Towards Power Optimization in Nanoscale Systems through the use of Many/electron Correlations

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1.- Introduction:

2.- Analytical results for electron power in correlated systems:

3.- Numerical simulation of ballistic nanoelectronic devices:

4.- Conclusions and Future work:

1. Introduction:

What ITRS says about power dissipation?

- ❑Computational State Variables Other than Solely Electron Charge
- ❑Non-Thermal Equilibrium Systems
- ❑Novel Energy Transfer Interactions
- ❑Nanoscale Thermal Management
- ❑Sub-lithographic Manufacturing Process
- ❑Alternative Arquitectures

[1] International Technology Roadmap for Semiconductors (2010 Update) http://www.itrs.net

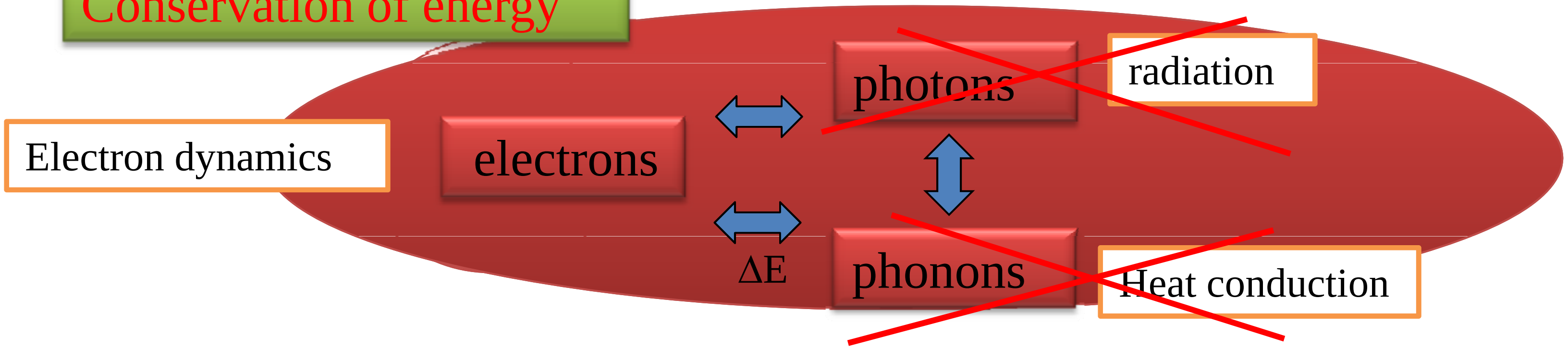
Power in FETs

P = Dynamic Power $\approx CV^2_{DD}f$ + ~~Static Power $\approx I_{OFF}V_{DD}$ (Gate leakage, Sub-threshold current, Drain junction leakage)~~

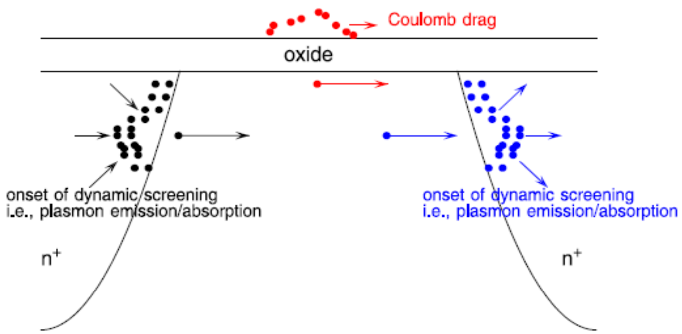
Intrinsic effect

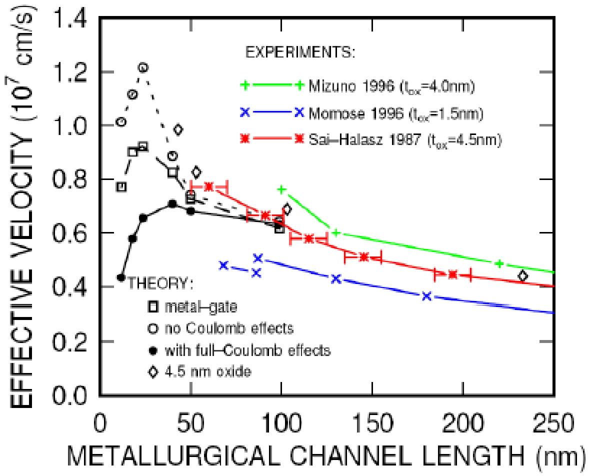
1. Introduction:

Conservation of energy



Previous works on the effect of many-particle Coulomb correlations in FETs





[1] M.V. Fischetti et al. J. Comput. Electron, 8, 60-77 (2009).

[2] Nobuyuki Sano. J. Comput. Electron, (2010).

