Nano-devices driven by noise: graphene based metamaterials and memristors

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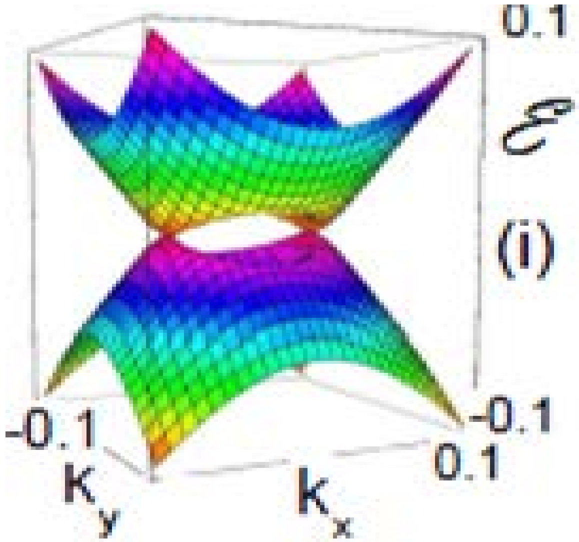
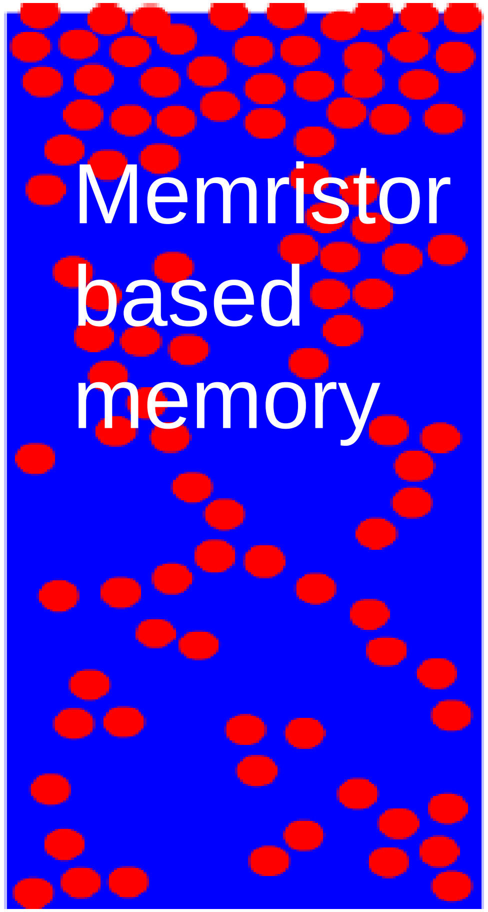
Graphene





Thanks for invitation

Prof. Alexander Gorban

Dr. Ivan Tyukin

Looking forward for future collaboration

Key collaborators

Fabio Marchesoni (*Physics Department, Univ. of Camerino, Italy*)

Peter Hanggi (*University of Augsburg, Germany*)

Franco Nori (*RIKEN, Japan; University of Michigan, USA*)

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Stanley Williams and Sasha Bratkovsky (*Hewlett-Packard Laboratories, Californiaity, USA)*,

Sasha Alexandrov (*Loughborough University, UK*)

Alex Zagoskin (*Loughborough University, UK*)

Simon Bending (*University of Bath, UK*)

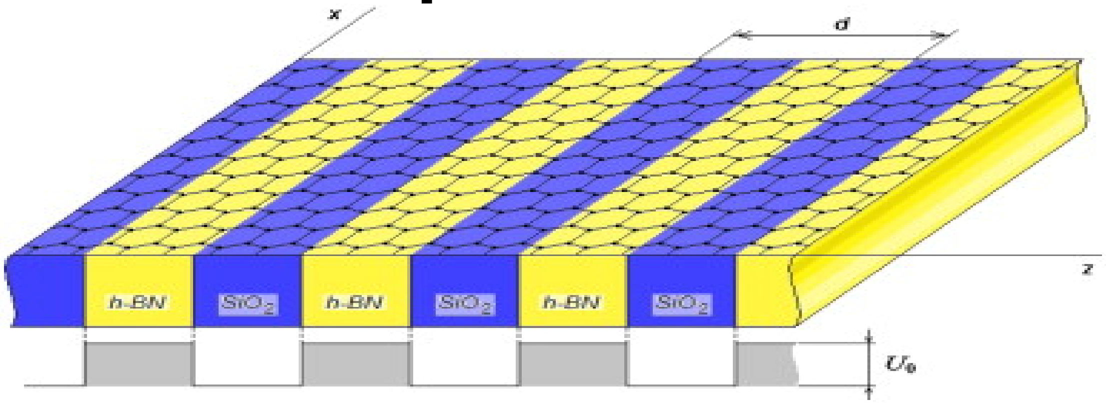
Outline

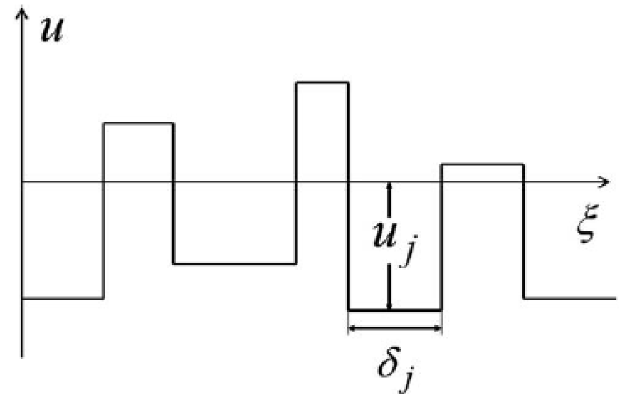
Graphene in space- and time-dependent potentials as metamaterial to comtrol electron transport.

Relativistic Brownian motion on a graphene chip.

