Quantum Pumping in Graphene

Babak Abdollahipour

University of Tabriz

Workshop on "Quantum transport in graphene"

(In memory of late Prof. Malek Zareyan)

IPM

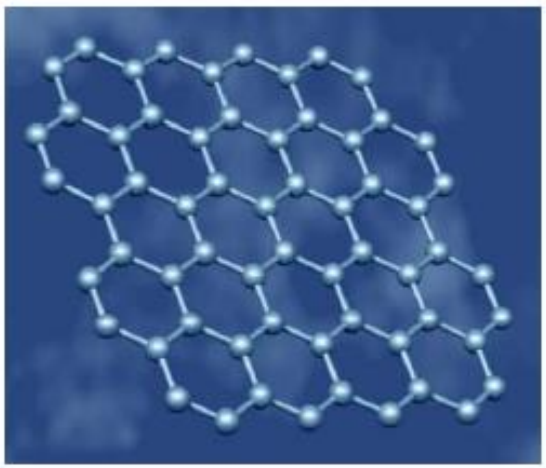
Ordibehesht-1393

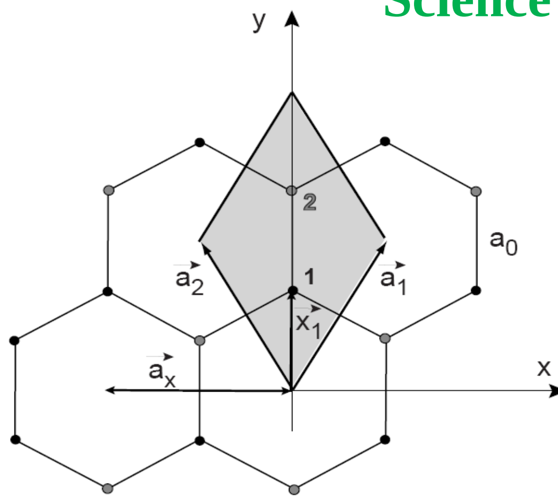
Contents

- **Graphene and its unique properties**
- **Quantum pumping in mesoscopic systems**
- **Proposed quantum pumps in graphene**
- **New features of the graphene quantum pump**

Graphene structure

Science 306, 666 (2004)

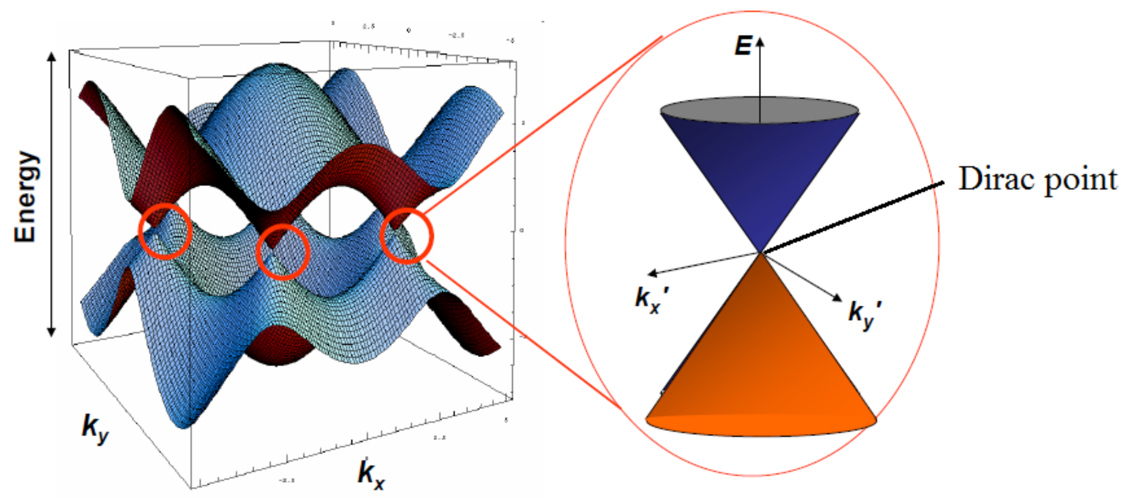




two carbon atoms in unit cell

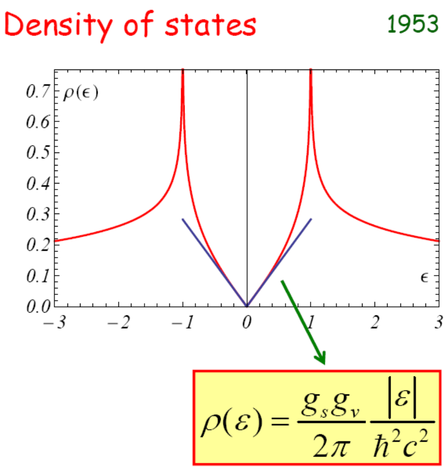
Band structure of Graphene

Electrons in graphene behave like massless Dirac fermions

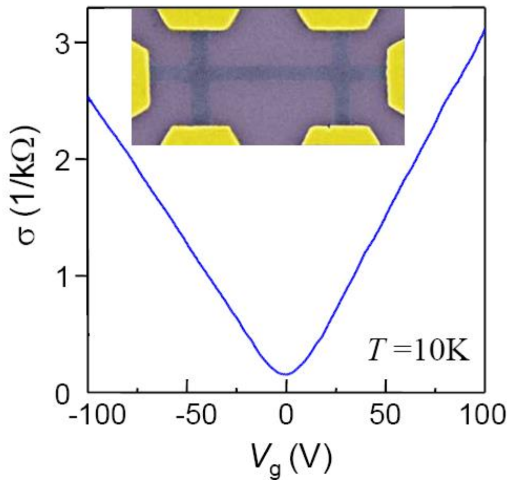


Graphene and its unique properties

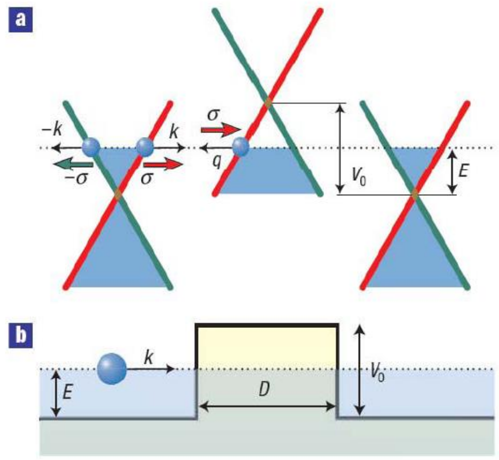
Minimal conductivity of graphene



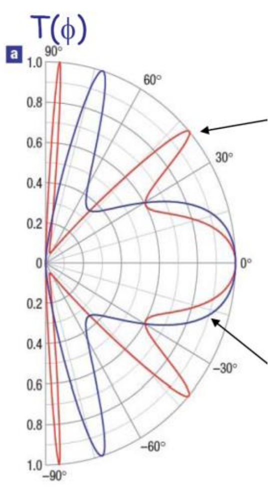
Nature 438, 197 (2005)