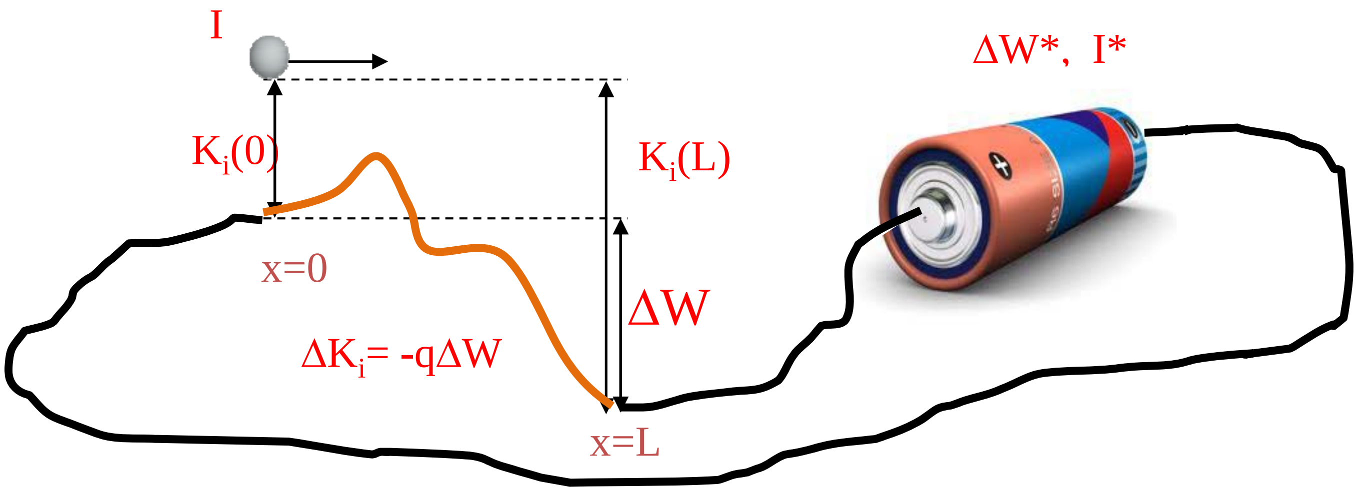
Coulomb correlation on the current, on the noise….

Our goal: …on the power …?

1. Introduction:

Why electrons gain energy ΔE inside an electron device?

A single-electron in a open ballistic (i.e. without phonons) system



$$P(t)=\frac{d(Work(t))}{dt}=\frac{d\int_{\vec r(0)}^{\vec r(t)} q\vec E(\vec r(t'))\cdot d\vec r(t')}{dt}=q\cdot\vec v(t)\cdot\vec E(\vec r(t))=\frac{d\left(\frac{1}{2}m\vec v^{2}(t)\right)}{dt}=\frac{dK}{dt}$$

ΔW*= ΔW, I*=I,

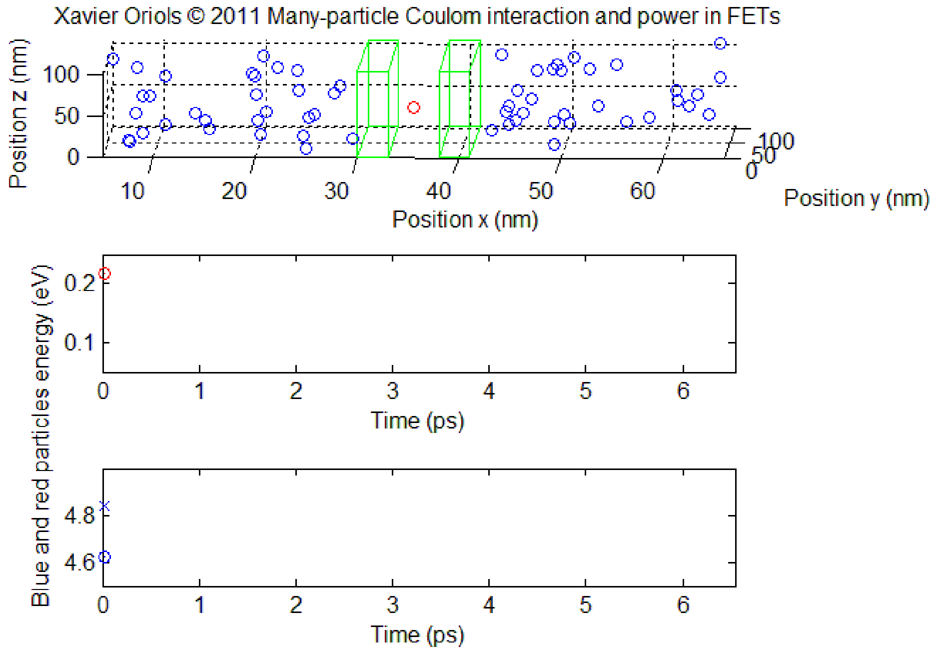
1. Introduction:

How electrons gain energy inside an electron device (open system)?

