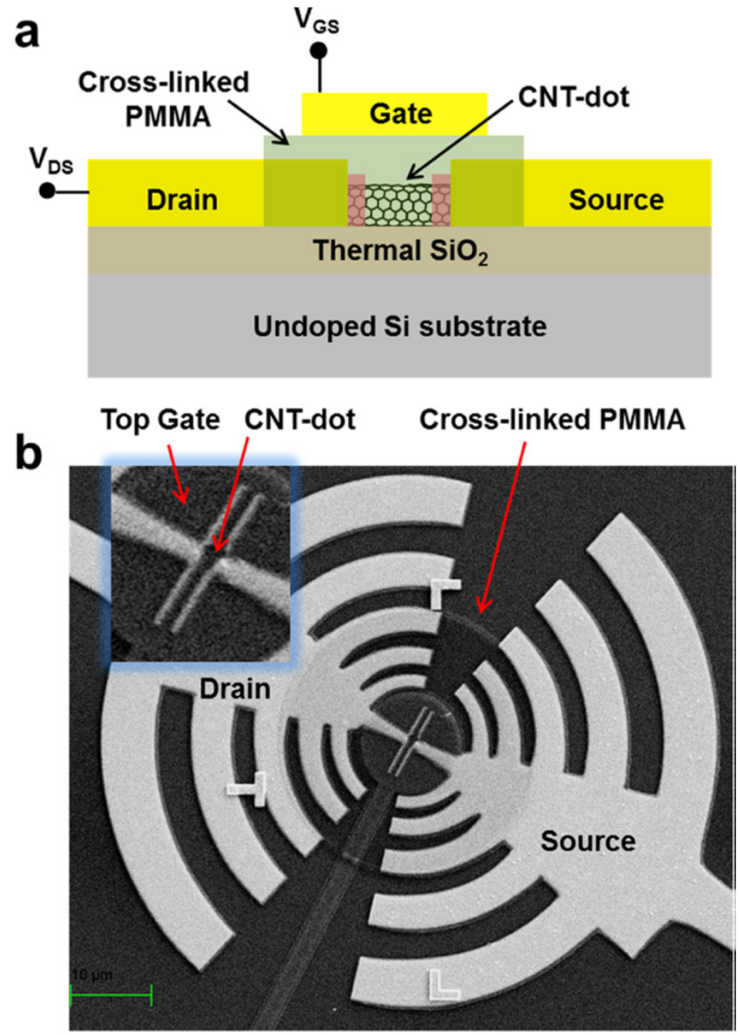


(a) A CNT junction exposed to an external THz field. The transport inside the CNT sections is chiral while the intersectional tunneling is non-chiral. (b) Quantized levels formed inside the biased quantum dot. (c),(d) The difference between the chiral (ch) and non-chiral steady state tunneling probabilities.