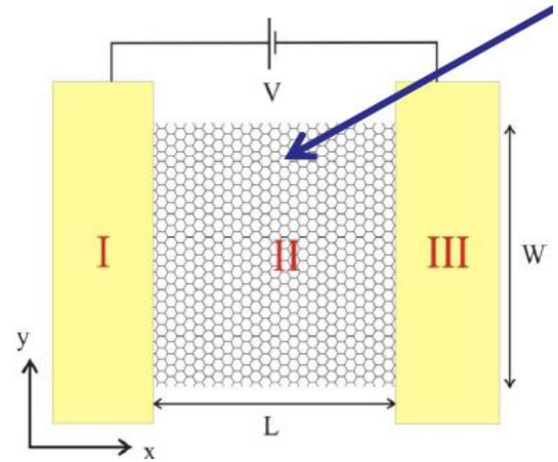
Klein tunneling in graphene



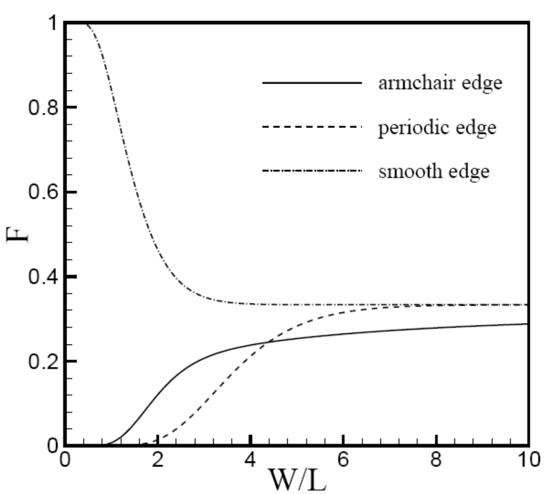
Science 315, 1252 (2007)



Pseudo-diffusive transport in graphene



Phys. Rev. Lett. 96, 246802 (2006)



Quantum Pumping
(How to generate a current at zero bias)

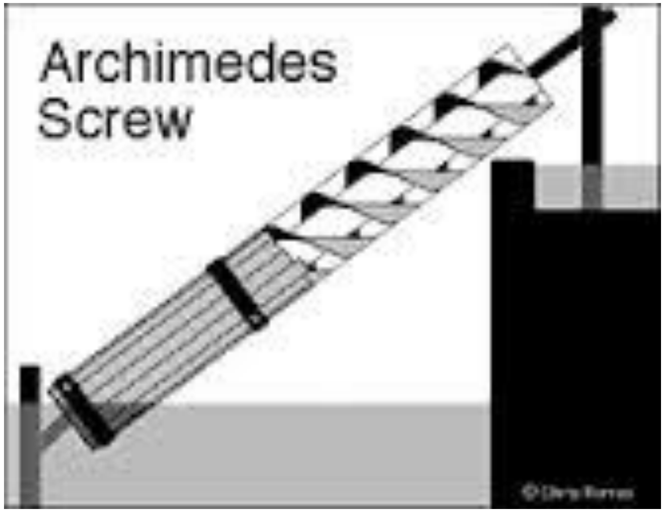
A dc current is usually associated to a dissipative flow of the electrons in response to an applied bias voltage. However, in systems of mesoscopic scale a dc current can be generated even at zero bias. This captivating quantum coherent effect is called quantum pumping.

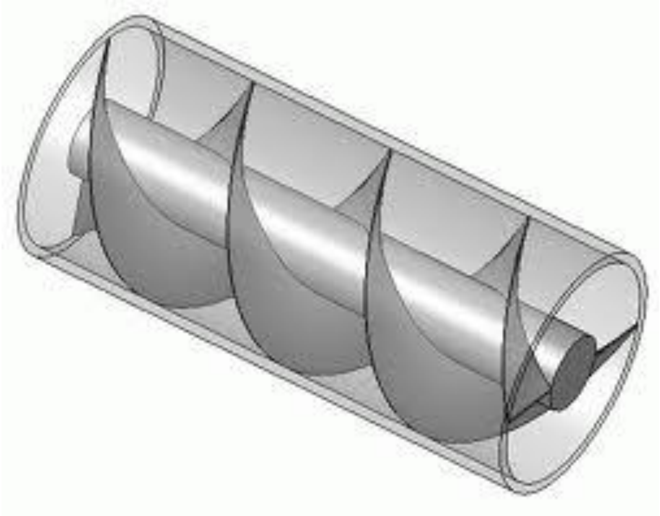
Quantum Pumping allows exploring fundamental issues regarding the role of different symmetries in transport.

A *Quantum Pump* may provide novel ways of reducing the dissipation of energy as wasteful heat, define a better current standard closing the metrological triangle, or even be used for quantum computing.

