SPIN MAGNETIZATION and ELECTRON LOCALIZATION in SEMICONDUCTOR QUANTUM WIRES and QUANTUM POINT CONTACTS

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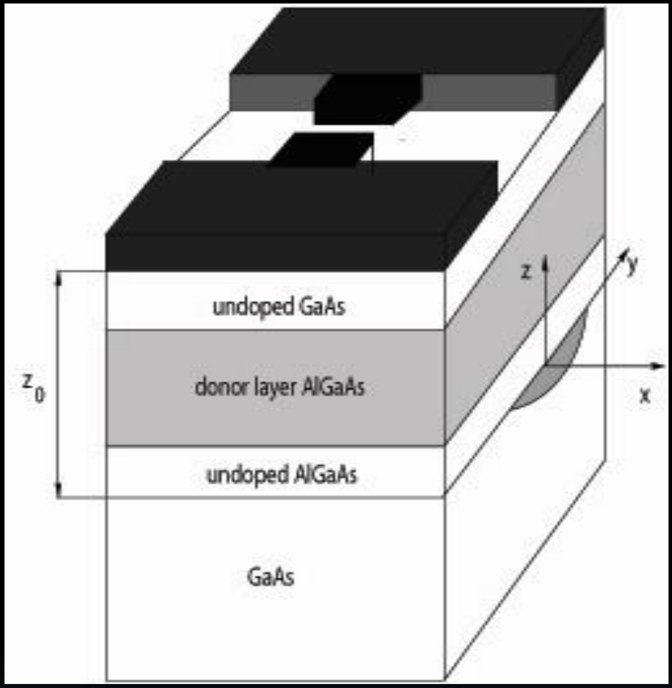
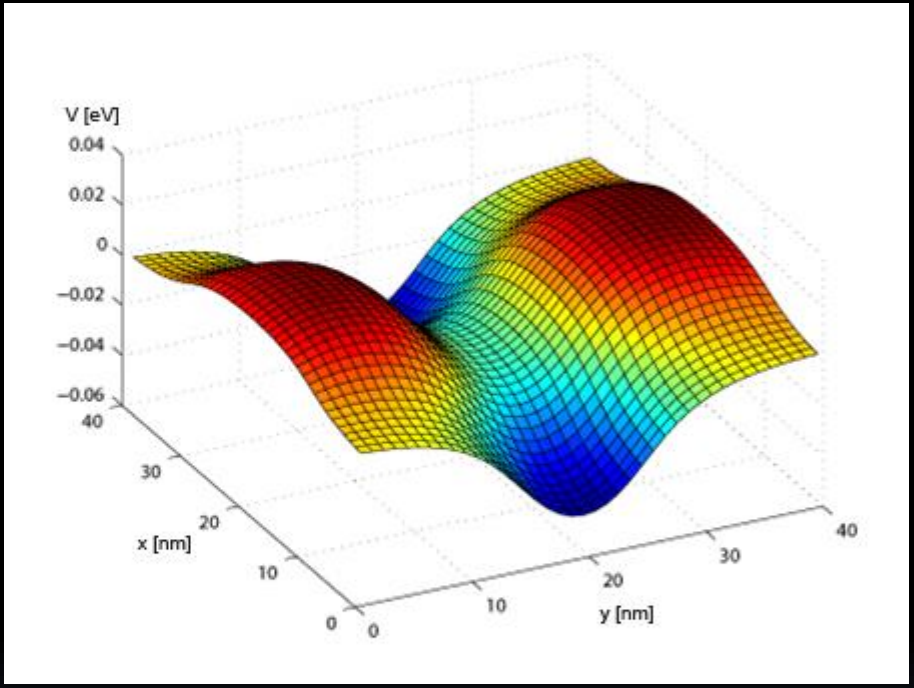
CONTENT:

- Model of semiconductor quantum point contact
- Quantized conductance
- Magnetization and conductance anomalies
- Bound states and electron localization in quantum point contacts
- Magnetization in biased quantum wire

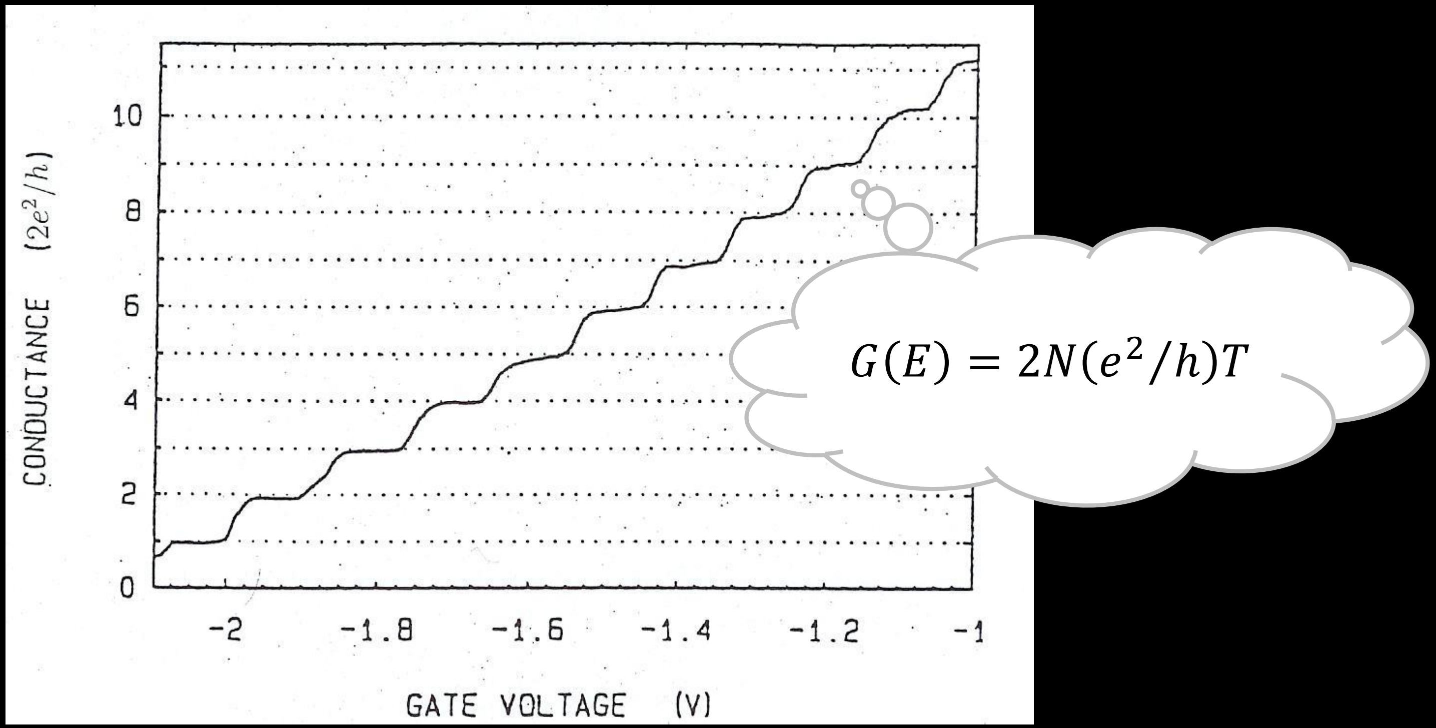
MODULATION-DOPED SEMICONDUCTOR HETEROSTRUCTURE





Model of a realistic device based on semiconductor heterostructure with patterned metallic gates

EXPERIMENTAL EVIDENCE OF QUANTIZED CONDUCTANCE



The first observation of step-like conduction in GaAs/AlGaAs structure:

- B. J. van Wees *et al.*, Phys. Rev. Lett. 60, 848 (1988)
- D. A. Wharam *et al.*, J. Phys. C 21, 209 (1988)

LANDAUER-BÜTTIKER FORMULA

Particle in 1D:

$$\psi = exp(ikx)$$

Kinetic energy:

$$E = \frac{\hbar^2 k^2}{2m}$$

Density of states per spin:

$$D(E) = \frac{1}{2\pi}\left(\frac{dE}{dk}\right)^{-1} = \frac{m}{2\pi\hbar^2 k} \sim \frac{1}{\sqrt{E}}$$

Velocity:

$$v_x = p_x/m = \hbar k/m \sim \sqrt{E}$$

Current at voltage drop V:

$$I(E) = \int_{E-eV/2}^{E+eV/2} D(E)(ev)T(E)dE = (e^2/h)TV,$$

T is the transmission coefficient.

Conductance per spin direction:

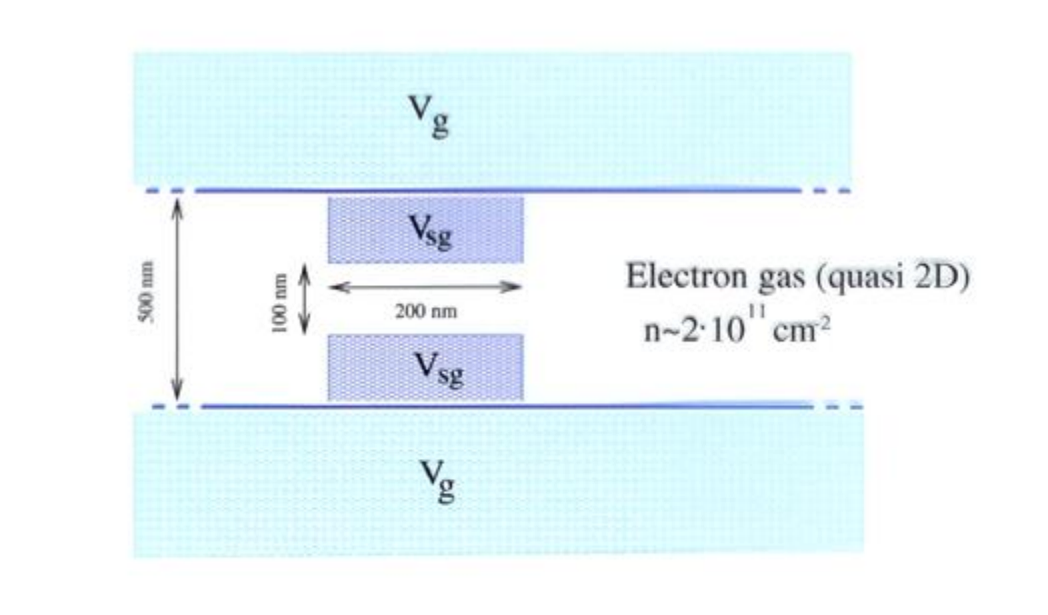
$$G(E) = I/V = (e^2/h)T$$

Conductance for the two spin directions:

$$G(E) = (2e^2/h)T$$

Single-channel Landauer-Büttiker formula

PARTICLE IN 1D CHANNEL



$$\psi(x,y) = exp(ikx)\phi(y)$$

Particle in multi-1D channel:

$$\psi_n(x,y) = exp(ik_n x)\phi_n(y)$$

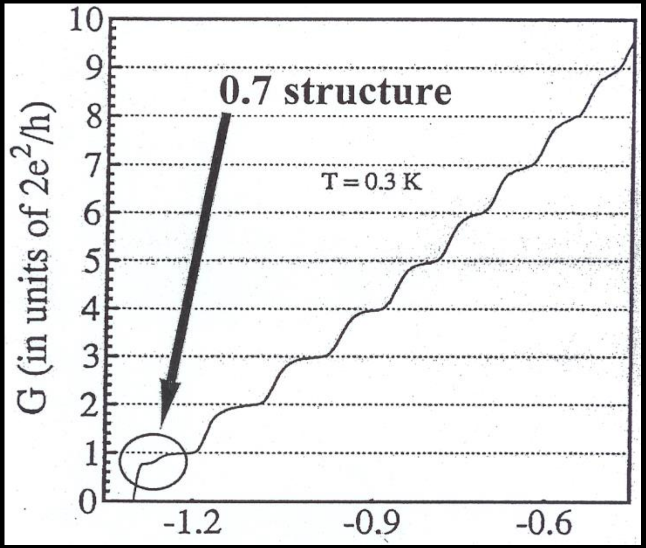
Conductance for N channels:

$$G(E) = 2N(e^2/h)T \text{ or}$$

$$G(E) = (N_\downarrow + N_\uparrow)(e^2/h)T$$

Multi-channel Landauer-Büttiker formula

0.7 CONDUCTANCE ANOMALY



V_g (V)

0.7 structure (from C.-T. Liang *et al.*, Phys. Rev. B60, 10687, 1999) discovered by K. J. Thomas *et al.*, Phys. Rev. Lett. 77, 135 (1996).

- Static spin-polarization model:

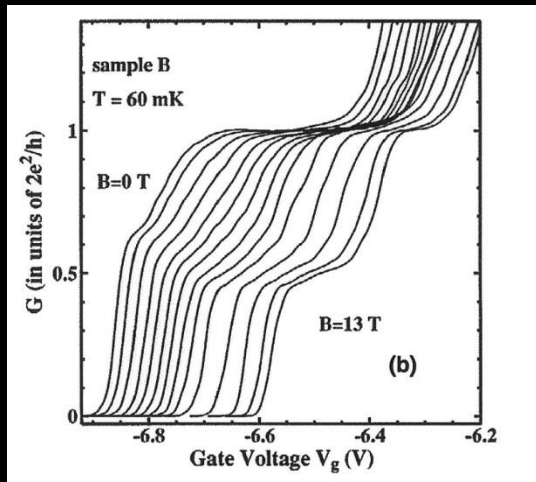
The first theoretical explanation:

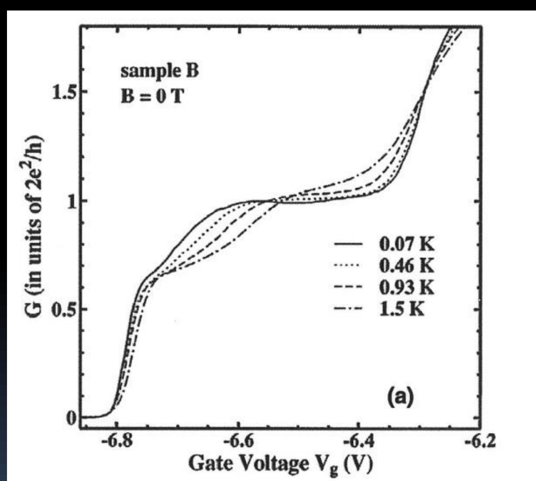
- C.-K. Wang and K.-F. Berggren. Phys. Rev. B57, 4552 (1998);
- K.-F. Berggren and I.I. Yakimenko, Phys. Rev. B66, 085323 (2002).

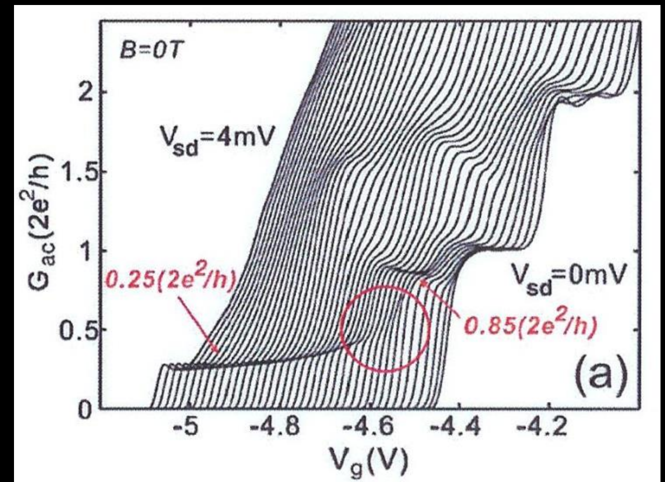
- Dynamic spin-polarization model:

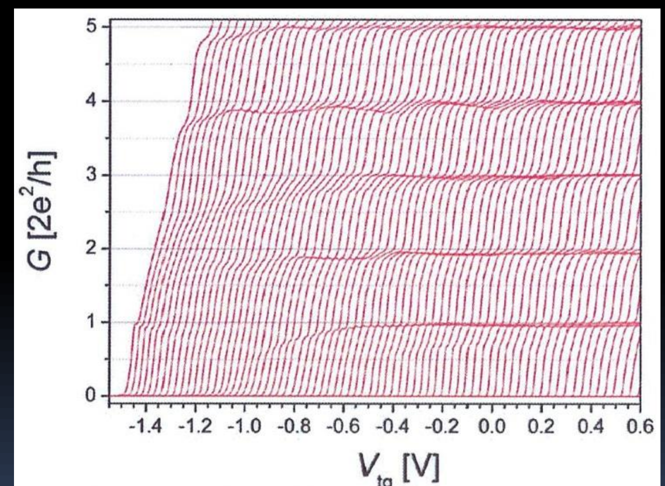
K. Hirose, Y. Meir, and N.S. Wingreen, Phys. Rev. Lett. 90, 026804 (2003).