Simulating memristors and future flash memory

Graphene as metameterials

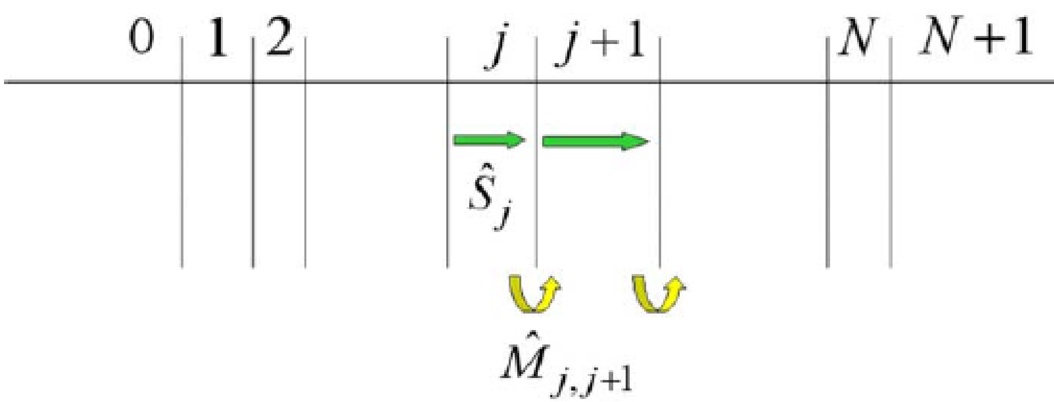




$$v_F(\vec{\sigma}\cdot\hat{\mathbf{p}})\Psi=(E-V)\Psi$$

$$\psi_{(A,B)_j}=\psi^{(+)}_{(A,B)_j}e^{i\kappa_j\xi}+\psi^{(-)}_{(A,B)_j}e^{-i\kappa_j\xi},\quad \text{where}\quad \kappa_j=\sqrt{(\varepsilon-u_j)^2-\beta^2}$$

$$(\psi^{(+)}_{j+1},\psi^{(-)}_{j+1})^T=\hat{M}_{j,j+1}(\psi^{(+)}_{j},\psi^{(-)}_{j})^T$$