B. L. Altshuler and L. Glazman, Science, 283, 1864 (1999)
K. Das Kunal, S. Kim and A. Mizel, Phys. Rev. Lett. 97, 096602 (2006)
Y. Avishai, D. Cohen and N. Nagaosa, Phys. Rev. Lett. 104, 196601 (2010)
L. Wang, M. Troyer and X. Dai, Phys. Rev. Lett. 111, 026802 (2013)

Classical Pumping

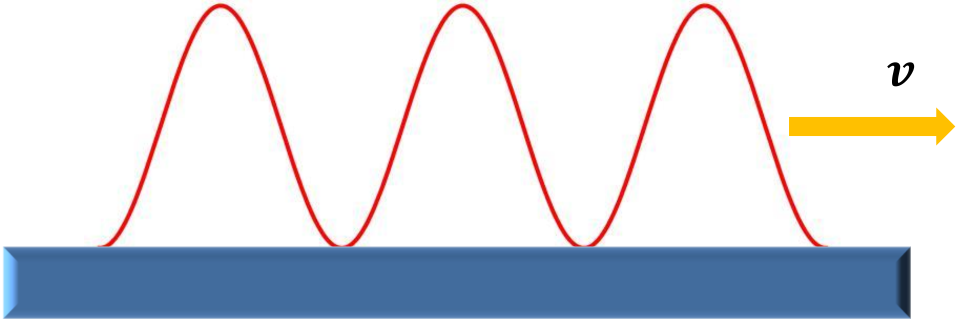




Quantum Pumping

Pumping of electrons by a moving periodic potential

$V(x) = V(x+a)$ $V(x,t) = V(x - vt)$



Quantized charge pumping

$$Q_P = I_P T = (nev)\left(\frac{a}{v}\right) = eN$$

D. J. Thouless, *Phys. Rev. B* 27, 6083 (1983)

Scattering approach to Quantum pumping

Scattering Matrix

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = S \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

S depends on parameters X_1 and X_2

Emissivity: charge emitted by contact m in response to a variation of the parameter X

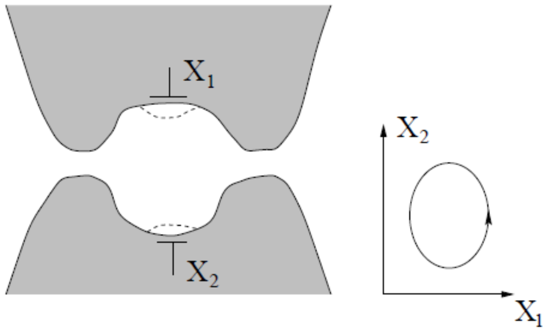
$$\frac{dn_m}{dX} = \frac{1}{2\pi} \sum_{\alpha \in m,\beta} \mathrm{Im}\left\{ \frac{\partial S_{\alpha,\beta}}{\partial X} S^*_{\alpha,\beta} \right\}$$

Büttiker et al., Z. Phys. B **94**, 133, (1994)

Pumping parameters

$$\delta X_1(t) = \delta X_1 \sin(\omega t)$$

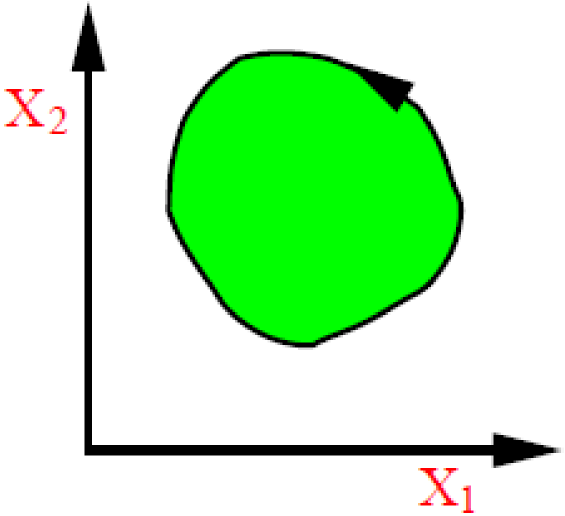
$$\delta X_2(t) = \delta X_2 \sin(\omega t - \phi)$$



Brouwer's formula

$$Q_m = \frac{e}{\pi} \int_A dX_1 dX_2 \sum_{\alpha \in m, \beta} \Pi_{\alpha,\beta}$$

with $\Pi_{\alpha,\beta} = \text{Im} \left\{ \frac{\partial S^*_{\alpha,\beta}}{\partial X_1} \frac{\partial S_{\alpha,\beta}}{\partial X_2} \right\}$



P. Brouwer, Phys. Rev. B 58, R10135 (1998)

Pumped current per cycle:

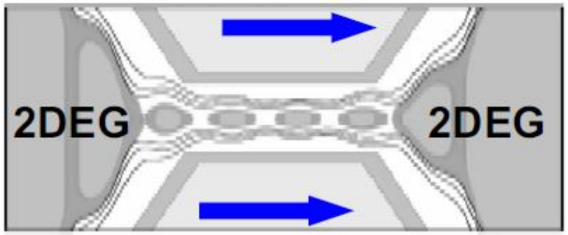
Weak pumping: δX_i small such that $\Pi_{\alpha,\beta}$ is constant during the cycle

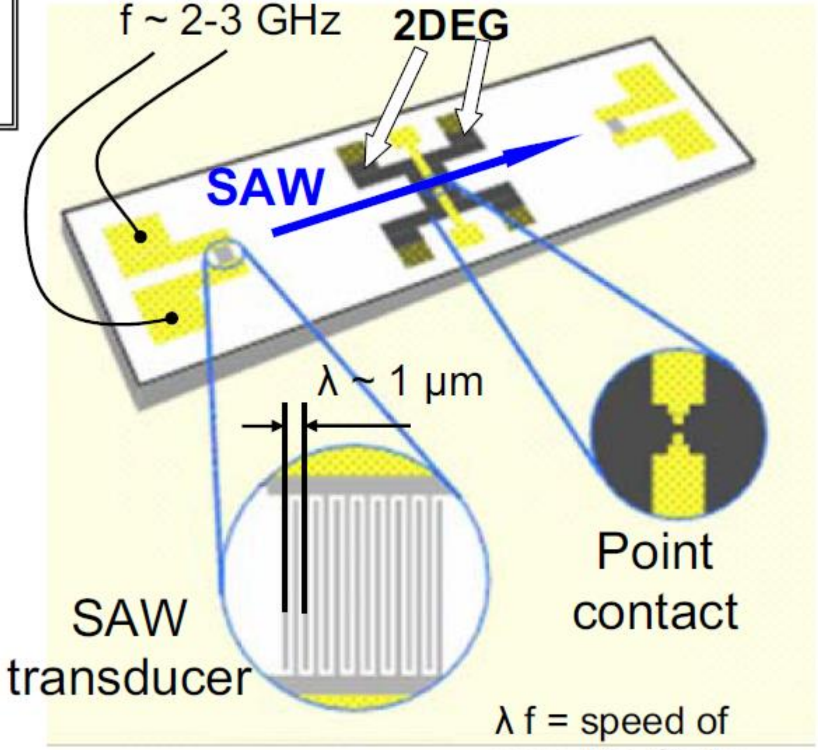
$$\delta I = \frac{\omega e \sin\phi \, \delta X_1 \delta X_2}{2\pi} \sum_{\alpha \in 1} \sum_{\beta} \text{Im} \frac{\partial S^*_{\alpha\beta}}{\partial X_1} \frac{\partial S_{\alpha\beta}}{\partial X_2}$$