0.7 ANOMALY: DEPENDENCE ON MAGNETIC FIELD, TEMPERATURE AND BIAS





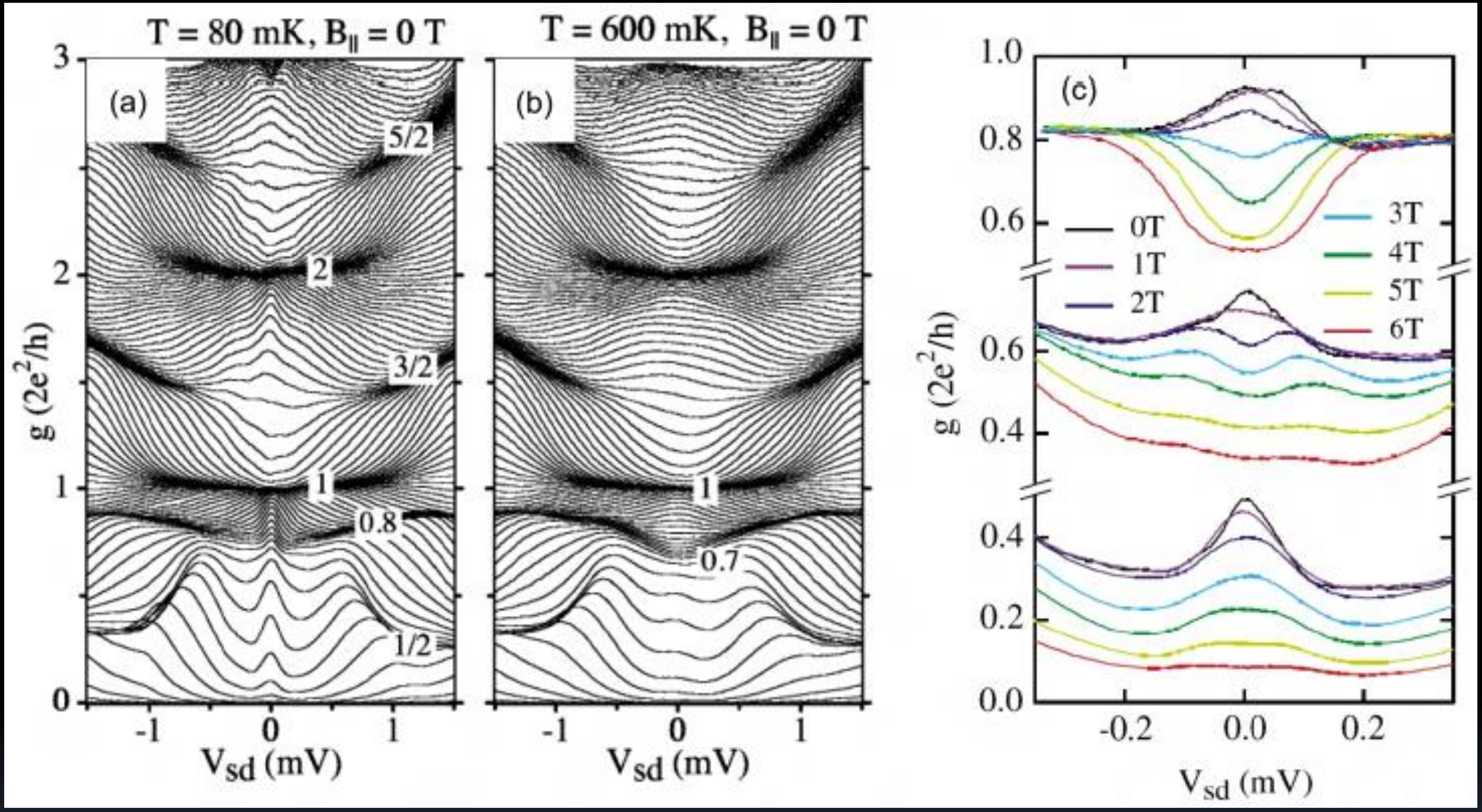




K. J. Thomas *et al.*, Phys. Rev. B 58, 4846 (1998)

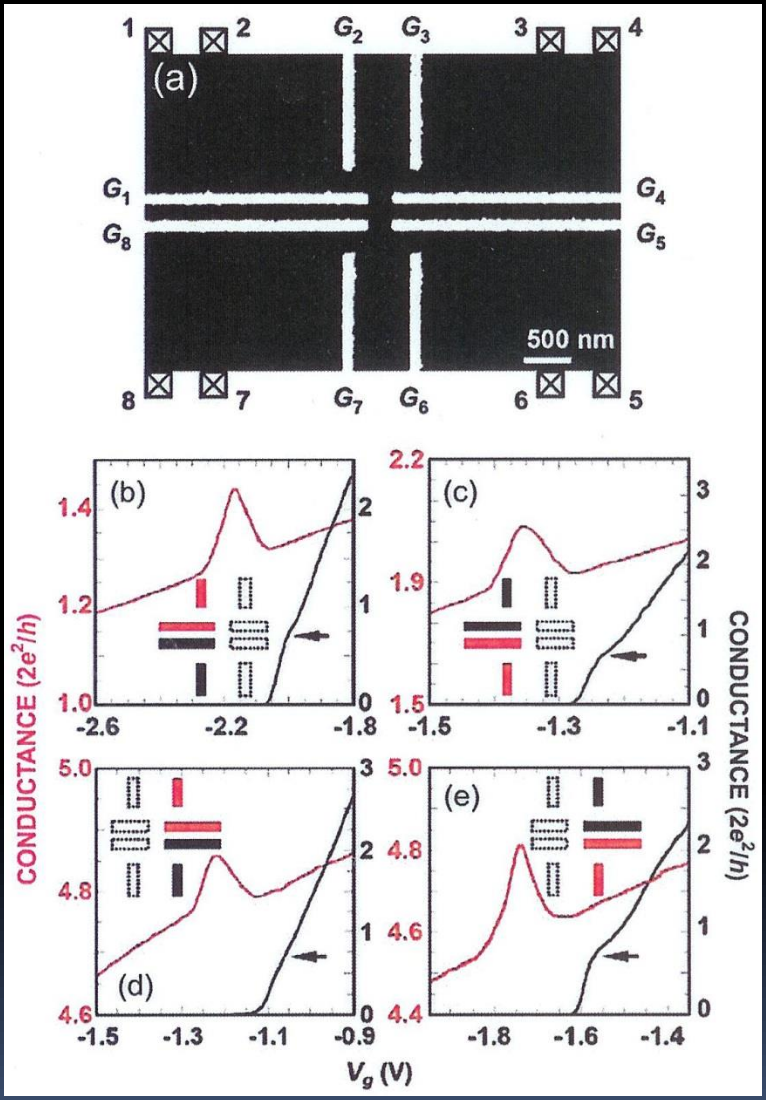
- T.-M. Chen *et al.,* Appl. Phys. Lett. 93, 032102 (2008)
- W. K. Hew *et al.*, Phys. Rev. Lett. 102, 056804 (2009)

DIFFERENTIAL CONDUCTANCE



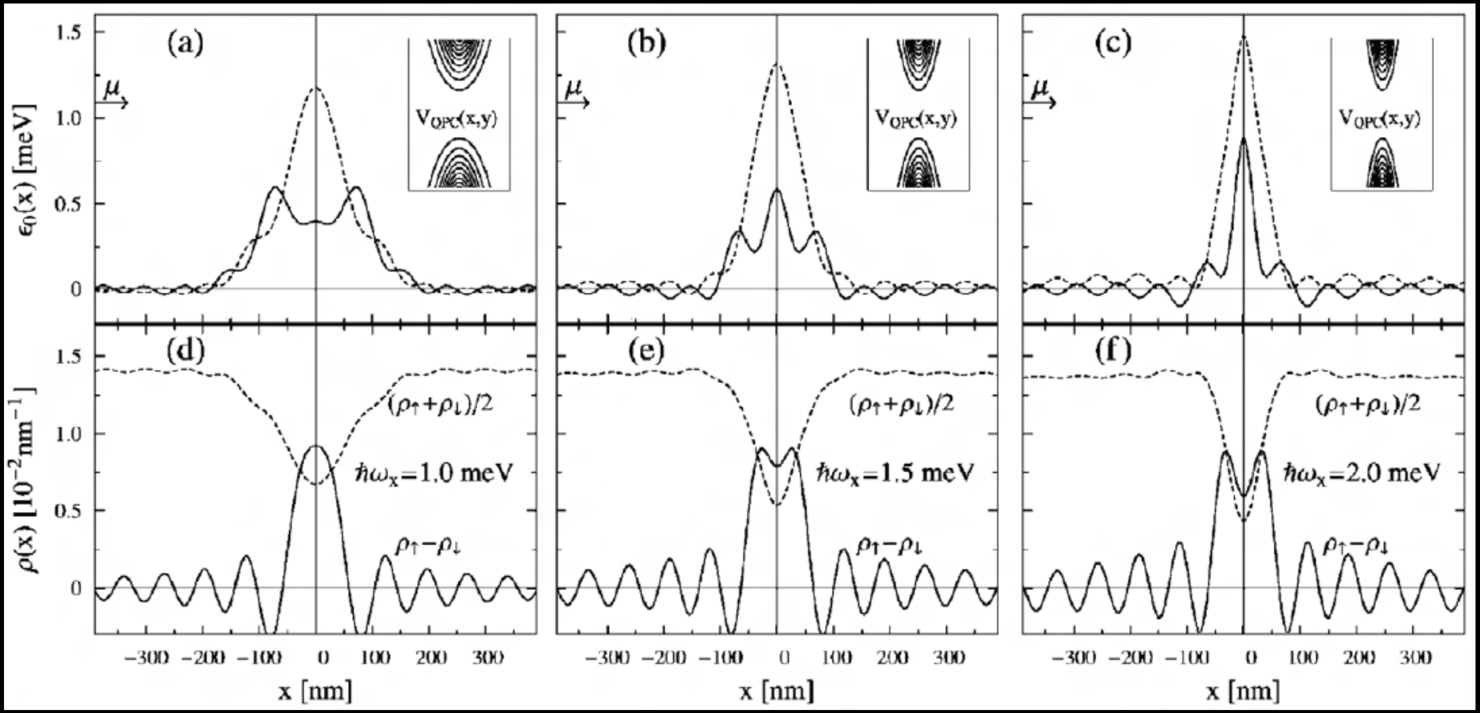
Cronenwett S. M. *et al.*, Phys. Rev. Lett. 88, 226805 (2002).

COUPLED QPCs



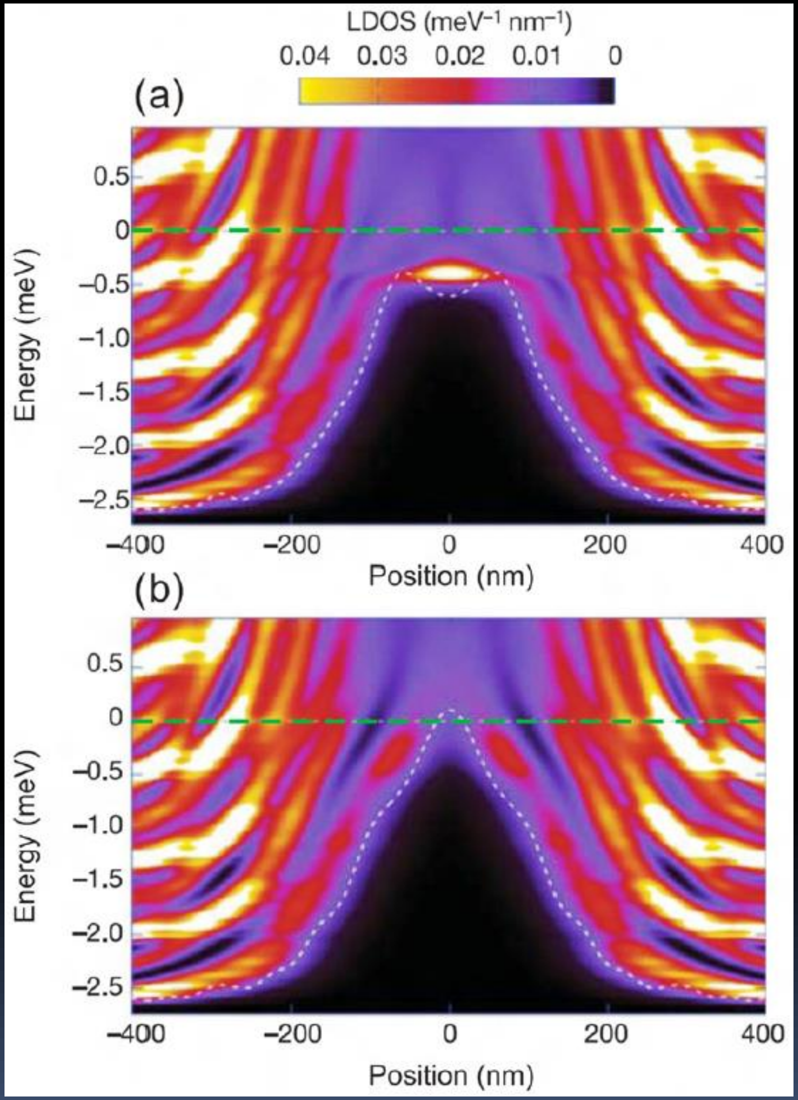
Y. Yoon *et al.*, Phys. Rev. Lett. 99, 136805 (2007).