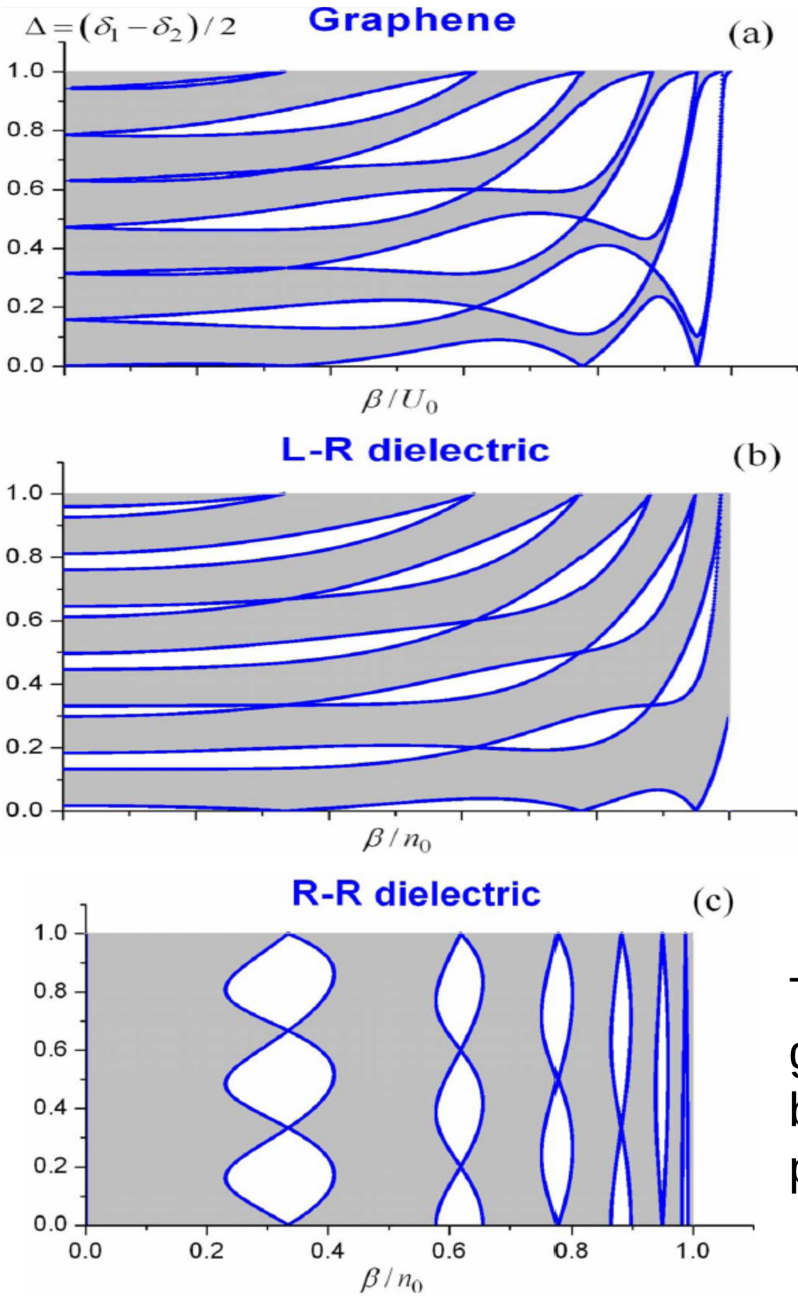


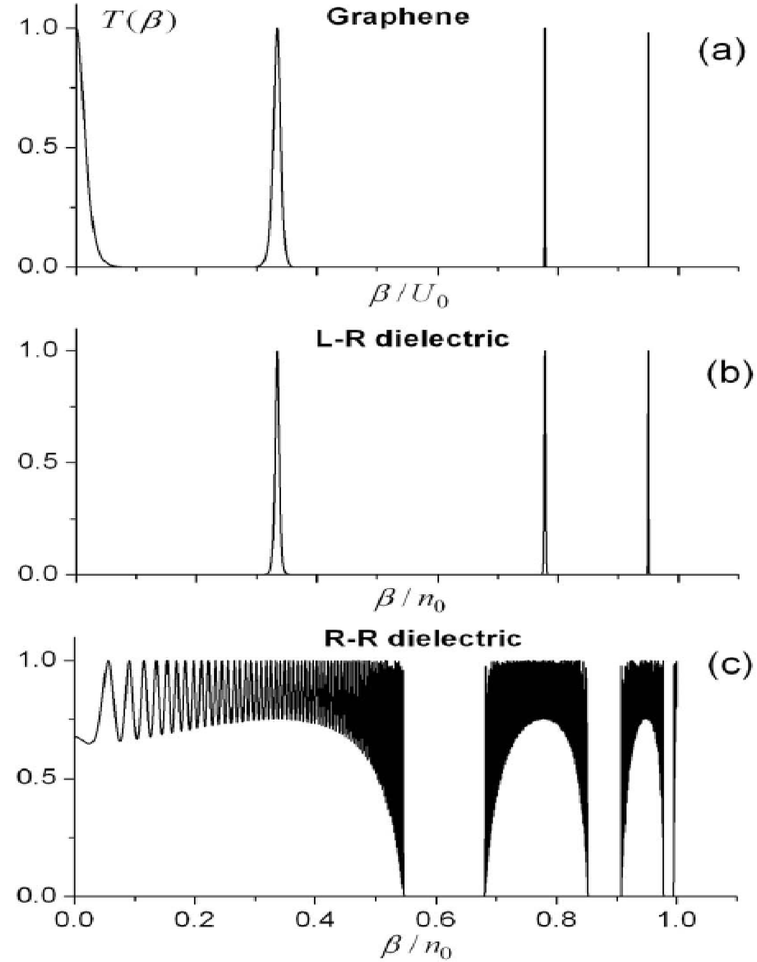
Such a transmission matrix approach is always used for optical photonic crystals.

This allows us to compare transmission of Dirac electrons in periodic electrostatic potentials and electromagnetic waves in photonic crystals.

Phys. Rev. B **79**, 075123 (2009).

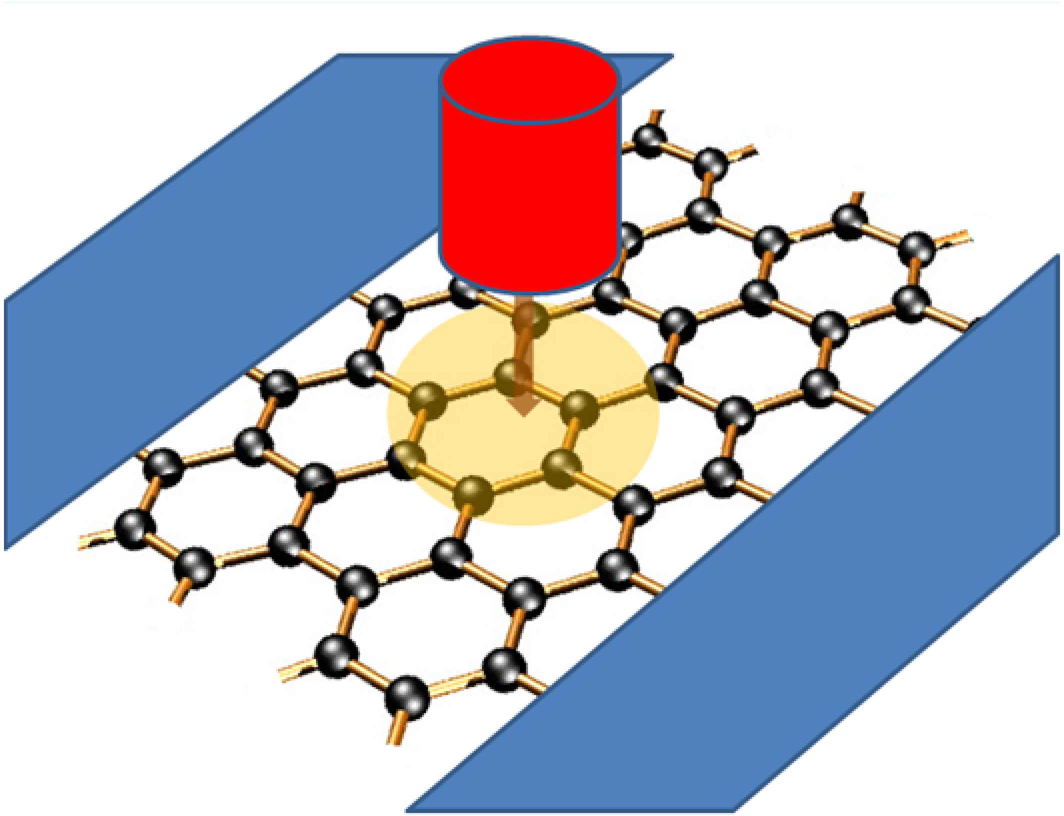
Graphene superlattices and Photonic crystals





Transmission coefficient for a) periodic graphene subject to an alternating potential, b) periodic L-R dielectric structure, and c) periodic R-R dielectric structure.

Laser controlled graphene electronics



Massless Dirac fermions in a laser field as a counterpart of graphene superlattices
S.E. Savel’ev and A.S. Alexandrov, Phys. Rev. B **84**, 035428 (2011)

Current Resonances in Graphene with Time-Dependent Potential Barriers
S.E. Savel’ev, W. Häusler, P. Hänggi, Phys. Rev. Lett. **109**, 226602 (2012)

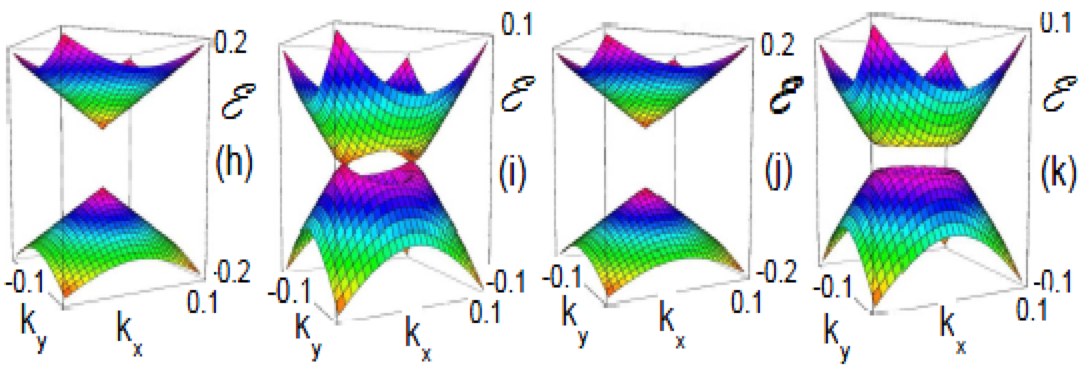
Graphene in a strong laser field as a counterpart of graphene superlattices