Experimental realization

Quantized pumping with **S**urface **A**coustic **W**aves

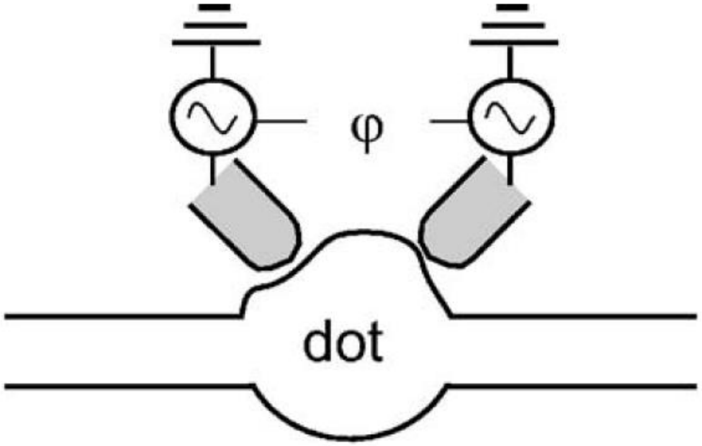
- A running wave of mechanical deformation creates a **moving potential profile** due to piezoelectric properties of GaAs
- In the depleted region of a point contact **screening is reduced**
- Periodic potential can capture and transfer an integer number of electrons

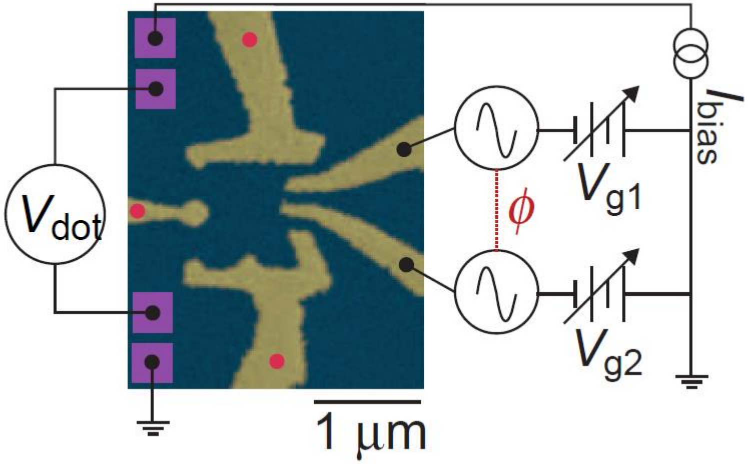




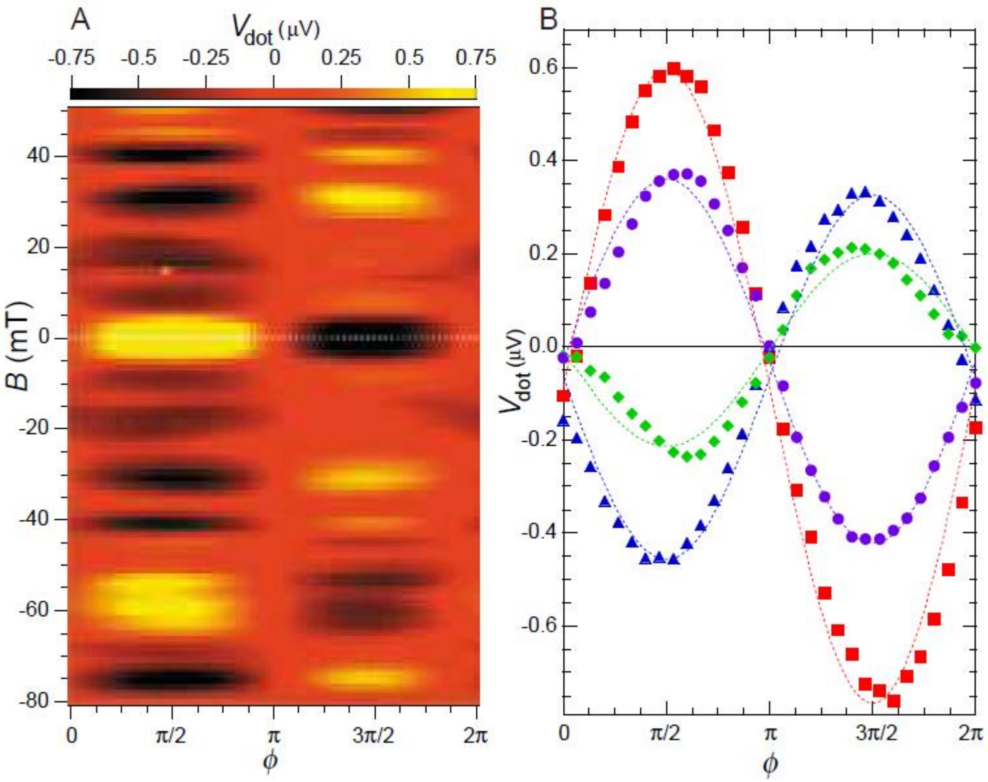
V. I. Talyanskii, *et al.* Phys. Rev. B 56, 23 (1997)