CNT quantum dot sensor



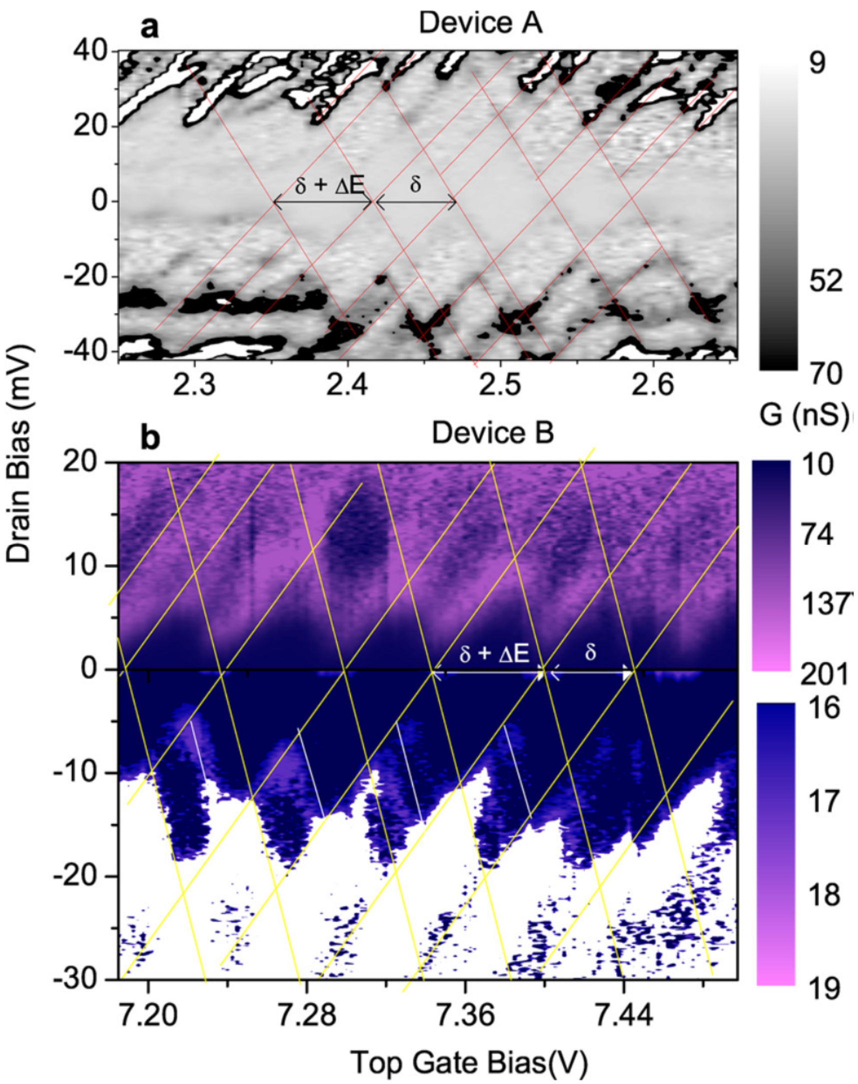
Shafranjuk, 2012



Top: The I-V-curve of the THz CNT-Dot sensor. Right: (a) The device structure. (b) Scanning electron microscope image of the device. Inset: Zoom-in of the quantum dot region. (Rinzan, 2012)