Closed system= M particles

Open system with M-N(t) particles (blue particles)

Open system with N(t) particles (red particles)



$$P(t)=\frac{d\left(\sum_{i=1}^{N(t)}\frac{1}{2}m\vec{v}_i^{\,2}(t)\right)}{dt}=\frac{d\sum_{i=1}^{N(t)}K_i}{dt}$$

Electron power in an open system

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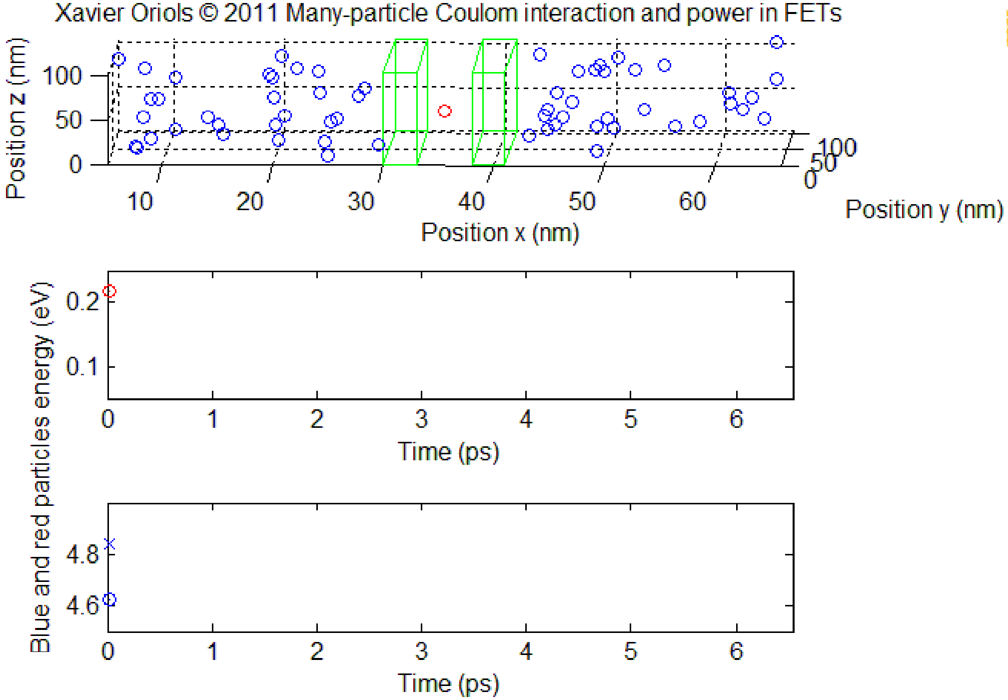
2.- Analytical results for electron power in correlated systems

Closed system = M particles

$$m\frac{d\vec{v}_i(t)}{dt} = -q\cdot\nabla_{\vec{r}_i} W_i(t) = -q\nabla_{\vec{r}_i}\left(\sum_{\substack{j=1\\ j\neq i}}^{M}\cdot\frac{q}{4\pi\varepsilon}\frac{1}{\left|\vec{r}_i(t)-\vec{r}_j(t)\right|}\right)$$

Newton law



Open system
with N(t) particles

$$P(t) = \frac{d}{dt}\left(\sum_{i=1}^{N(t)} K_i\right) = -\sum_{i=1}^{N(t)} q\cdot\frac{dW_i(t)}{dt} - \frac{1}{4}\sum_{i=1}^{N(t)}\sum_{\substack{j=1\\ j\neq i}}^{N(t)}\frac{q^2}{4\pi\varepsilon}\frac{\frac{d}{dt}\left|\vec{r}_i(t)-\vec{r}_j(t)\right|^2}{\left|\vec{r}_i(t)-\vec{r}_j(t)\right|^3} + \sum_{i=1}^{N(t)}\sum_{j=1}^{M}\frac{q^2}{4\pi\varepsilon}\frac{\vec{r}_i(t)-\vec{r}_j(t)}{\left|\vec{r}_i(t)-\vec{r}_j(t)\right|^3}\vec{v}_j(t)$$