Pumping through an open quantum dot





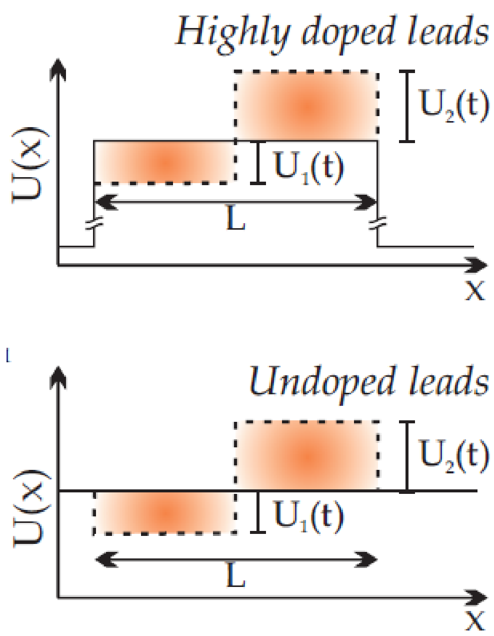
M. Switkes, *et al*. Science 283, 1905 (1999)

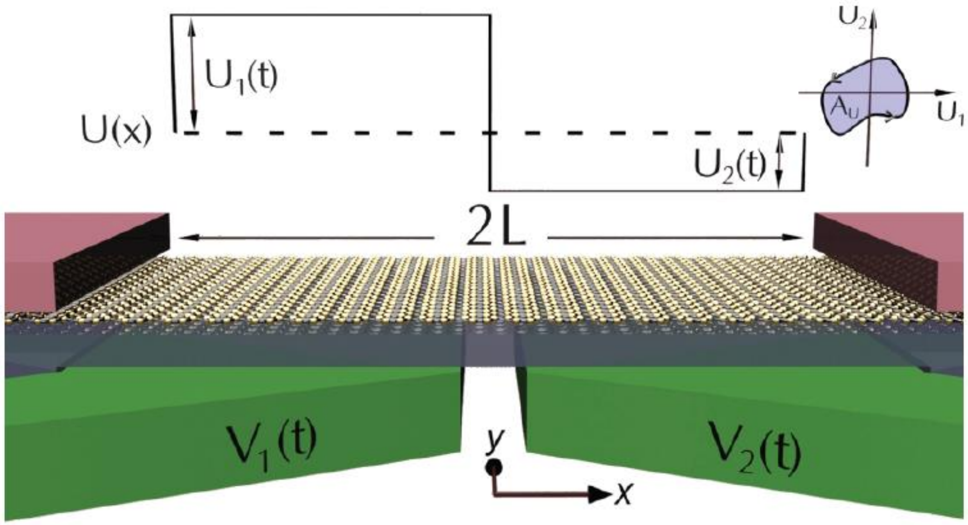


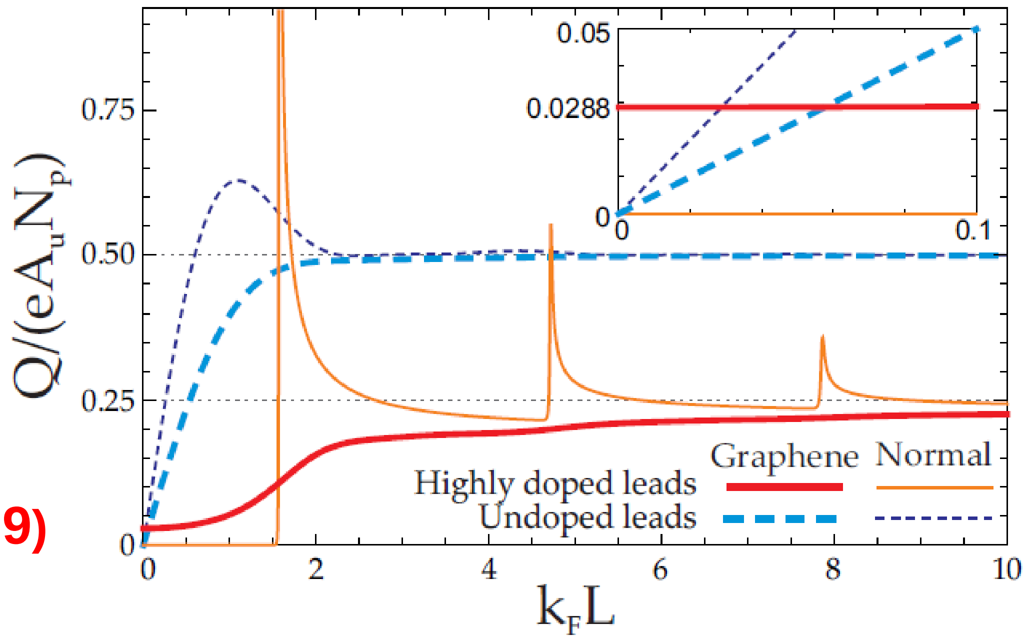
$T = 330$ mK

$f = 10$ MHz

Pumping by two square barriers

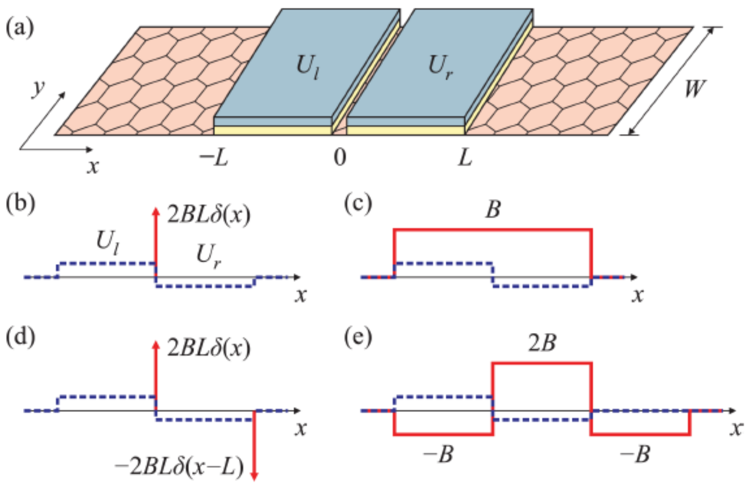


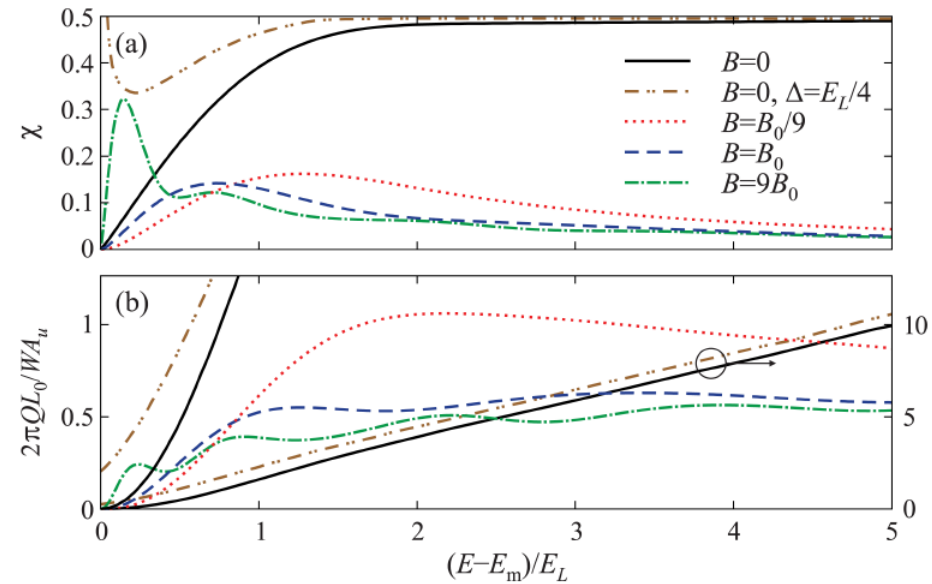




E. Prada, *et al.*
Phys. Rev. B 80, 245414 (2009)

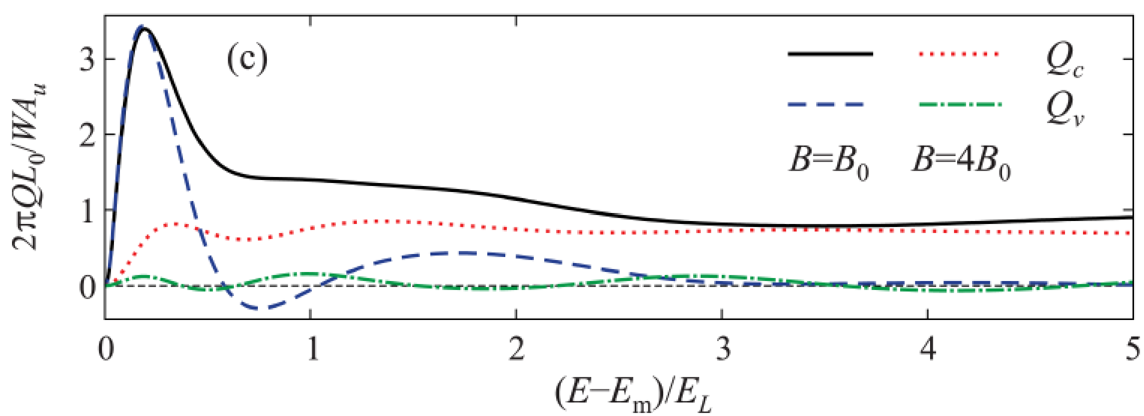
Effect of the magnetic barriers



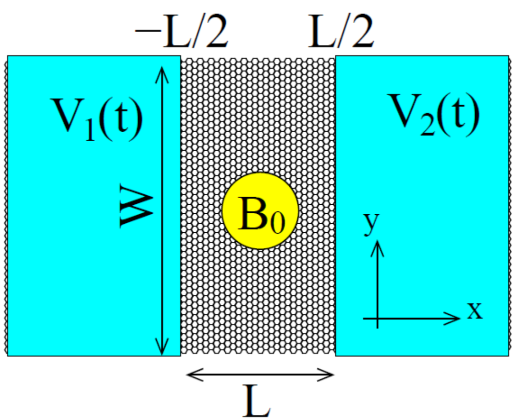