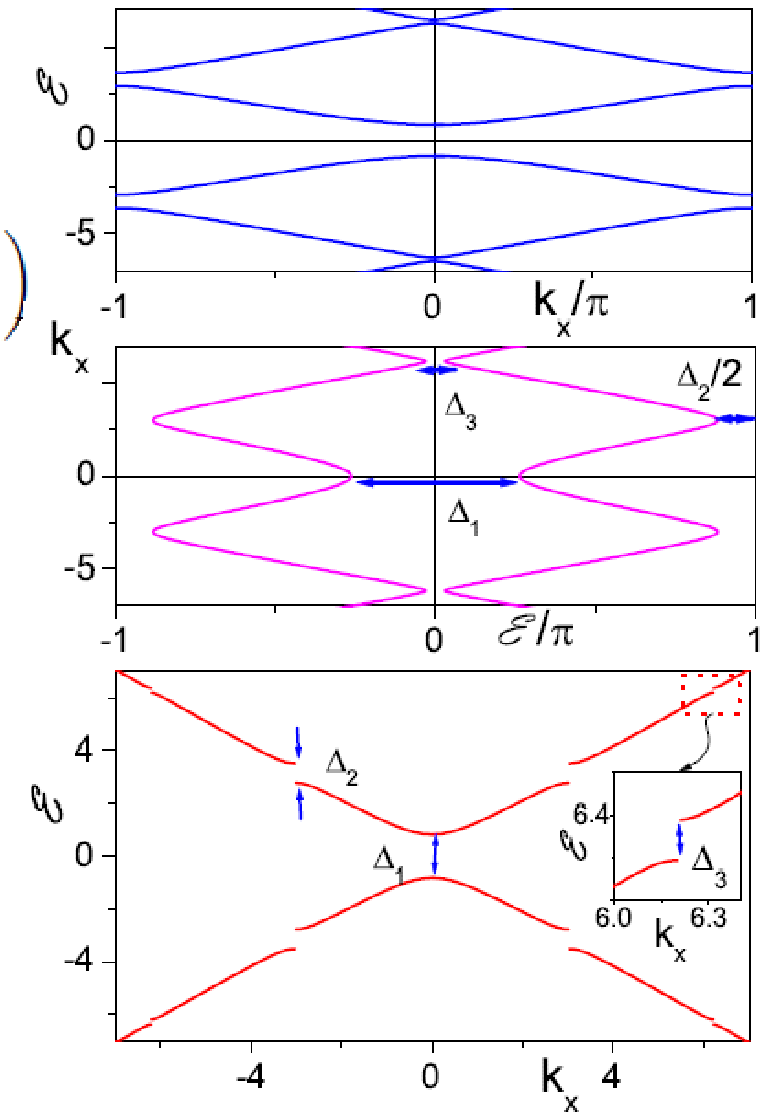
$$i\frac{d}{dx}\begin{pmatrix}\varphi_A\\ \varphi_B\end{pmatrix}=\begin{pmatrix} ik_y & -\mathcal{E}+U(x)\\ -\mathcal{E}+U(x) & -ik_y\end{pmatrix}\begin{pmatrix}\varphi_A\\ \varphi_B\end{pmatrix}$$

$$i\frac{d}{dt}\begin{pmatrix}\phi_A\\ \phi_B\end{pmatrix}=\begin{pmatrix} 0 & k_x-A_x(t)-ik_y\\ k_x-A_x(t)+ik_y & 0\end{pmatrix}\begin{pmatrix}\phi_A\\ \phi_B\end{pmatrix}$$

$$\tilde{\phi}_A=(\phi_A-i\phi_B)/\sqrt{2} \qquad \tilde{\phi}_B=(\phi_B-i\phi_A)/\sqrt{2}$$

$$i\frac{d}{d\xi}\begin{pmatrix}f_A\\ f_B\end{pmatrix}=\begin{pmatrix} i\beta & Q+\mu(\xi)\\ Q+\mu(\xi) & -i\beta\end{pmatrix}\begin{pmatrix}f_A\\ f_B\end{pmatrix}$$





Current resonances in graphene with time dependent potential barriers

$$H_0 = v_{\mathrm{F}}\left[\hat{\tau}_z\hat{\sigma}_x\hat{p}_x + \hat{\sigma}_y\hat{p}_y\right]$$