Two-particle (correlation) power

electrons in the channel

electrons in the channel and outside

2.- Analytical results for electron power in correlated systems

$$P(t)=\frac{d}{dt}\left(\sum_{i=1}^{N(t)}K_i\right)=-\sum_{i=1}^{N(t)}q\cdot\frac{dW_i(t)}{dt}-\frac{1}{4}\sum_{i=1}^{N(t)}\sum_{\substack{j=1\\j\neq i}}^{N(t)}\frac{q^2}{4\pi\varepsilon}\frac{\frac{d}{dt}\left|\vec{r}_i(t)-\vec{r}_j(t)\right|^2}{\left|\vec{r}_i(t)-\vec{r}_j(t)\right|^3}+\sum_{i=1}^{N(t)}\sum_{j=1}^{M}\frac{q^2}{4\pi\varepsilon}\frac{\vec{r}_i(t)-\vec{r}_j(t)}{\left|\vec{r}_i(t)-\vec{r}_j(t)\right|^3}\vec{v}_j(t)$$

Time Average power

$$\langle P\rangle=\lim_{T\to\infty}\frac{1}{T}\int_{-T/2}^{T/2}P(t)\cdot dt=\langle P\rangle_1+\langle P\rangle_2+\langle P\rangle_3$$

Term 1:

$$\langle P\rangle_1=\left\langle\sum_{i=1}^{N(t)}(-q)\cdot\frac{dW_i(t)}{dt}\right\rangle=\langle I\rangle\cdot\langle\Delta W\rangle$$

- <current> $\langle I\rangle$
- <scalar potential drop> $\langle\Delta W\rangle$

Term 2:

$$\langle P\rangle_2=\left\langle\frac{-1}{4}\sum_{i=1}^{N(t)}\sum_{\substack{j=1\\j\neq i}}^{N(t)}\frac{q^2}{4\pi\varepsilon}\frac{\frac{d}{dt}\left|\vec{r}_i(t)-\vec{r}_j(t)\right|^2}{\left|\vec{r}_i(t)-\vec{r}_j(t)\right|^3}\right\rangle$$

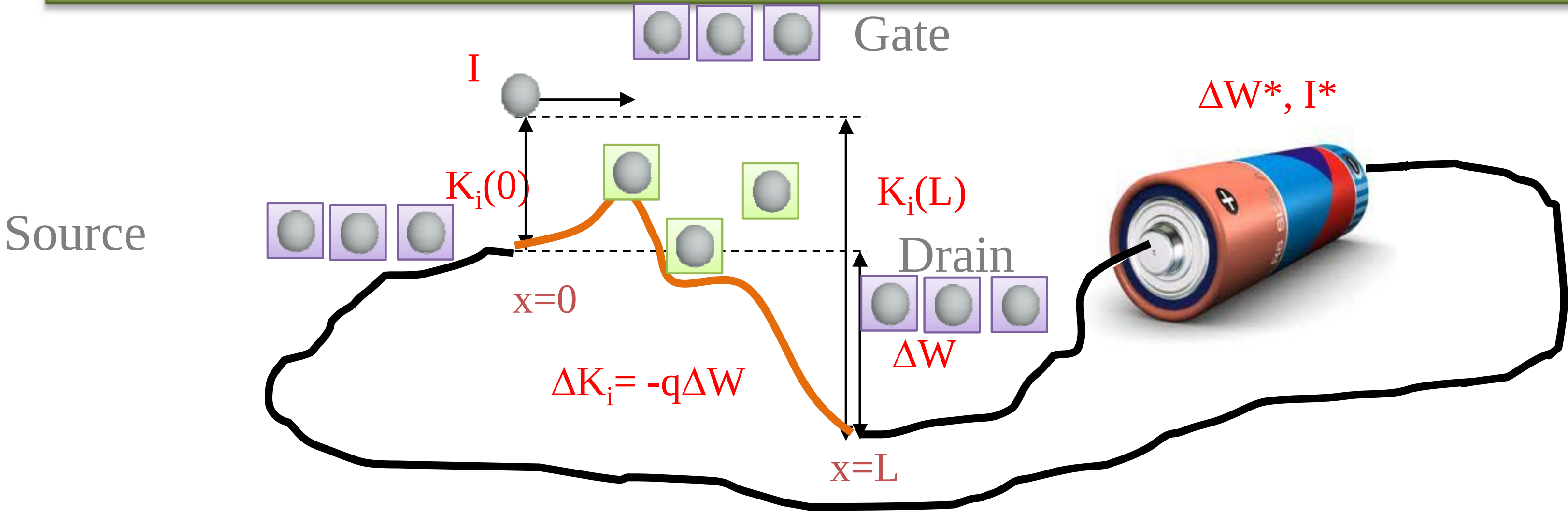
- Bounching $\langle P\rangle_2>0$
- Antibounching $\langle P\rangle_2<0$