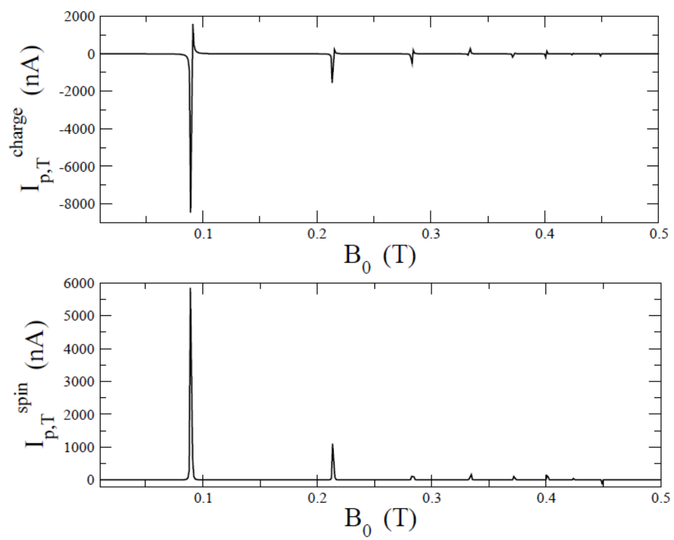
Valley-polarized pumped current

E. Grichuk and E. Manykin
Eur. Phys. J. B 86, 210 (2013)



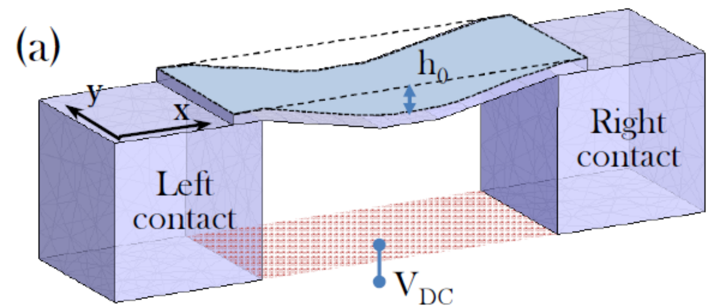
Spin current pumping



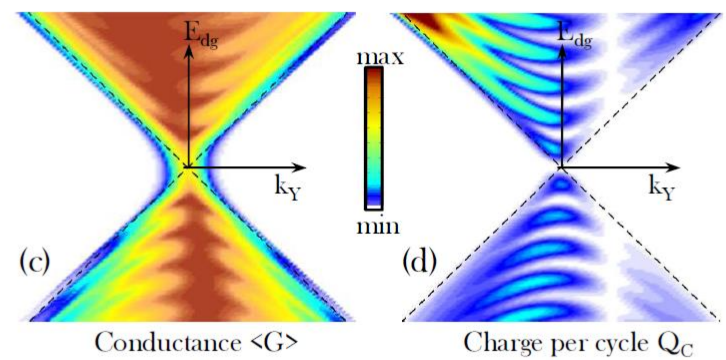


R. P. Tiwari and M. Blaauboer, Appl. Phys. Lett. 97, 243112 (2010)

Electron pumping in graphene mechanical resonators



Time varying deformation of graphene modifies its electronic spectrum through the modulation of electrostatic doping and in-plane strain