Quantum dot characterization

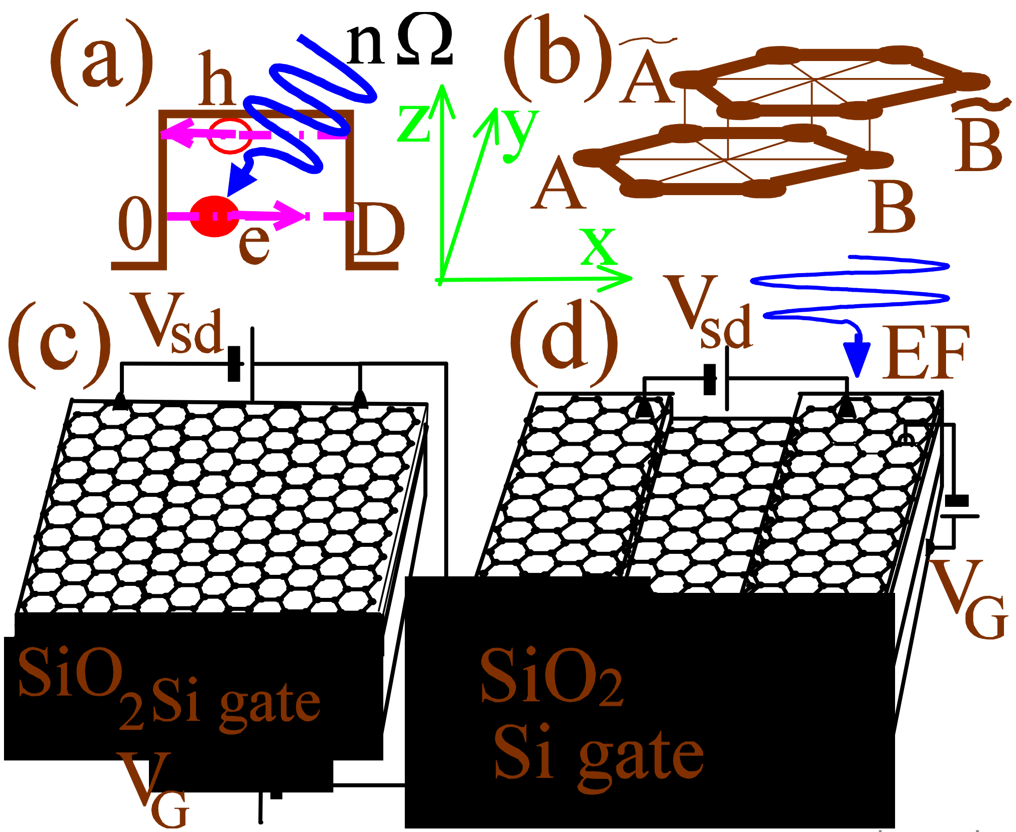
Rinzan, 2012



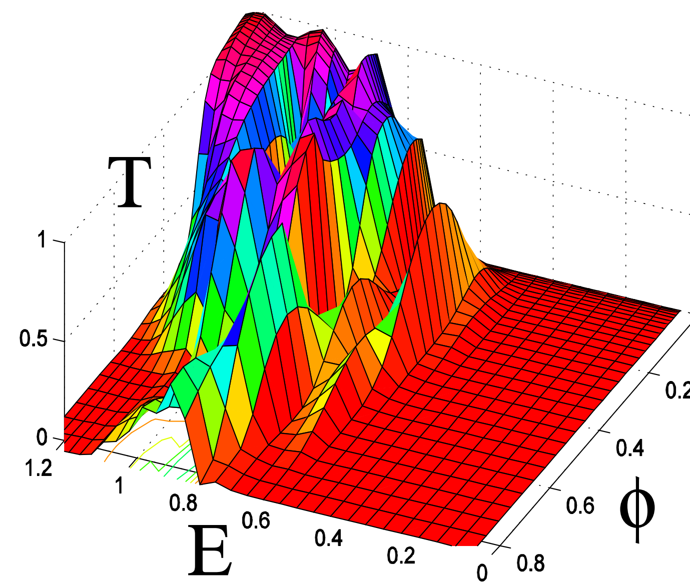
(a) Differential conductance as a function of gate voltage and source-drain bias for device A. (b) The corresponding diamond pattern. The extracted parameters: charging energy for sensor A (B) is δ = 13.7 (7.4) meV. The source and drain capacitances are C_S = 3.7 (11.8) aF and C_D = 4.4 (6.1) aF, the gate capacitance C_G = 3.6 (3.8) aF and the energy level spacing is ΔE = 3.3 (1.9) meV.

Photon-assisted chiral tunneling in bilayer graphene junctions

An ideal THz field sensor, S. Shafraniuk (2008)