Term3:

$$\langle P\rangle_3=\left\langle\sum_{i=1}^{N(t)}\sum_{j=1}^{M}\frac{q^2}{4\pi\varepsilon}\frac{\vec{r}_i(t)-\vec{r}_j(t)}{\left|\vec{r}_i(t)-\vec{r}_j(t)\right|^3}\vec{v}_j(t)\right\rangle$$

2.- Analytical results for electron power in correlated systems

A summary,



Macroscopic view…conservation of energy

$\langle P \rangle = \langle I^* \rangle \cdot \langle \Delta W^* \rangle$ Power supplied by the battery=power gain by (all) electrons

Microscopic view…¿ redistribution of power in the simulated active region ?

$$\langle P \rangle = \langle P \rangle_1 + \langle P \rangle_2 + \langle P \rangle_3 \neq \langle I \rangle \cdot \langle \Delta W \rangle \qquad \langle P \rangle_1 = \langle I \rangle \cdot \langle \Delta W \rangle$$

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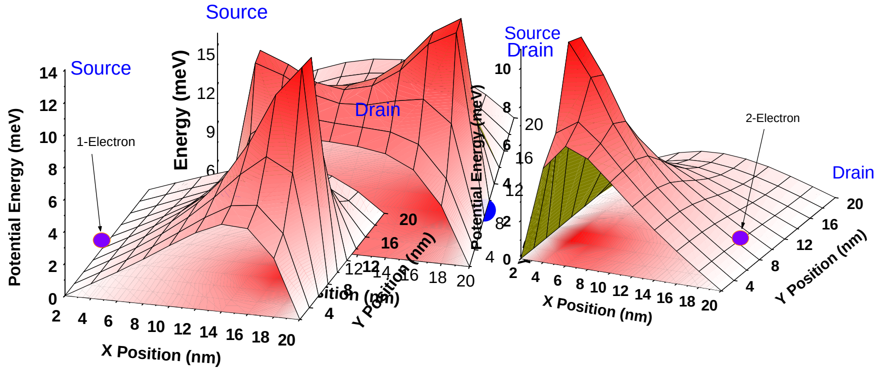
How to include Term2 in numerical simulations ?

$$H = \sum_{k=1}^{N(t)} \left\{ \tilde{K}(\vec{p}_k) + eW_k(\vec{r}_1,\ldots,\vec{r}_{N(t)},t) - \frac{1}{2}\sum_{j=1}^{N(t)} eV(\vec{r}_k,\vec{r}_j) \right\}$$

Open System beyond mean field

$$\vec{\nabla}_k^2\left(\varepsilon W_k\left(\vec{r}_1,\ldots,\vec{r}_{N(t)},t\right)\right) = \rho_k\left(\vec{r}_1,\ldots,\vec{r}_{N(t)}\right)$$

$$\rho_k\left(\vec{r}_1,\ldots,\vec{r}_{N(t)}\right) = \sum_{\substack{j=1 \\ j\neq k}}^{N(t)} e\cdot\delta\left(\vec{r}_k-\vec{r}_j\right)$$



A 3D Poisson equation for each electron

[1] G. Albareda, J. Suñé and X. Oriols, Physical Review B, 79, 075315 (2009)

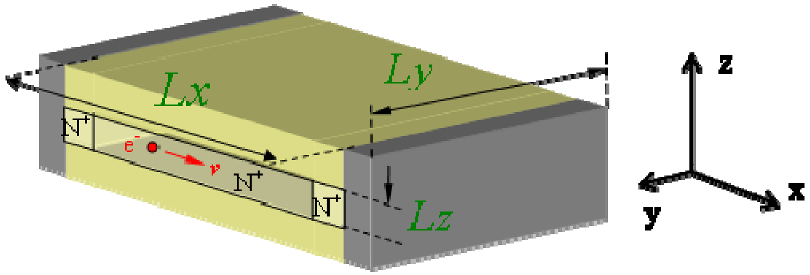
How to include Term3 in numerical simulations ?

Imposing overall-charge neutrality in the boundary of the simulation region

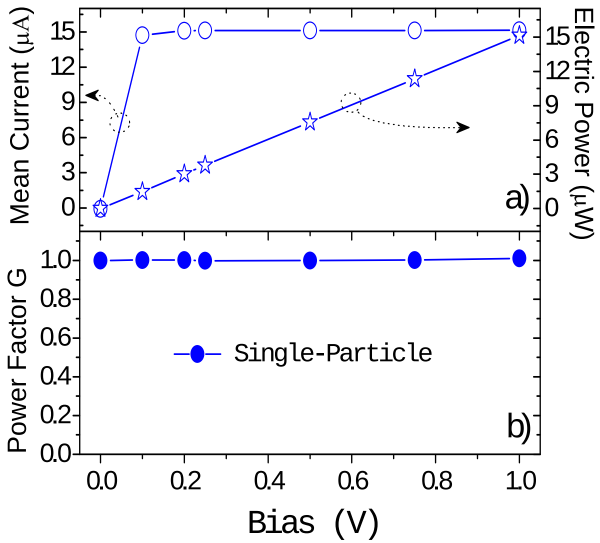
[2] G. Albareda, H. López, X. Cartoixà, J. Suné, and X. Oriols, Phys. Rev. B, 82, 085301 (2010).