DYNAMICAL SPIN-POLARIZATION MODEL



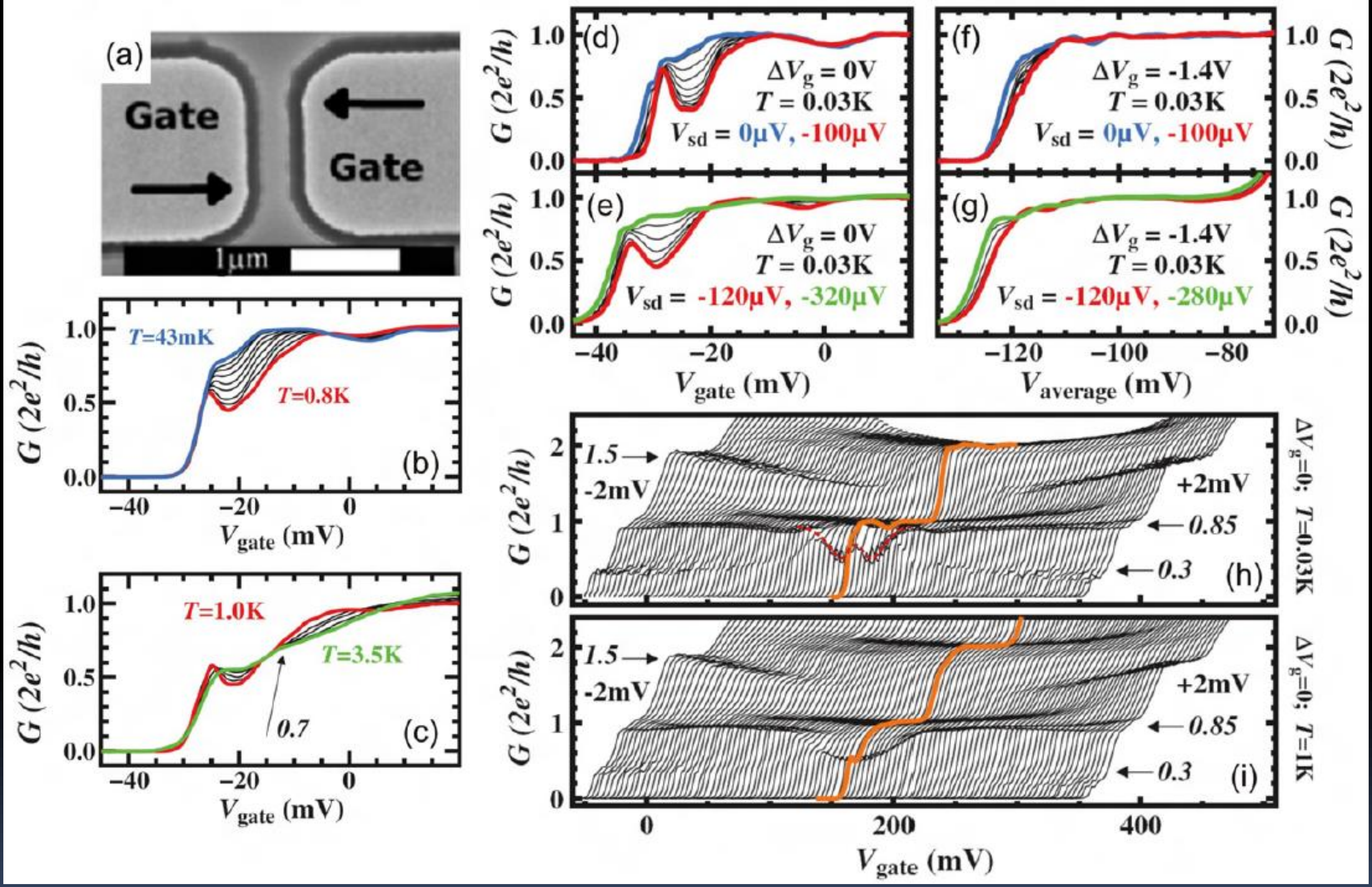
K. Hirose, Y. Meir, and N.S. Wingreen, Phys. Rev. Lett. 90, 026804 (2003).

DYNAMICAL SPIN-POLARIZATION MODEL



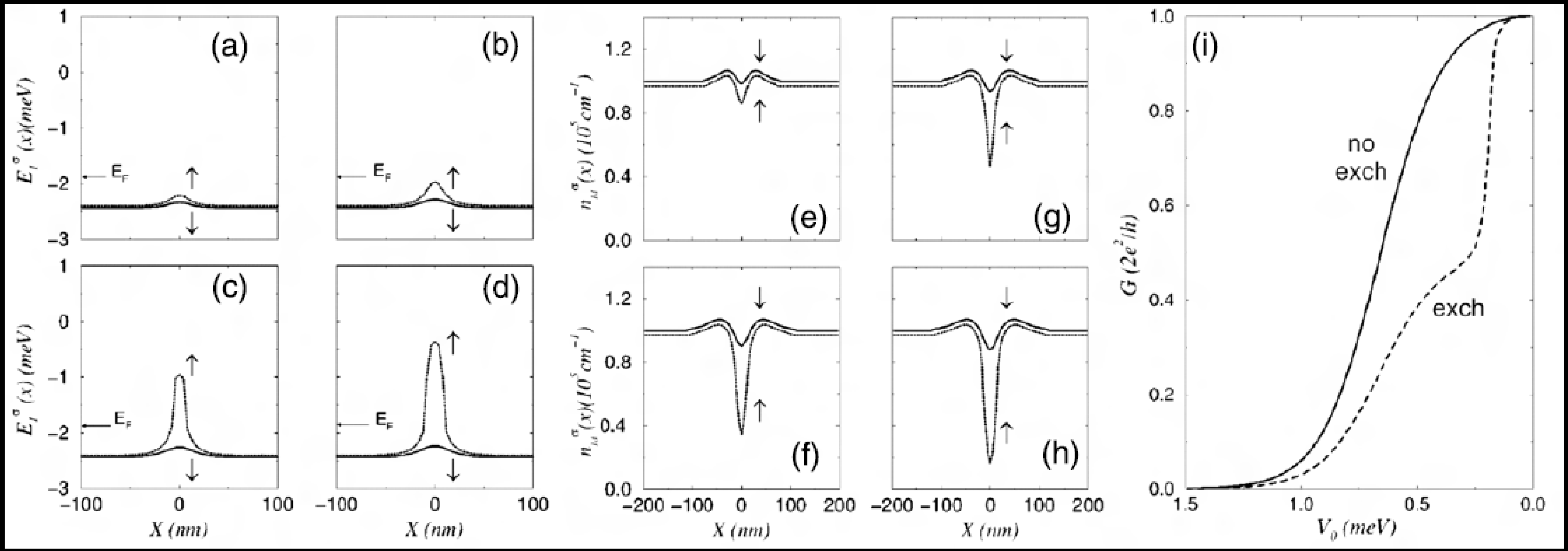
T. Rejec and Y. Meir, Nature, 442, 900 (2006).

KONDO EFFECT VERSUS 0.7 ANOMALY



F. Sfigakis *et al.*, Phys. Rev. Lett. 100, 026807 (2008).

STATIC SPIN-POLARIZATION MODEL



The first theoretical explanation: C.-K. Wang and K.-F. Berggren. Phys. Rev. B57, 4552 (1998).

KOHN-SHAM LOCAL SPIN-DENSITY APPROXIMATION (LSDA)

$$-\frac{\hbar^2}{2m^*}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\varphi^\sigma(x,y)+[U^c(x,y)+U^e(x,y)+U^\sigma_{xc}(x,y)$$
$$-g\mu_B B\sigma]\varphi^\sigma(x,y)=E^\sigma\varphi^\sigma(x,y),$$

where $U^c(x,y)=eV_g(\mathbf{r},z)+eV_d+eV_s$ is the confinement potential which consists of gate, donor layer and surface states potentials;

$U^e(x,y)=\frac{e^2}{4\pi\varepsilon\varepsilon_0}\int\rho(\mathbf{r}')\left[\frac{1}{|\mathbf{r}-\mathbf{r}'|}-\frac{1}{\sqrt{|\mathbf{r}-\mathbf{r}'|^2+4p^2}}\right]d\mathbf{r}'$ the Hartree potential including mirror charges contribution; $U^\sigma_{xc}(x,y)=U^\sigma_{ex}(\mathbf{r})+U^\sigma_c(\mathbf{r})$ the exchange-correlation potential.

Exchange potential:

$$U^\sigma_{ex}(\mathbf{r})=-\frac{e^2}{\varepsilon\varepsilon_0(\pi)^{3/2}}\rho_\sigma^{1/2}(\mathbf{r})\ (\sigma=\pm1/2)$$

Electron density:

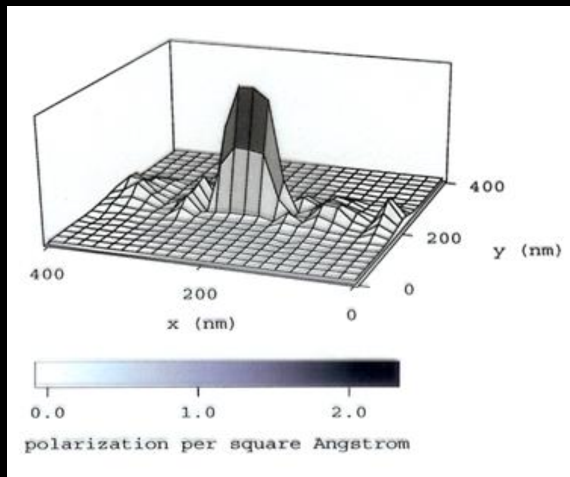
$$\rho_\sigma(\mathbf{r})=\sum_{E_i\le\mu}|\phi_i^\sigma(x,y)|^2$$

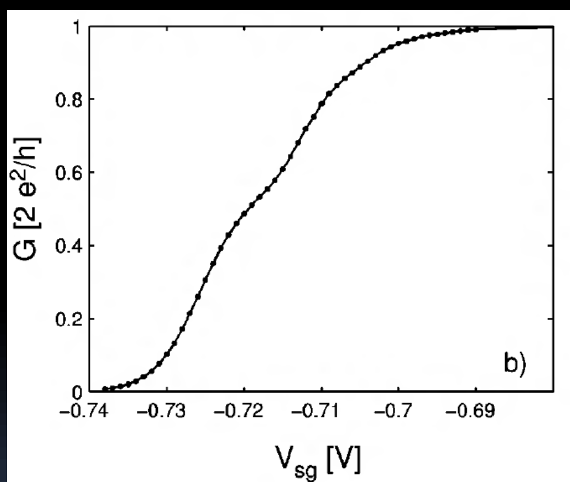
The spin polarization in the system:

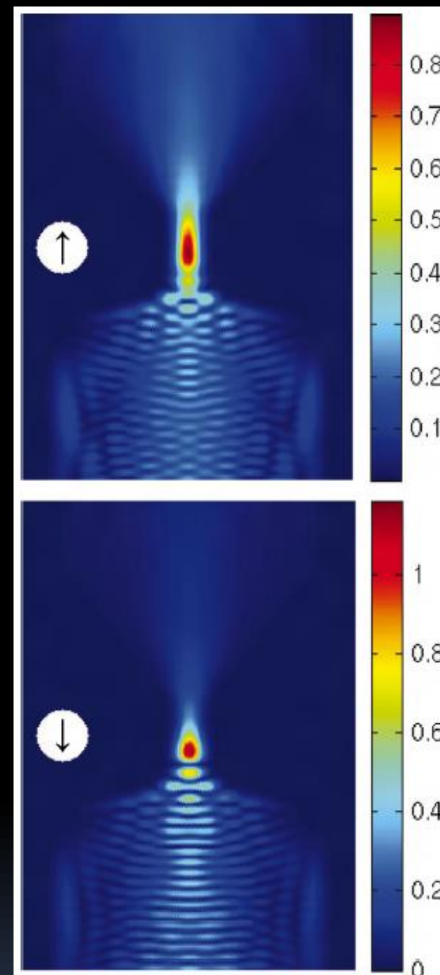
$$p=\rho_{(\sigma=1/2)}-\rho_{(\sigma=-1/2)}$$