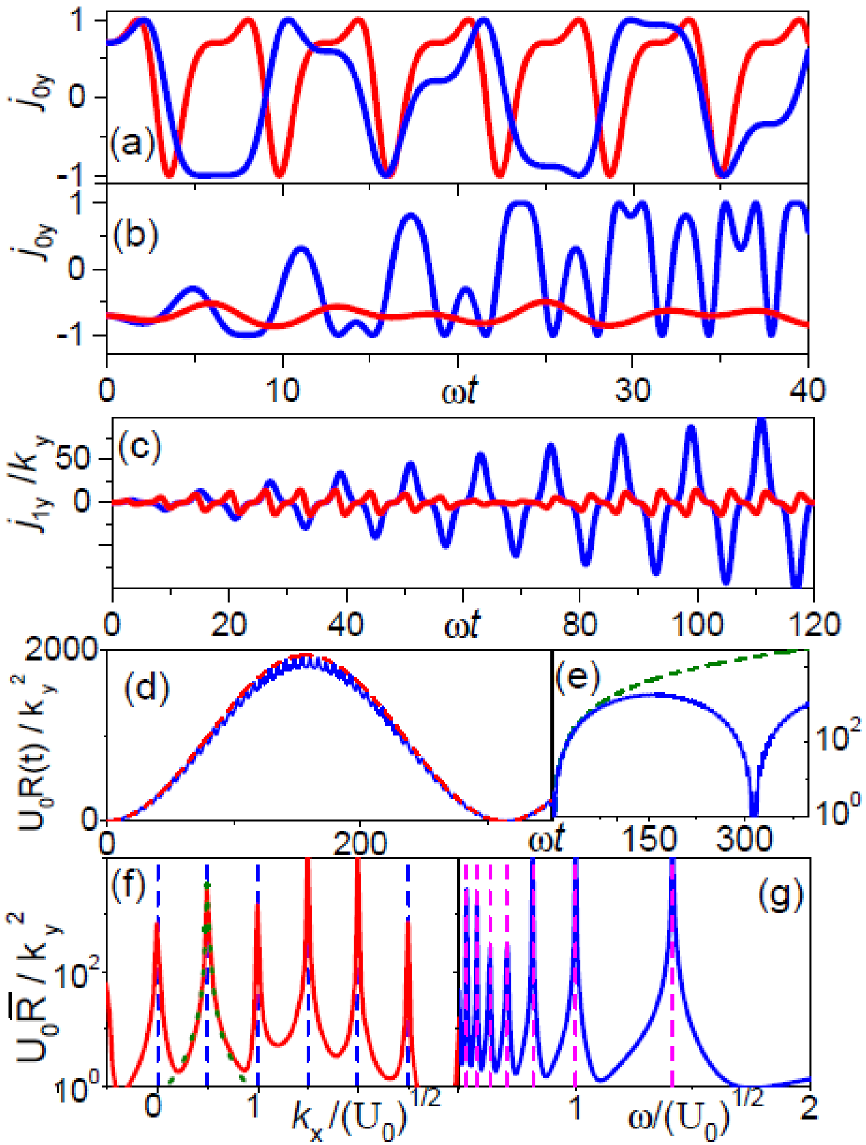
$$\Psi_{k_y}(x,y,t) = \Psi(x,t)\exp(ik_y y)$$

$$\begin{pmatrix} U(x,t) & -i\tau_z\frac{\partial}{\partial x} \\ -i\tau_z\frac{\partial}{\partial x} & U(x,t) \end{pmatrix}\Psi + ik_y\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}\Psi = i\frac{\partial}{\partial t}\Psi$$

$$\Psi = \sum_{n=0}^{\infty}(ik_y)^n\begin{pmatrix} 1 \\ \tau_z \end{pmatrix}\Psi_{n,+} + \sum_{n=0}^{\infty}(ik_y)^n\begin{pmatrix} 1 \\ -\tau_z \end{pmatrix}\Psi_{n,-}$$

$$\left(U(x,t) \mp i\frac{\partial}{\partial x} - i\frac{\partial}{\partial t}\right)\Psi_{n,\pm} \pm \tau_z\Psi_{n-1,\mp} = 0$$

Current resonances in graphene



$$j_{0x} = 2(|a_{0+}|^2 - |a_{0-}|^2)$$

$$j_{0y} = 4\tau_z |a_{0+}a_{0-}| \sin(\varphi + \phi_0)$$

$$R(x,t) := -j_{2x}/j_{0x} = k_y^2|A_{1-}(x,t)|^2/2$$

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Transverse Ratchets in graphene

$$(\Psi_A, \Psi_B) = (\exp[iS_A/\hbar], \exp[iS_B/\hbar])$$

$$\left(\frac{\partial S}{\partial x}\right)^2 + \left(\frac{\partial S}{\partial y}\right)^2 - \frac{1}{v_F^2}\left(\frac{\partial S}{\partial t} - \mathcal{U}\right)^2 = 0. \qquad \min\left\{\frac{\hbar v_F}{L}; \frac{\hbar\omega_y^2 U^2}{v_F A^2 L}\right\} \ll kT \lesssim U.$$

$$\mathcal{H} = \pm v_F\sqrt{p_x^2 + p_y^2} + \mathcal{U}$$

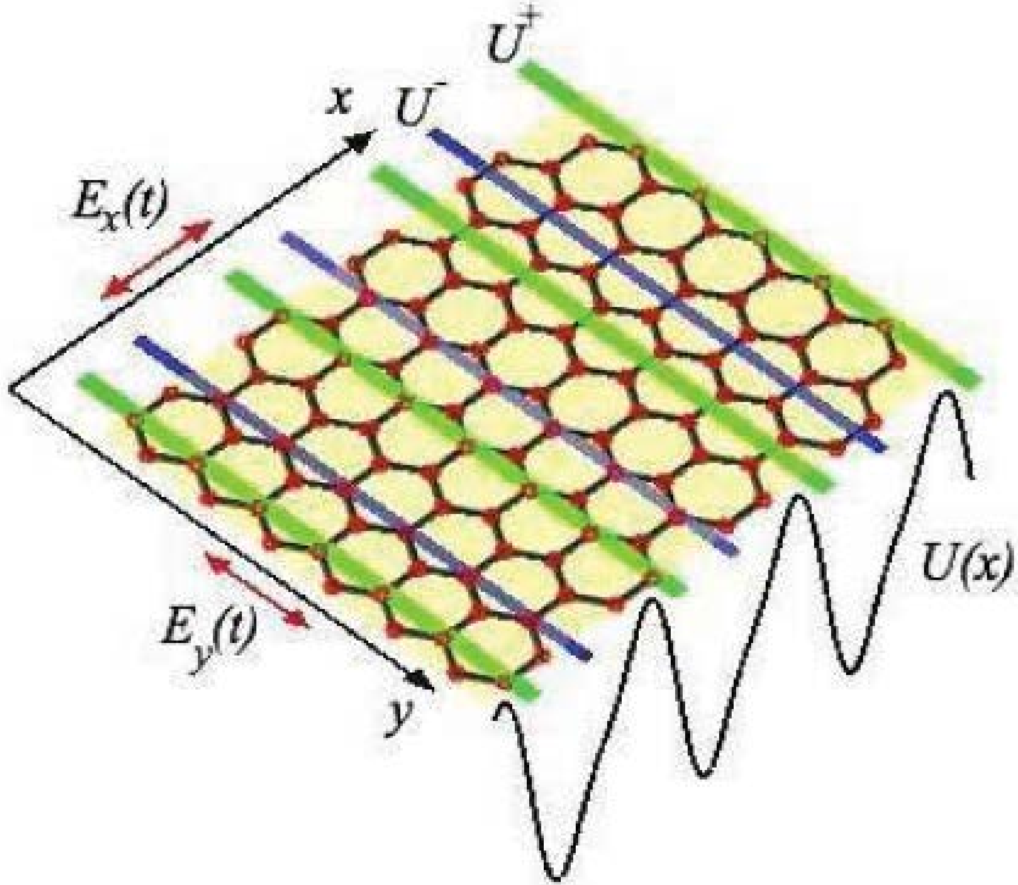
Potential along x, drive along y: no motion for classical systems and usually no motion for relativistic systems with no noise