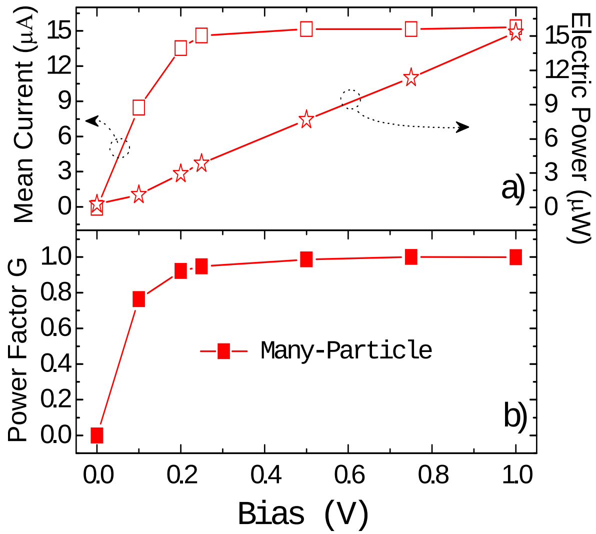
3.2.- Electron power in the active region of a nanoresistor

Ballistic transport (without phonons) but with Coulomb correlations.



Doping	L_x (nm)	L_y (nm)	L_z (nm)
6.25E18cm^{-3}	10	30	30





The power factor G

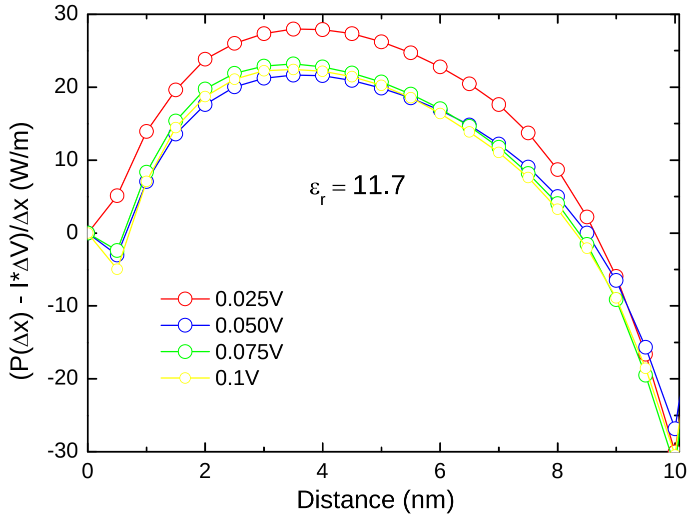
$$G = \frac{\langle P \rangle_1}{\langle P \rangle} = \frac{\langle I \rangle \cdot \langle \Delta W \rangle}{\langle P \rangle_1 + \langle P \rangle_2 + \langle P \rangle_3}$$

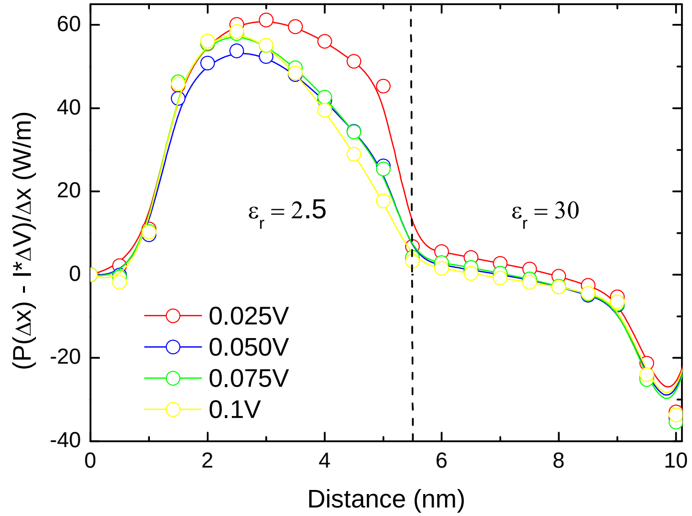
3.3.- Electron power spatial distribution in a nanoresistor