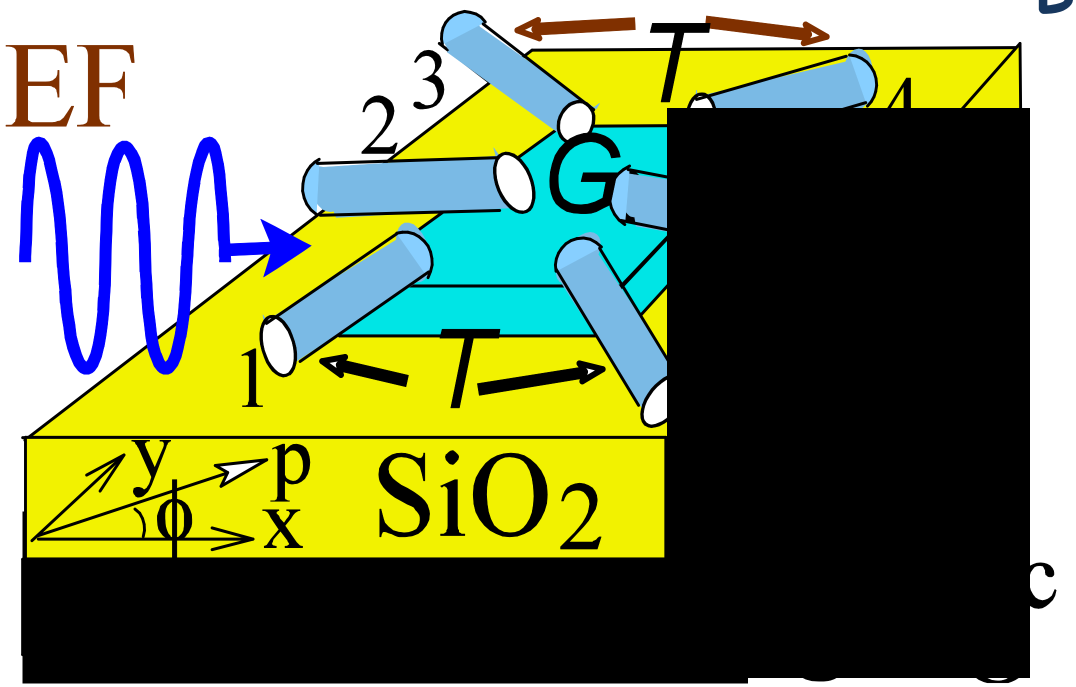
Transparency diagram



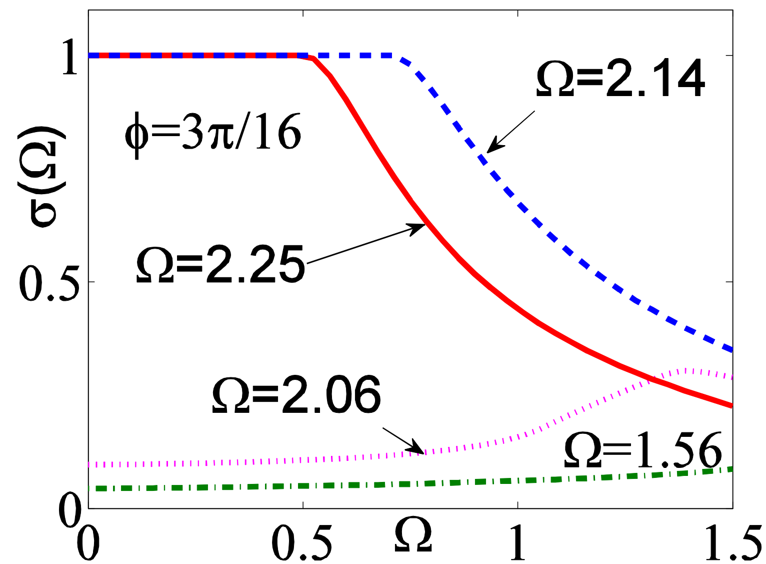
One exploits the a.c. field-induced angular redistribution of the d.c. current.