$$\dot{p_x} = -\gamma V_0 \frac{p_x}{p_0} - \frac{dU(x)}{dx} + E_x(t) + \sqrt{2kT\gamma}\,\xi_x(t),$$

$$\dot{p_y} = -\gamma V_0 \frac{p_y}{p_0} + E_y(t) + \sqrt{2kT\gamma}\,\xi_y(t),$$

$$\vec{V} = (\dot{x}, \dot{y}) = \frac{\partial \varepsilon}{\partial \vec{p}} = V_0 \frac{\vec{p}}{p_0}, \quad p_0 = \sqrt{p_x^2 + p_y^2}$$

Geometry of the problem



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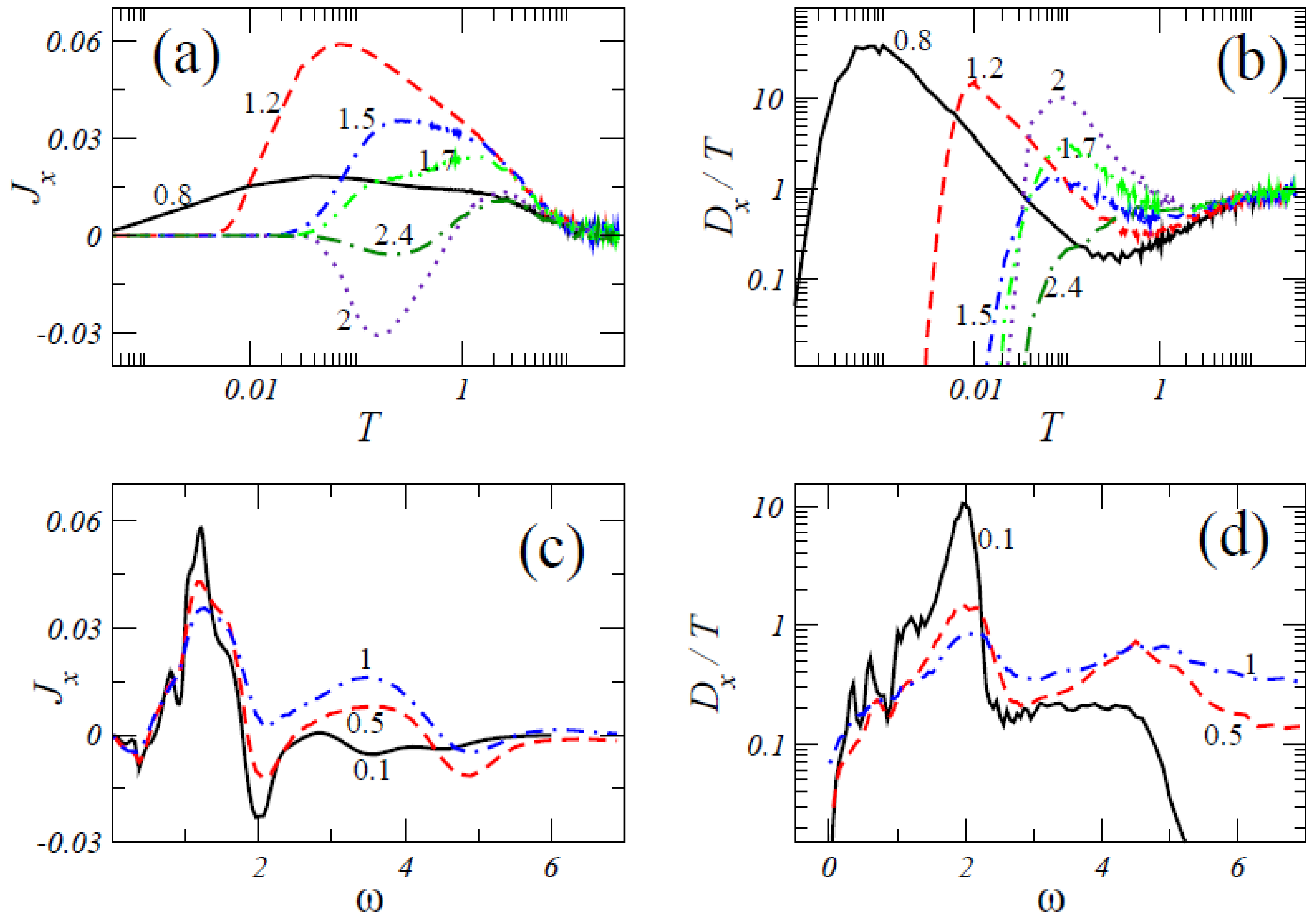
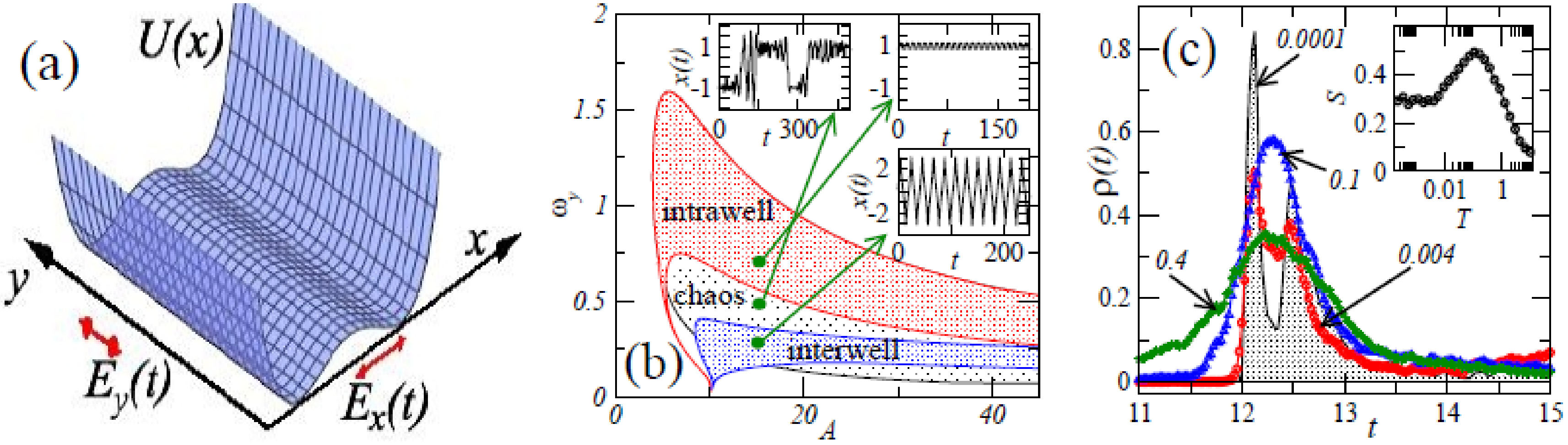