Electron power (spatial) density

$$\frac{\langle P(\Delta x)\rangle - \langle I\rangle \cdot \langle \Delta W\rangle}{\Delta x} = \frac{\langle P(\Delta x)\rangle_2 + \langle P(\Delta x)\rangle_3}{\Delta x}$$

more velocity | less velocity





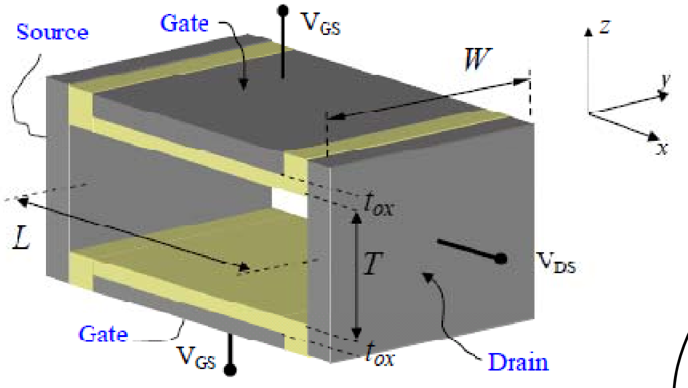
Term 2:

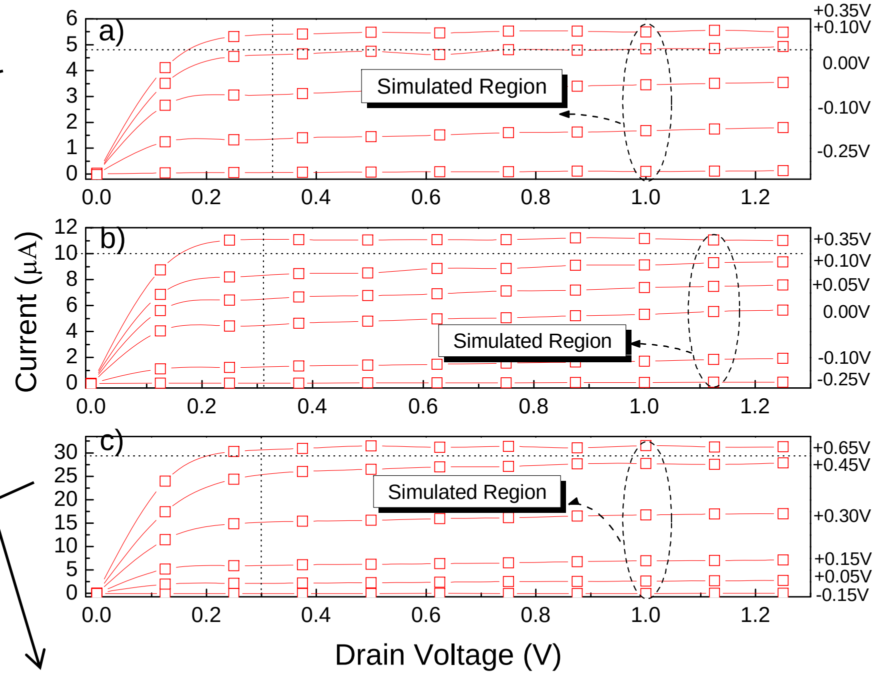
$$\langle P\rangle_2 = \left\langle \frac{-1}{4}\sum_{i=1}^{N(t)}\sum_{\substack{j=1\\ j\neq i}}^{N(t)} \frac{q^2}{4\pi\varepsilon}\frac{\frac{d}{dt}\left|\vec{r}_i(t)-\vec{r}_j(t)\right|^2}{\left|\vec{r}_i(t)-\vec{r}_j(t)\right|^3}\right\rangle$$

- Bounching: $\langle P\rangle_2 > 0$
- Antibounching: $\langle P\rangle_2 < 0$

3.4.- Electron power in 3D, 2D and 1D DG nanotransistors

Ballistic transport (without phonons) but with Coulomb correlations.