An ideal Klein tunneling sensor

S. Shafraniuk (2009)

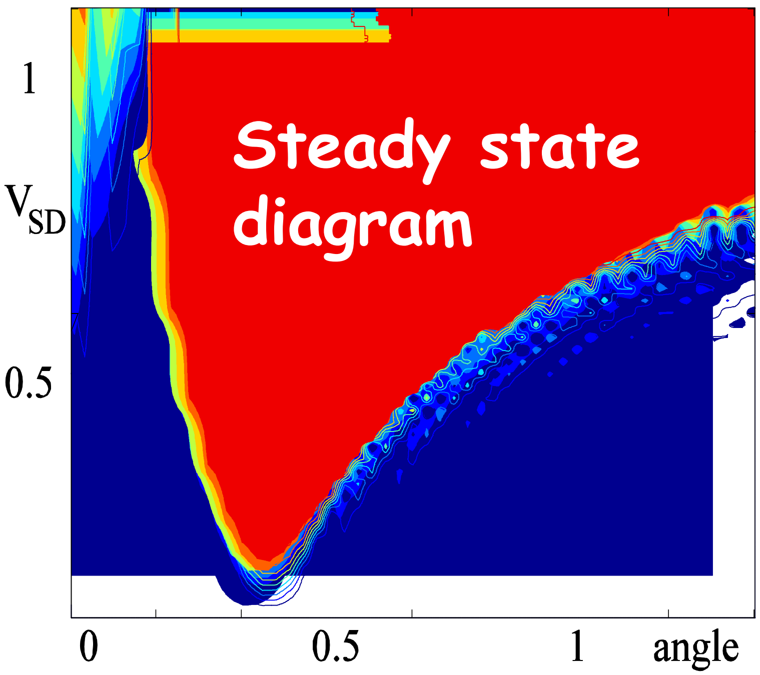


Between electrodes 2 and 4



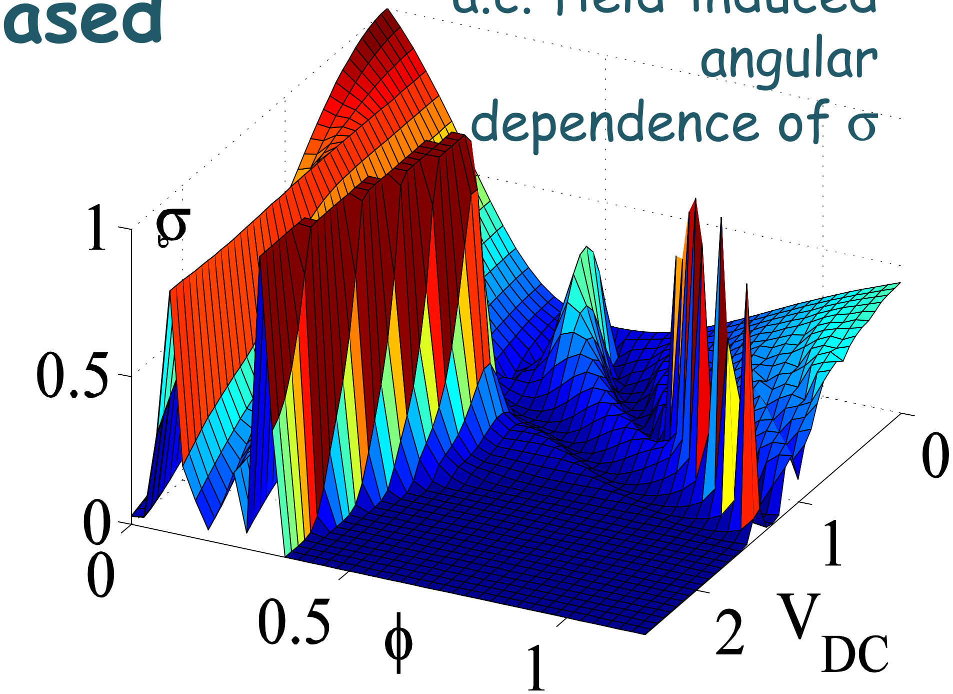
The deflection phenomena in a hybrid CNT/graphene junction exposed to an external electromagnetic field. The multi-terminal junction where the six carbon tube probes *T* are attached to the graphene ribbon *G*.

Directional photoelectric effect



Klein tunneling based

a.c. field-induced angular dependence of σ



<u>Possible applications</u>:

- The THz receivers/spectral analyzers.

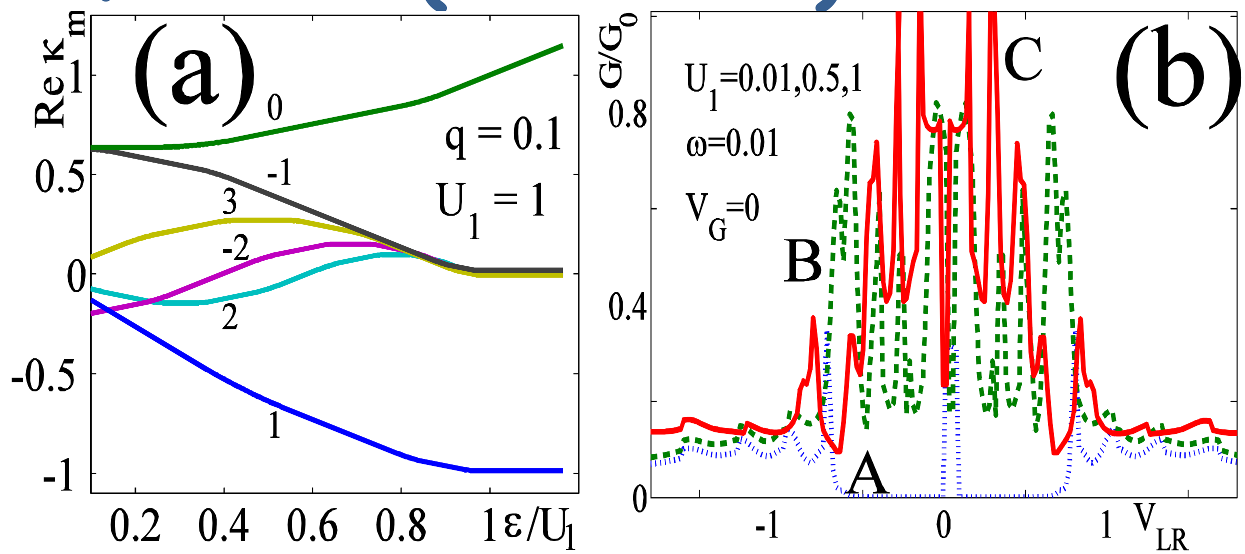
- THz field antennas.