T. Low, *et al.* Nano Lett. 12, 850 (2012)

New features of the graphene quantum pump

Charge pumping by oscillating and vibrating thin barriers

Oscillating thin barriers

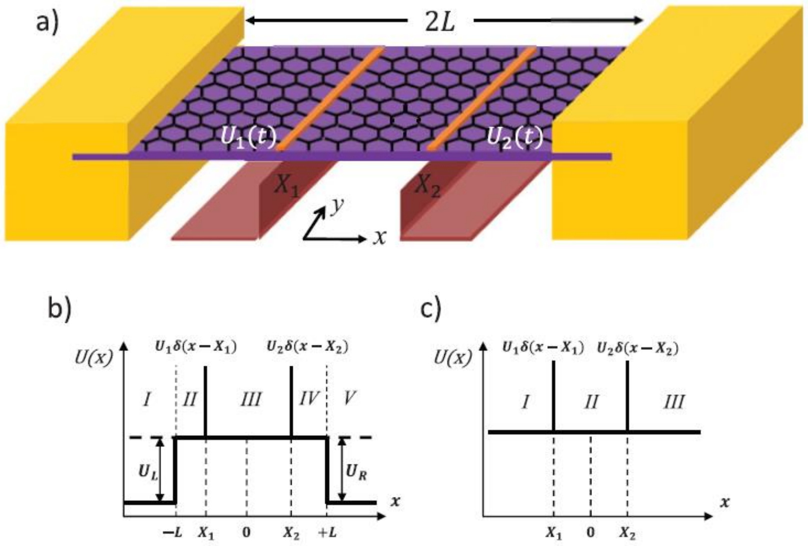
$$U_1(t) = U_{1,0} + \delta U_1 \cos(\omega t),$$
$$U_2(t) = U_{2,0} + \delta U_2 \cos(\omega t + \varphi),$$

$$I_0 = (\omega/2\pi) e \delta U_1 \delta U_2 \sin\varphi$$

Vibrating thin barriers

$$X_1(t) = X_{1,0} + \delta X_1 \cos(\omega t),$$
$$X_2(t) = X_{2,0} + \delta X_2 \cos(\omega t + \varphi),$$

$$I_0 = (\omega/2\pi) e \delta X_1 \delta X_2 \sin\varphi$$

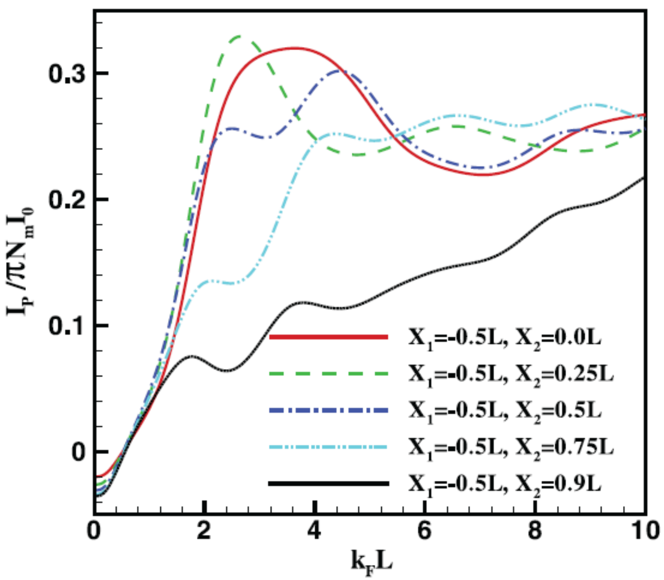


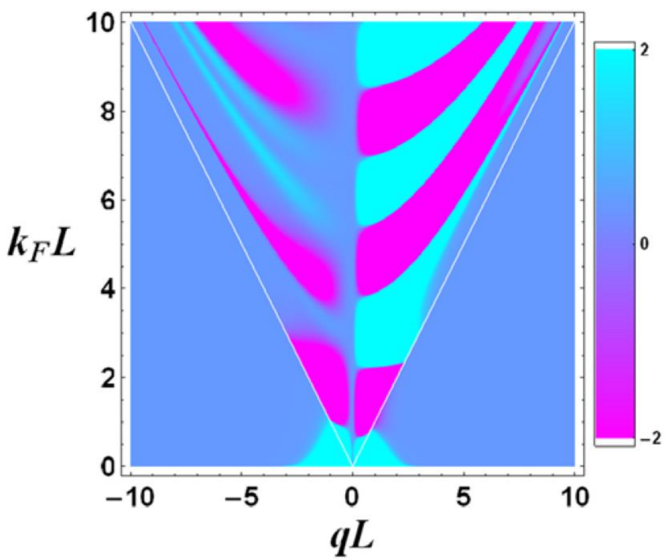
$$I_P = I_0 \sum_{\alpha = L,R} \mathrm{Im}\left(\frac{\partial S_{L,\alpha}}{\partial \eta_1} \frac{\partial S^*_{L,\alpha}}{\partial \eta_2} \right)$$