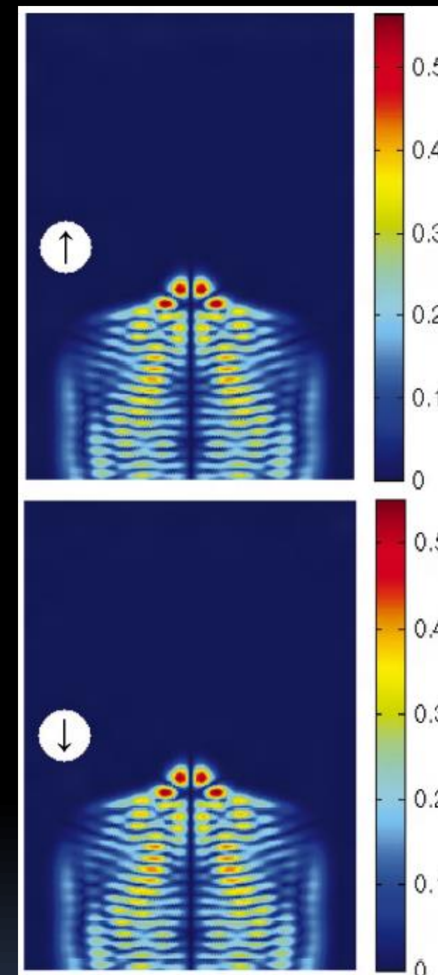
I.I. Yakimenko, A.M. Bychkov, and K.-F. Berggren, Phys. Rev. B63, 165309 (2001).

SPIN MAGNETIZATION



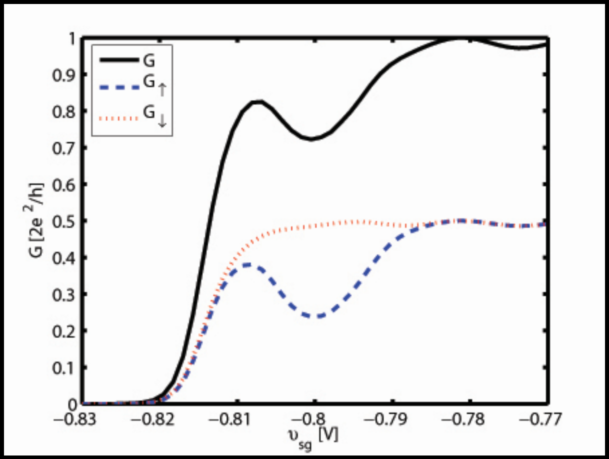


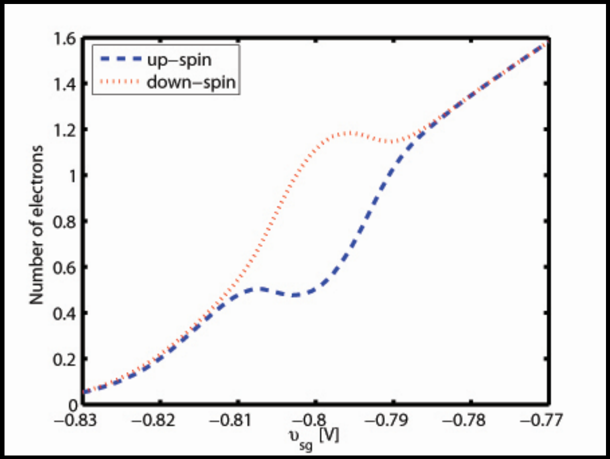




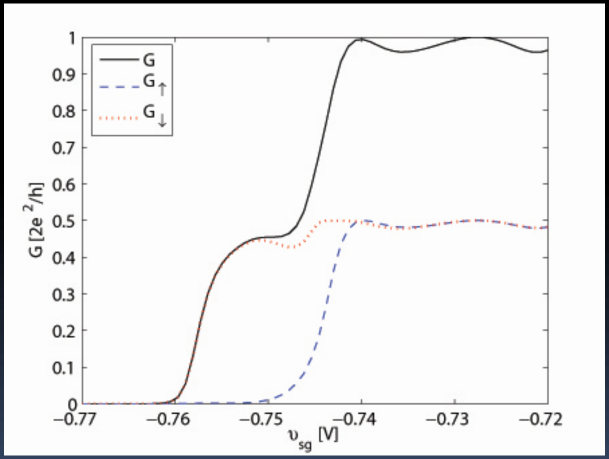
- A.M. Bychkov, I.I. Yakimenko, and K.-F. Berggren, Nanotechnology 11, 318 (2000).
- K.-F. Berggren and I.I. Yakimenko, Phys. Rev. B66, 085323 (2002).
- A.A. Starikov, I.I. Yakimenko, and K.-F. Berggren, Phys. Rev. B67, 235319 (2003).

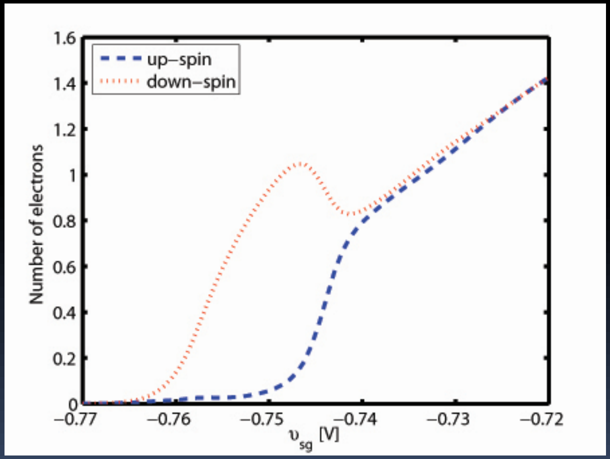
INFLUENCE OF GEOMETRY ON MAGNETIZATION IN QPC





L = 250 nm

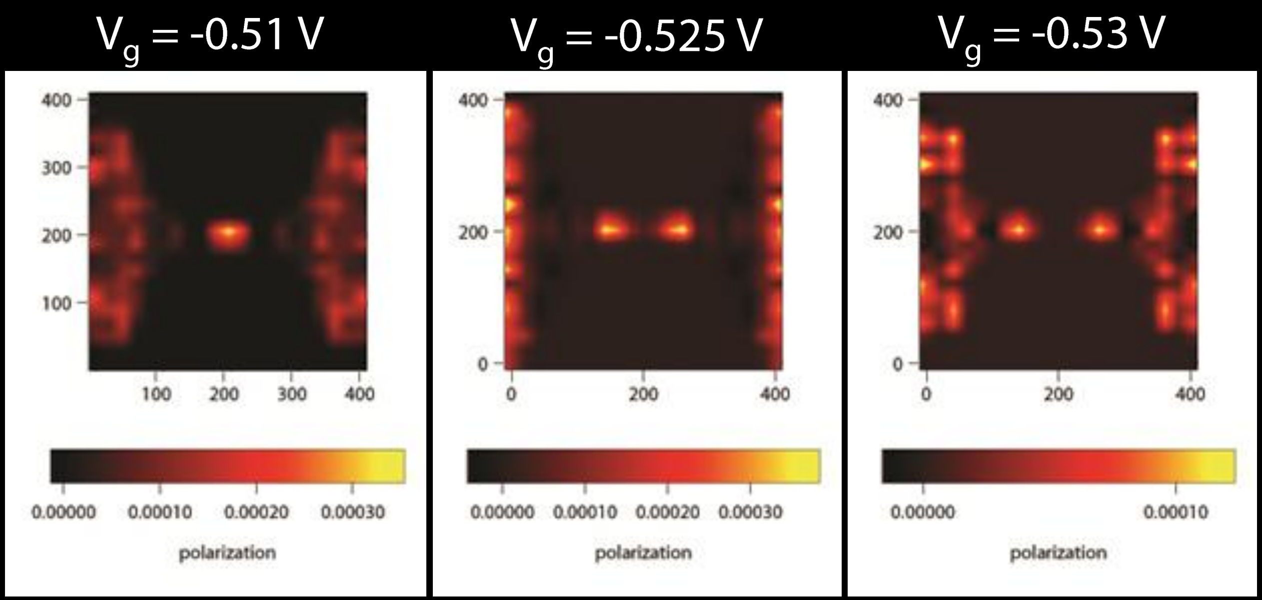




L = 400 nm

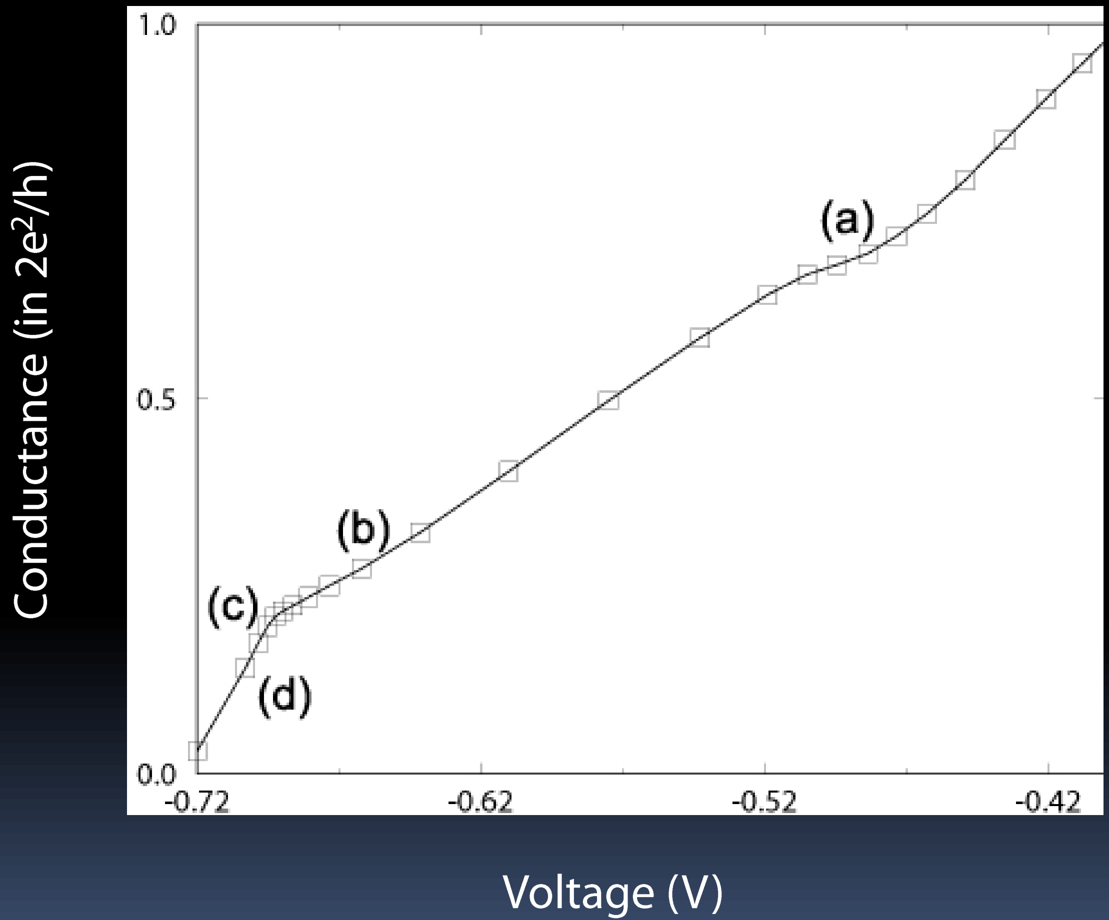
P. Jaksch, I.I. Yakimenko, K.-F. Berggren, Phys. Rev. B74, 235320 (2006).