-Electromagnetic wave and acoustic transmitters.

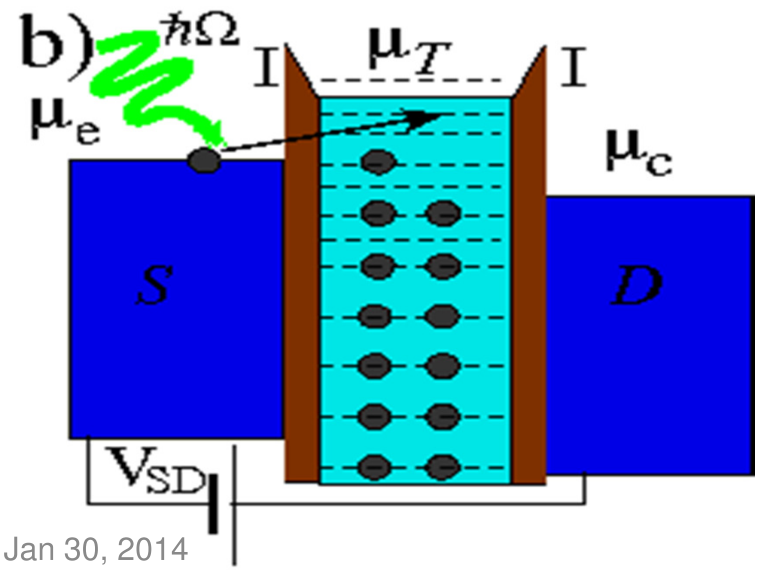
-Electric power sources and thermoelectric coolers.

Graphene/CNT THz sensor
S. Shafraniuk (2006-12)