Controlling signal-noise ratio by noise: no potential



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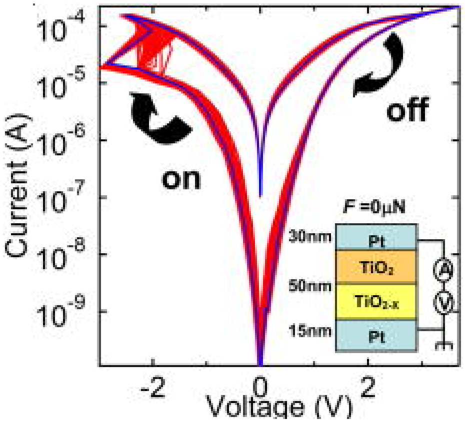
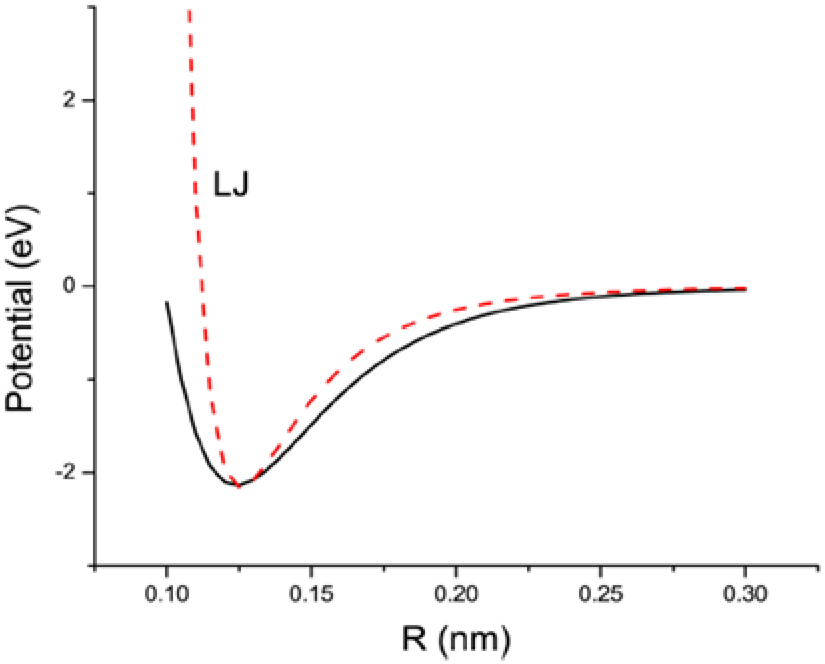
Switching of Memristors, HP-collaboration



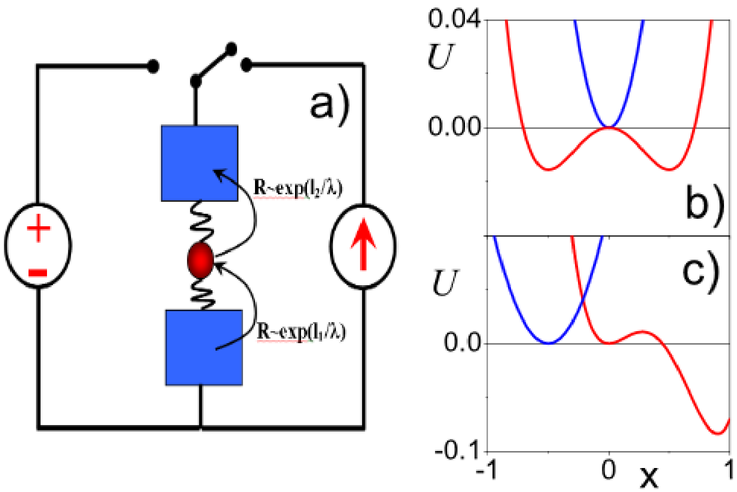
F. Miao, J.J. Yang, J.P. Strachan, D. Stewart, R.S. Williams, C.N. Lau Appl. Phys. Lett. 95, 113503 (2009)

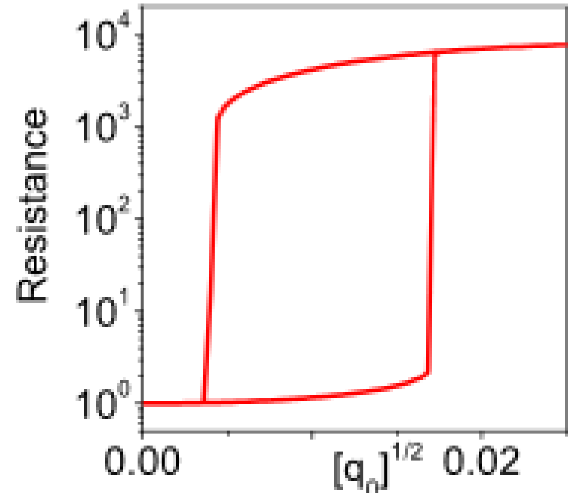
$$\eta \frac{d\boldsymbol{x}_i^\alpha}{dt} = F_i^\alpha(\boldsymbol{x}_i, \mathrm{t}) - \sum_i \frac{\partial U(\boldsymbol{x}_i)}{\partial x_i^\alpha} - \sum_{j\neq i} \frac{\partial W(\boldsymbol{x}_i - \boldsymbol{x}_j)}{\partial x_i^\alpha} + \sqrt{2k_B T\eta}\,\xi_i^\alpha(t).$$