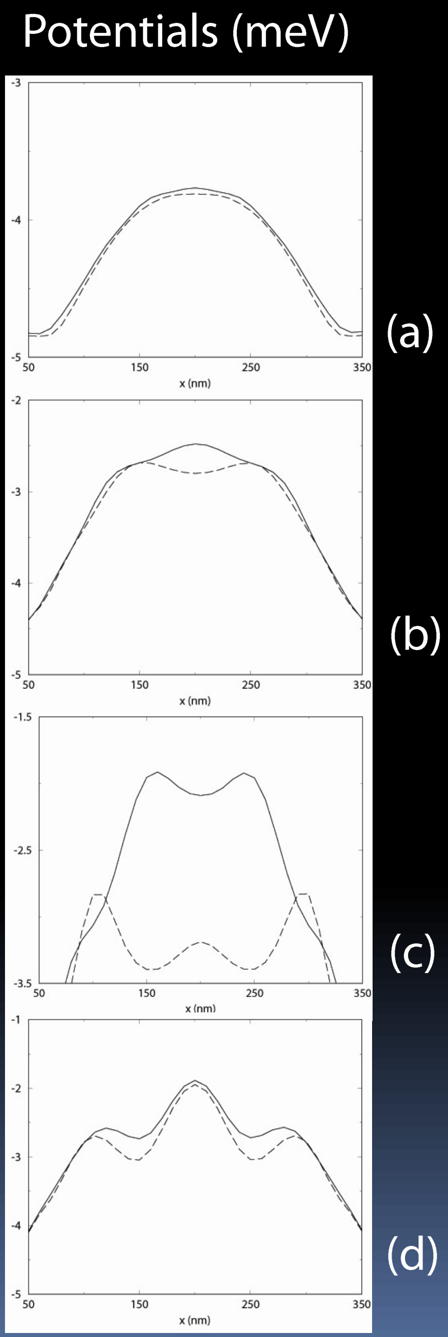
SPIN POLARIZATION IN QPC



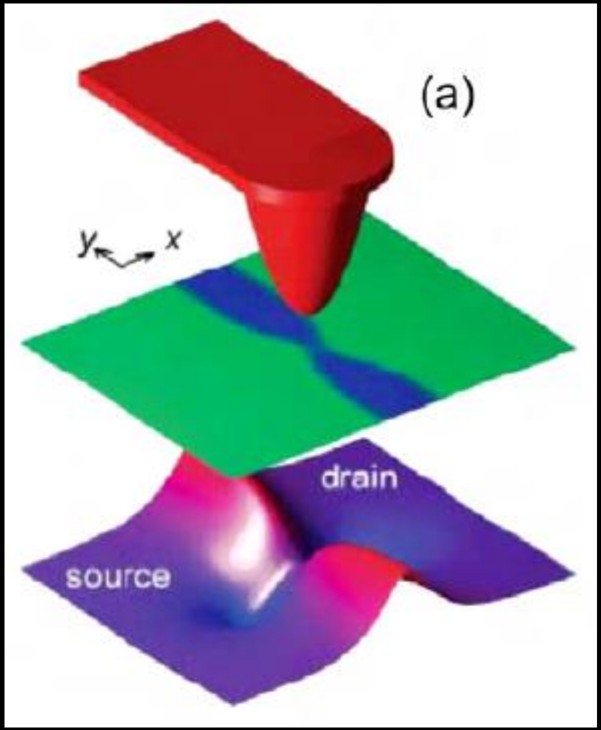
- K.-F. Berggren, I.I. Yakimenko, J. Phys.: Condens. Matter 20, 164203 (2008).
- I.I. Yakimenko and K.-F. Berggren, J. Supercond. Nov. Magn. 22, 449 (2009).

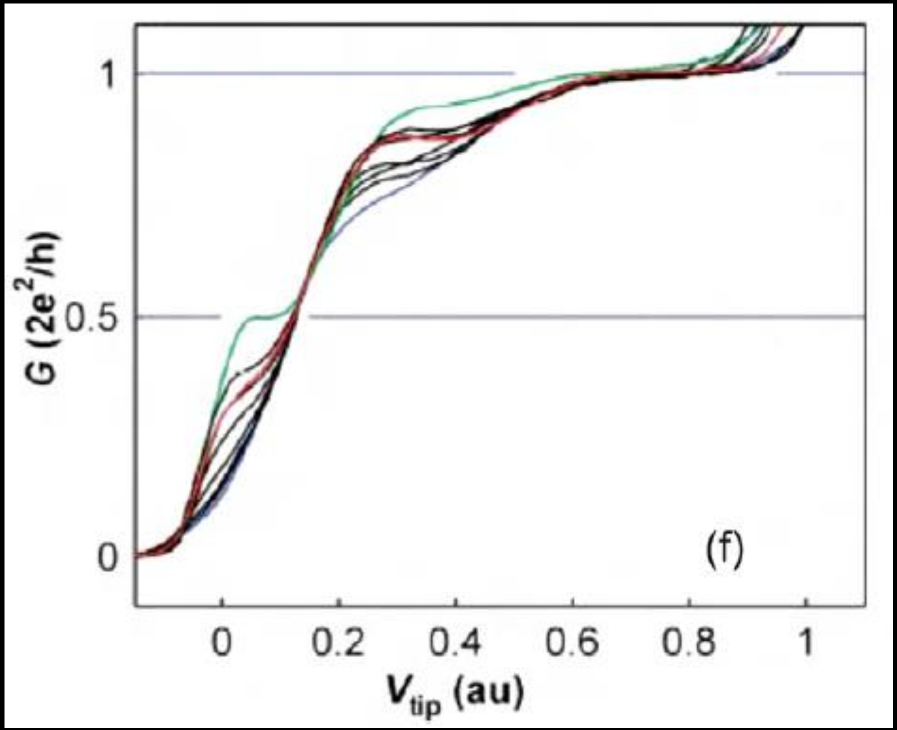
CONDUCTANCE





OBSERVATION OF 0.25 ANOMALY



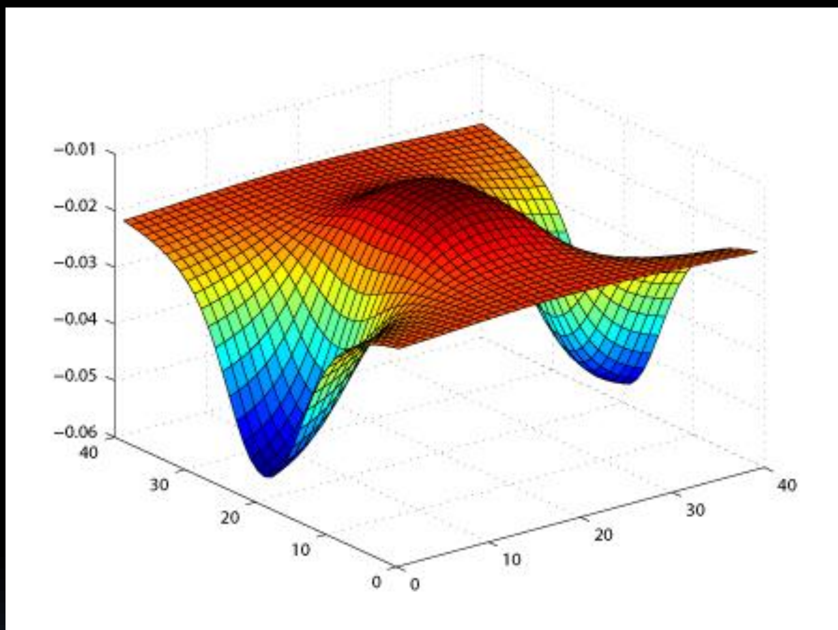


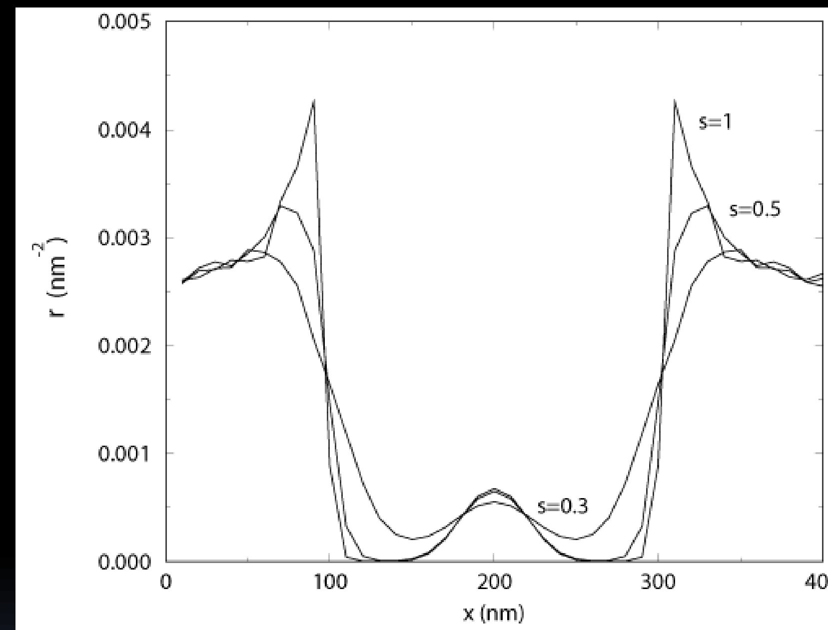
R. Crook *et al.*, Science, 312, 1359 (2006).