B. Abdollahipour and R. Mohammadkhani,
J. Phys.: Condens. Matter 26, 085304 (2014)

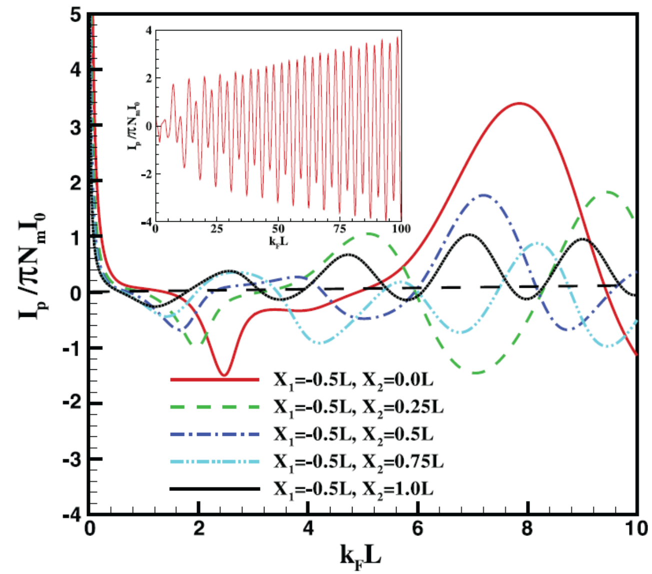
New features of the graphene quantum pump

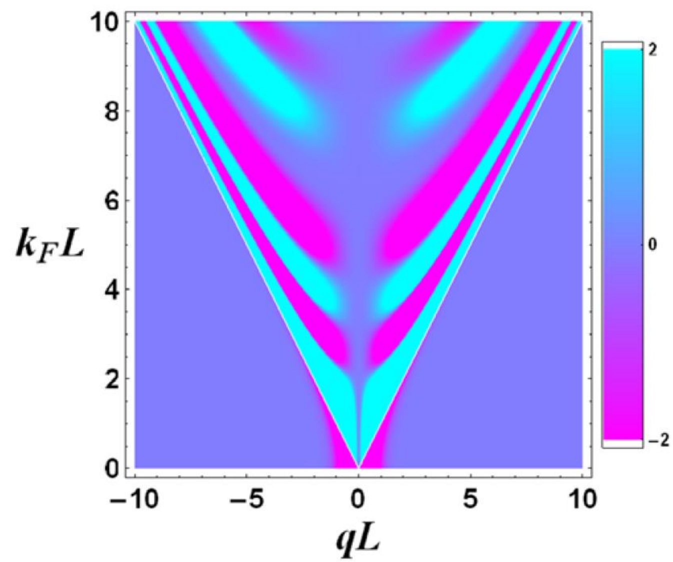
Oscillating thin barriers





Vibrating thin barriers

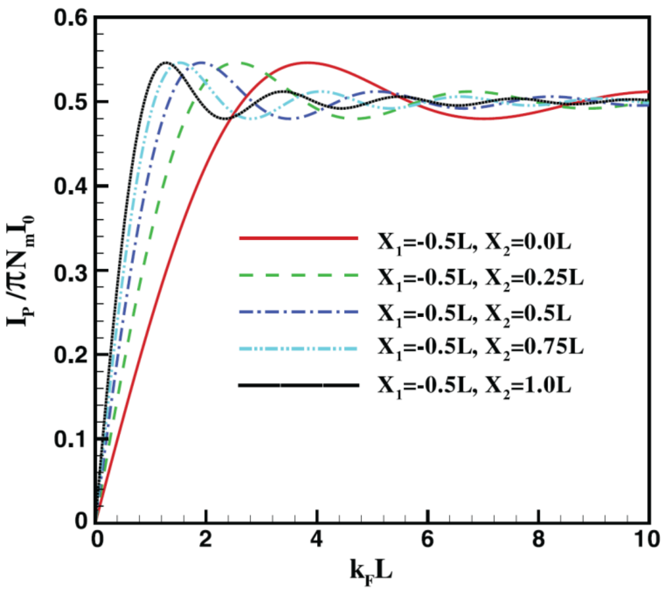




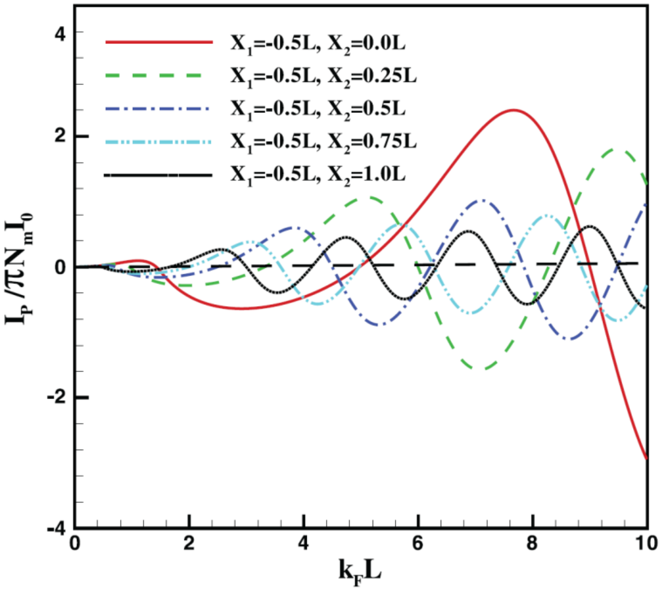
Highly doped leads

Undoped leads

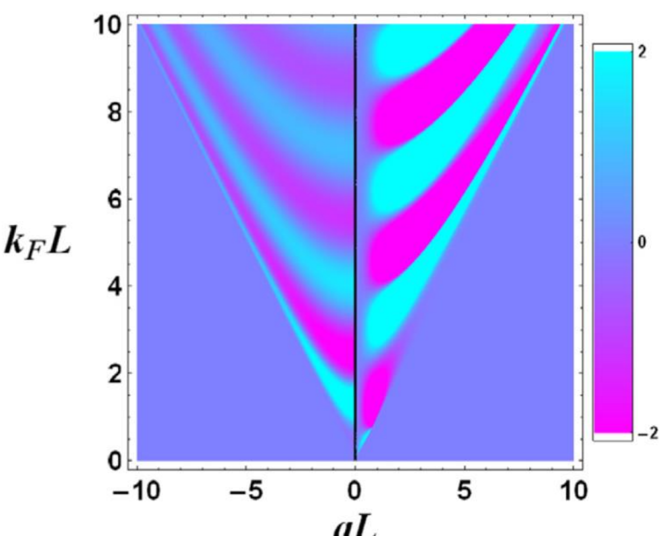
Oscillating thin barriers



Vibrating thin barriers



Comparison with the normal pump



Graphene

Thanks for your attention