APL 2011, APL 2011, Nanotechnology 2011, Applied Physics A 2011

Switching of Memristors: simple model

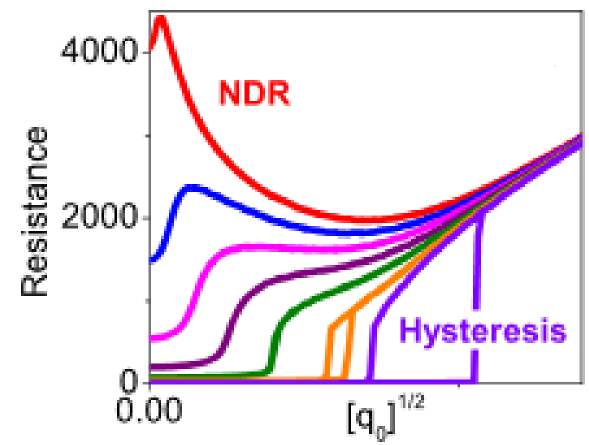




$$dx/dt + \partial U/\partial x = \sqrt{2T}\xi, \quad |x| < 1,$$
$$dT/dt = q(R(x)) - \kappa T,$$

Two fixed point for one minimum potential, slow temperature relaxation

$$dT/dt = q_0[\bar{r}(T)]^n - \kappa T,$$



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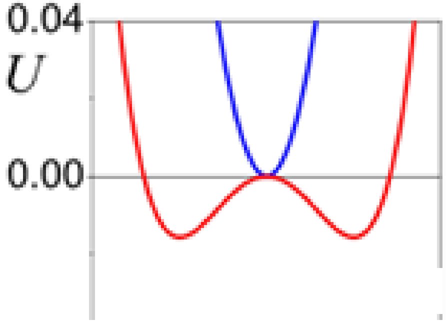
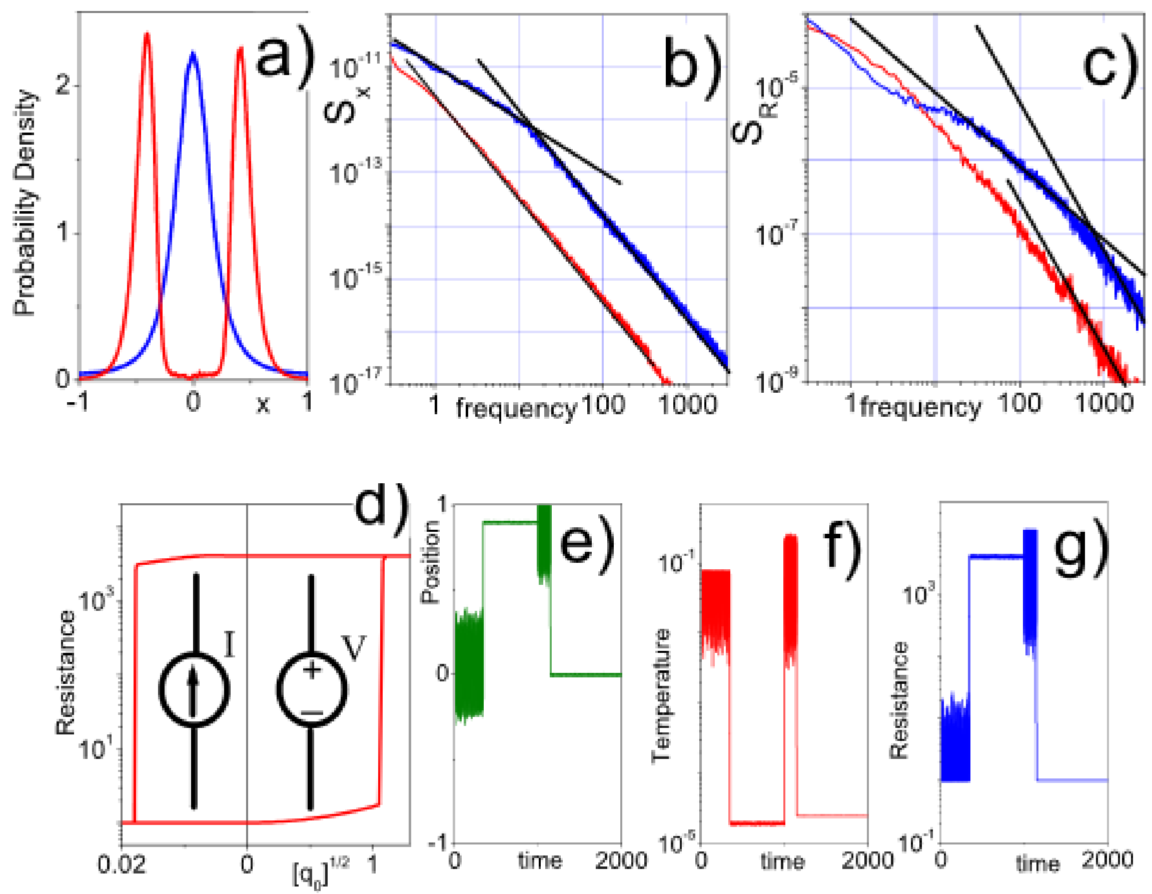
Switching of Memristors: simple model

$$dx/dt + \partial U/\partial x = [\cosh(x)]^{n/2}[2q_0/\kappa]^{1/2}\xi, \quad |x| < 1.$$





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(2013) 86: 501

Conclusions

- Temporal or spatial periodic potential allow to control band gap structure in graphene
- Interplay between noise and relativistic dynamics results in new class of stochastic effects
- Diffusive dynamics of oxygen vacancies allow to describe experiments for memristors and predict new regimes of memristor operation