ELECTRON LOCALIZATION IN MODEL POTENTIAL

Model confinement potential

Electron density in nm^{-2}

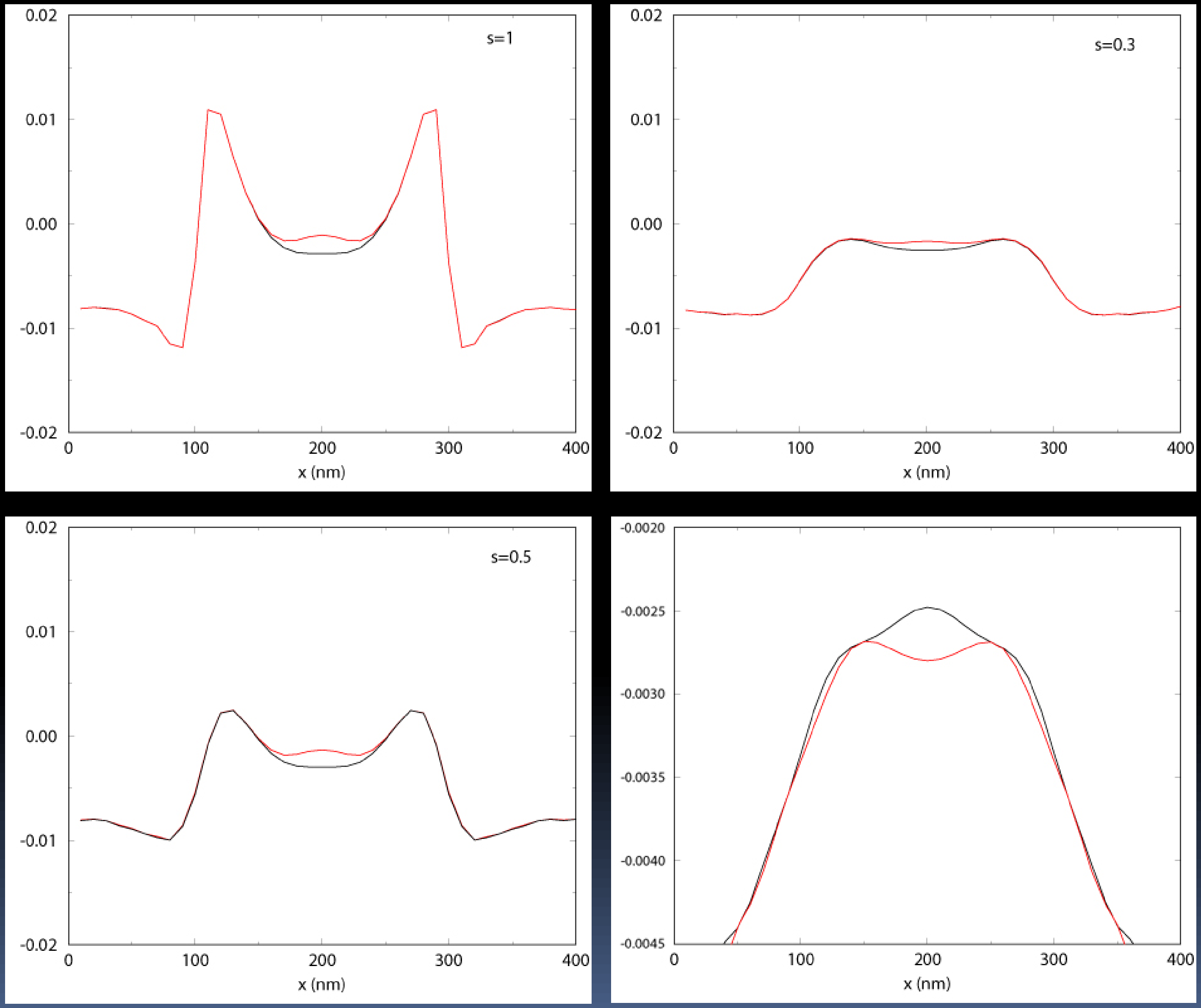




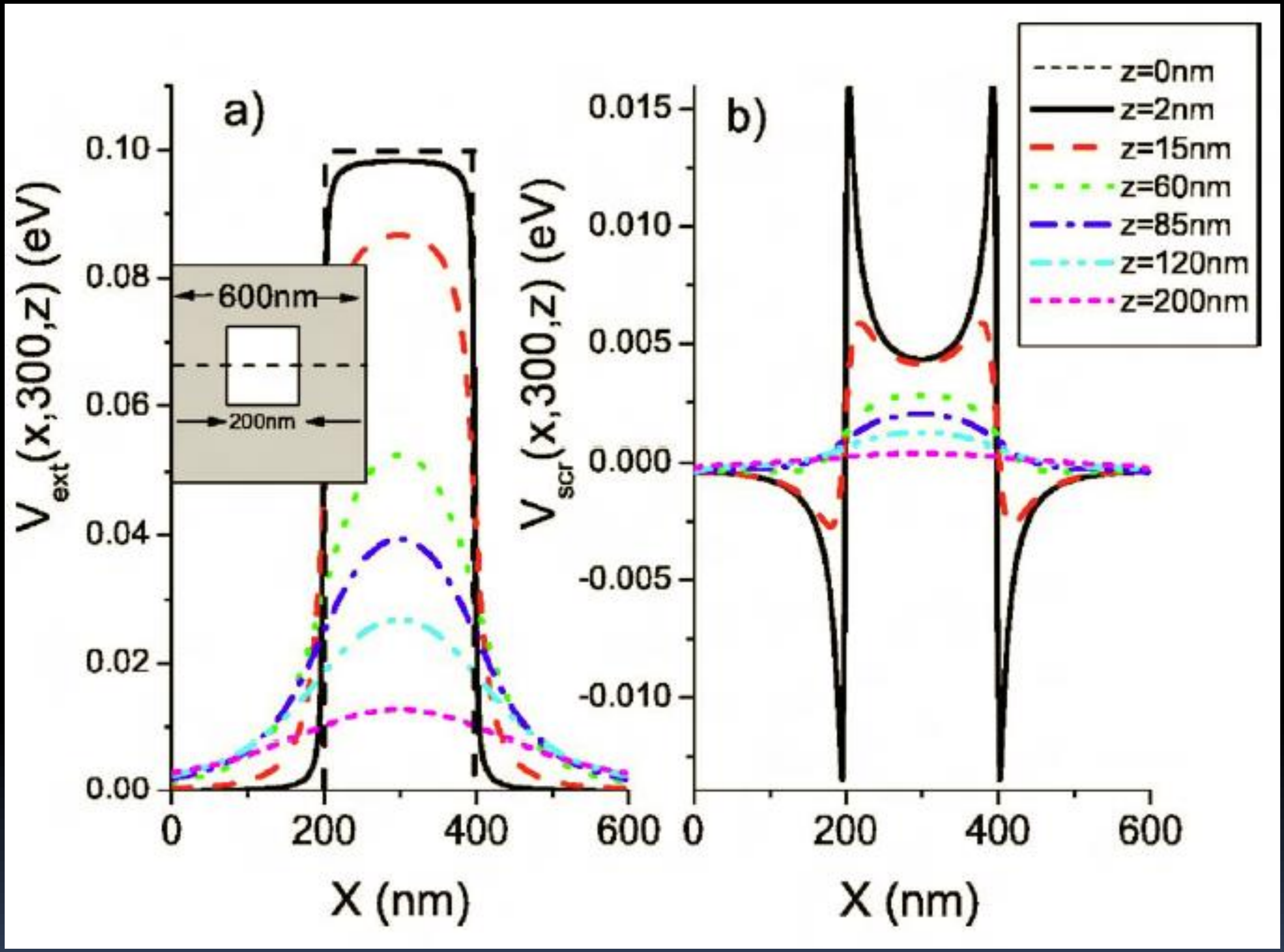
$$V_{conf} = V_g\left[\tanh\left(s(x + x_0)\right) - \tanh\left(s(x - x_0)\right)\right]$$

- I.I. Yakimenko, V. S. Tsykounov, K.-F. Berggren, submitted 2012.
- A. D. Güclü et al. Phys. Rev. B80, 201302(R) (2009).

ELECTRON TOTAL POTENTIALS (IN EV)