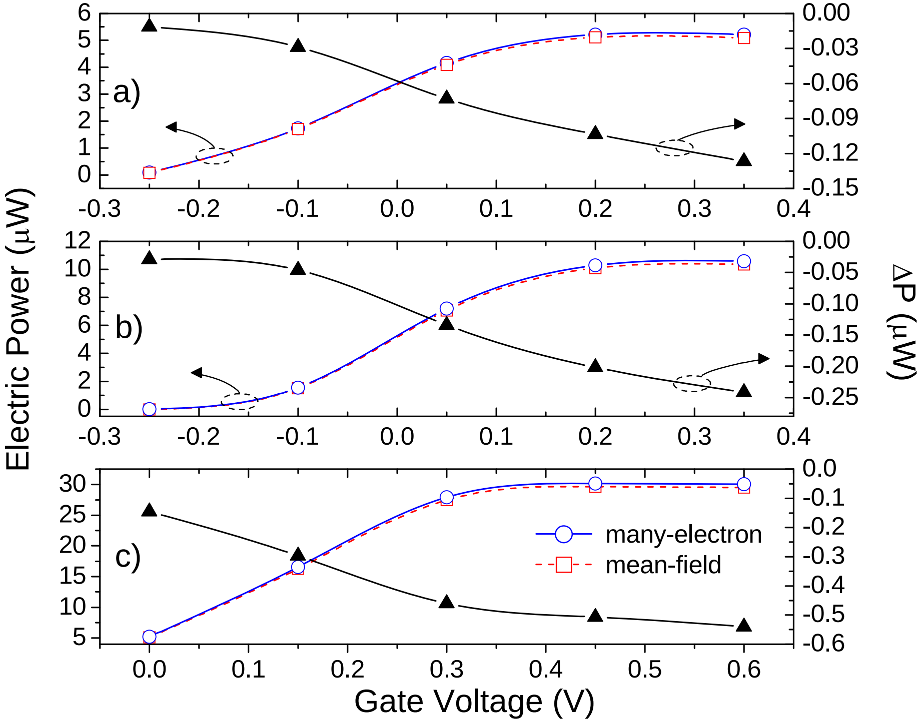


		Magnitude	3D Bulk	2D Quantum Well	1D Quantum Wire
Channel Dimensions	(nm)		15	15	15
			10	10	5
			8	2	2
Doping	(cm^{-3})	Channel	$2\cdot10^{19}$	$2\cdot10^{19}$	$2\cdot10^{19}$
		Contact	$2\cdot10^{19}$	$2\cdot10^{19}$	$2\cdot10^{19}$

[1] G. Albareda, A. Alarcón, and X. Oriols, Int. J. Numer. Model. 23, 354 (2010).

3.4.- Electron power in 3D, 2D and 1D DG nanotransistors

The "unexpected" effects of the correlations increases as dimensions decreases:



Error

$$\Delta P = \langle P \rangle - \langle I \rangle \cdot \langle \Delta W \rangle$$

	Error per Transistor	Power per CPU (x1E9)
3D Bulk	0.55μW	550W
2D Quantum Well	0.24μW	240W
1D Quantum Wire	0.12μW	120W

1.7 %

2.4 %

2.6 %

[1] G. Albareda, A. Alarcón, and X. Oriols, Int. J. Numer. Model. 23, 354 (2010).

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4.- Conclusions and future work

We have developed a simulator to compute many-particle electron power in the active region of nanoelectronic devices beyond mean-field approx.

In this work, we have shown that: $\langle P \rangle = \langle P \rangle_1 + \langle P \rangle_2 + \langle P \rangle_3 \neq \langle I \rangle \cdot \langle \Delta W \rangle$

because of the correlations with other electrons inside and outside (gate, drain and source electrons).

1.- We have numerically shown that this correlation is important to accurately predict the power gain by electrons in the active region.

Errors around 2% when power gain estimated without correlations. The errors increase when dimensions reduced.

2.- We show a new path to use of the correlations to manipulate the electron gain of energy in different parts of the active region.

Bounching/antibounching of electrons increase/decrease their gain of energy.

4.- Conclusions and future work

Future work

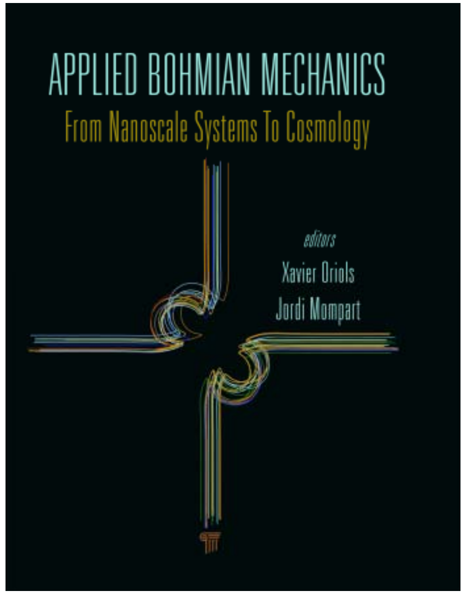
Discussion of the effect of correlations on the electron power in quantum devices:

$$m\frac{d\vec{v}_i(t)}{dt} = -q\nabla_{\vec{r}_i}\left(\sum_{\substack{j=1 \\ j\neq i}}^{M}\frac{q}{4\pi\varepsilon}\frac{1}{\left|\vec{r}_i(t)-\vec{r}_j(t)\right|}\right) - \nabla_{\vec{r}_i}\left(\sum_{i=1}^{M}Q_j(t)\right)$$

Coulomb correlations

Exchange correlations

[1] X. Oriols, Physical Review Letters, 98, 066803 (2007).



Acknowledgment

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Thank you very much for your attention