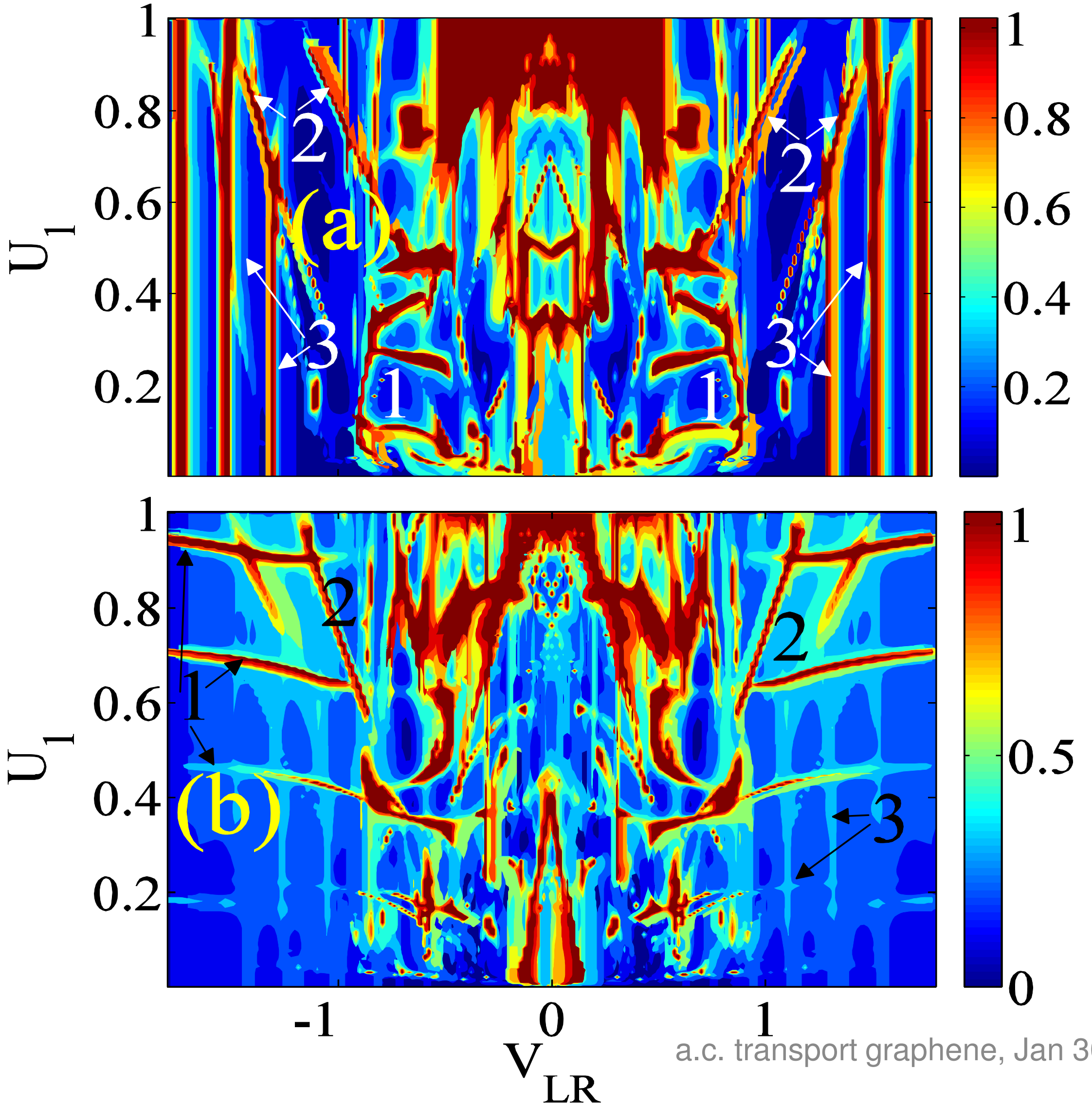
Electric differential conductivity of the CNT FET exposed to the THz field.
Method: Floquet technique + the non-equilibrium Green function method + S-matrix formalism.



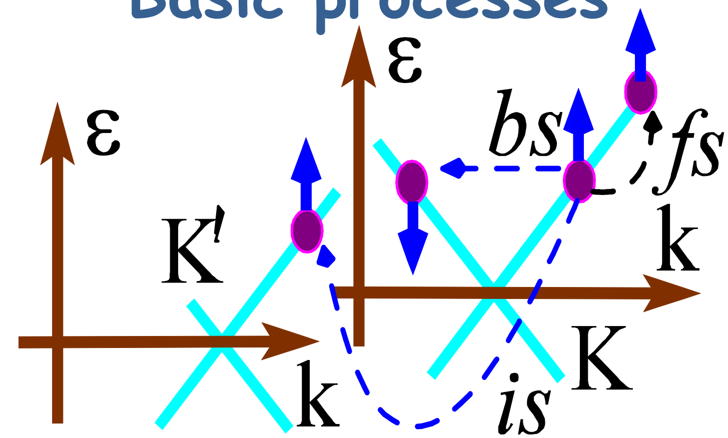
Energy diagram of SET FET



Photon-assisted Klein tunneling in graphene/CNT FET quantum dot



Basic processes



Improving the sensitivity:
The a.c. field influences the chiral tunneling. The sharp peaks and dark spots and lines in the contour plots: Resonances = (energy quant) X (charge quant) X (THz field quant).

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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