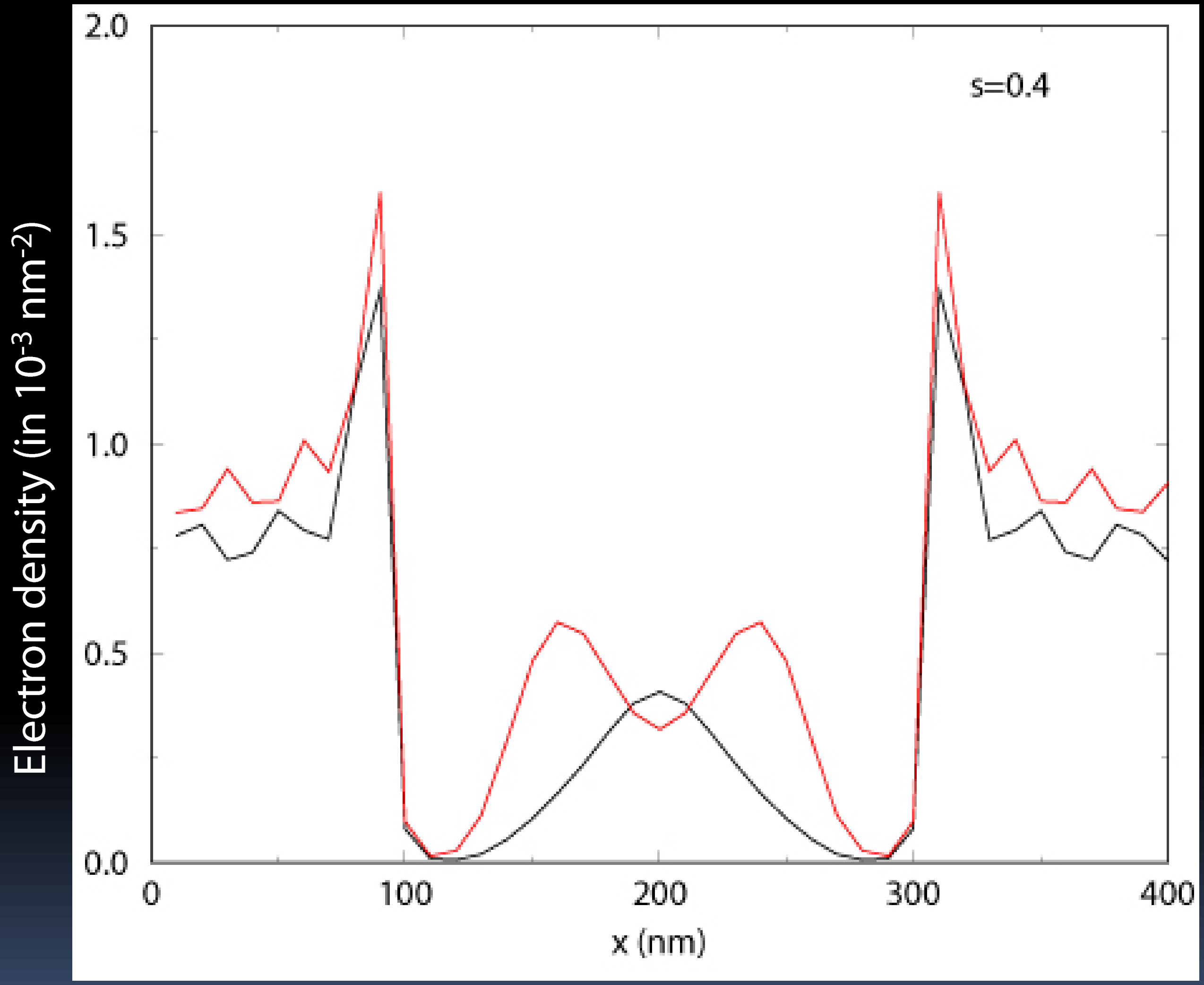


SCREENING EFFECTS

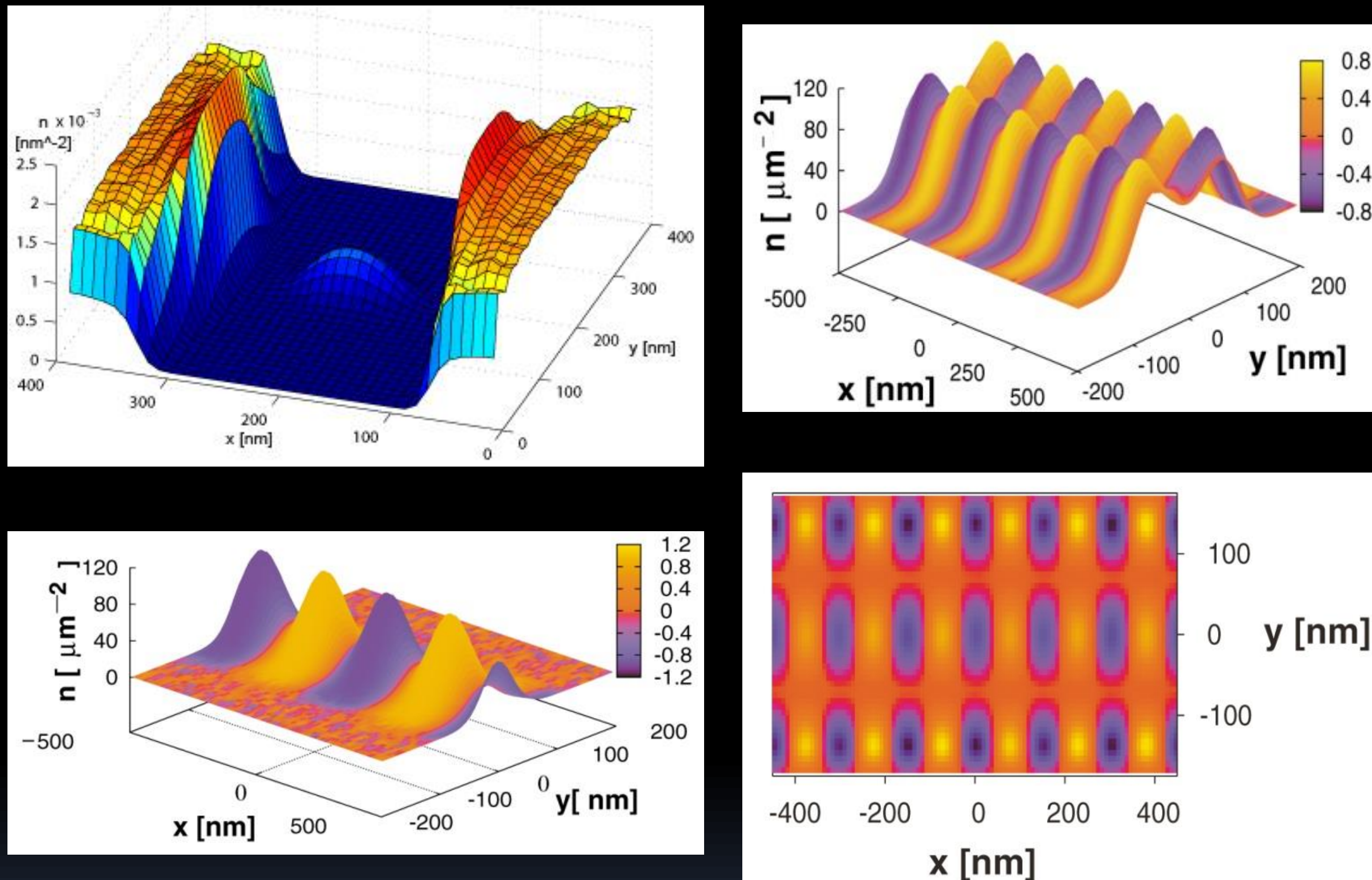


A. Siddiki, F. Marquardt, Phys. Rev. B. 75, 045325 (2007).

LOCALIZATION OF THREE ELECTRONS

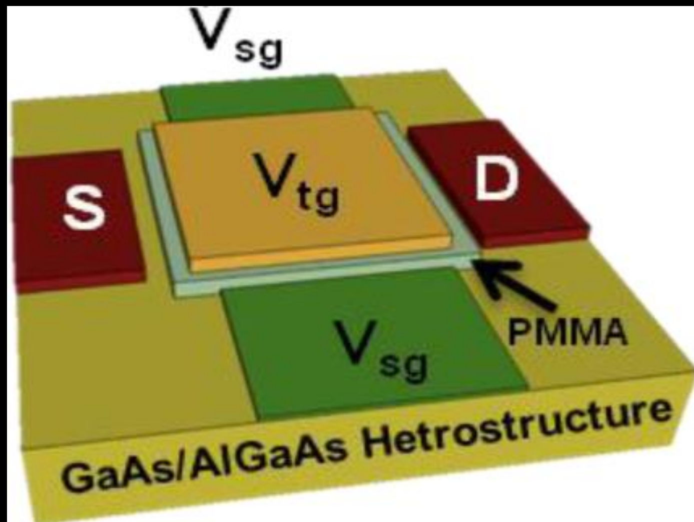


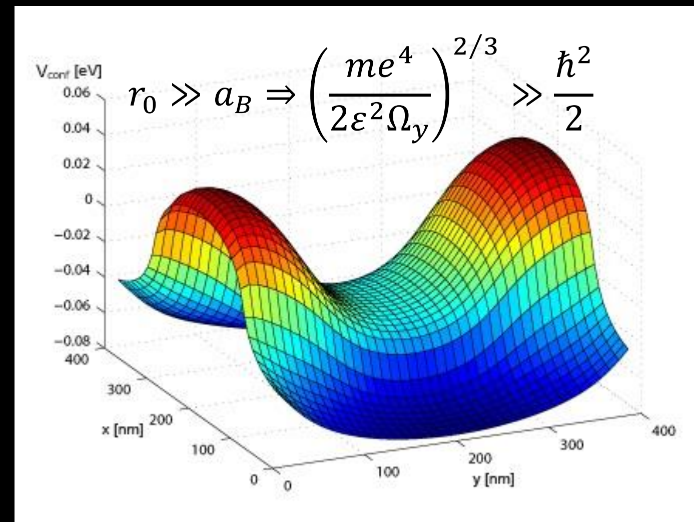
WIGNER SPIN LATTICES

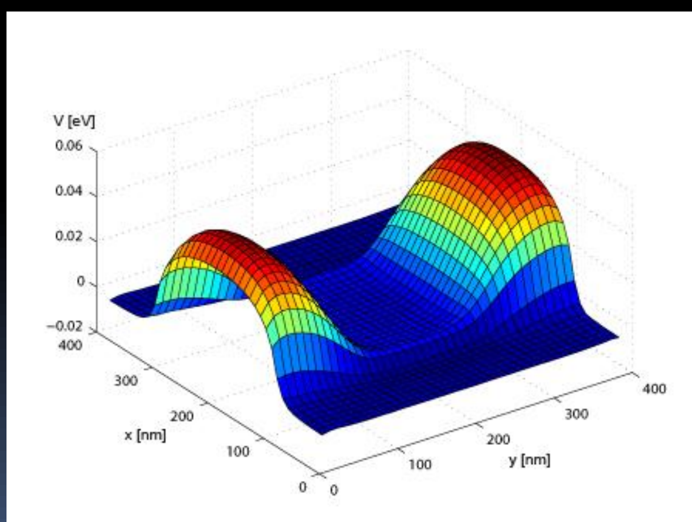


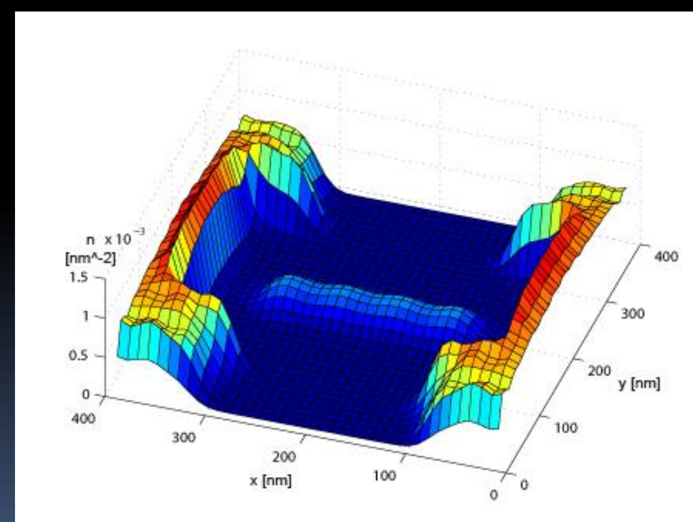
- E. Welander, I.I. Yakimenko, K.-F. Berggren, Phys. Rev. B 82, 073307 (2010).
- K.A. Matveev, Phys. Rev. Lett. 92, 106801 (2004).
- A.D. Klironomos et al., Phys. Rev. B 76, 075302 (2007).

ELECTRON LOCALIZATION FOR IMPLANT GATES









MODEL OF A BIASED QUANTUM WIRE

$$\hat{H}_0 \simeq -\frac{\hbar^2}{2m^*}\bar{\nabla}^2 + \frac{1}{2}m^*\omega_y^2 y^2 + \frac{1}{2}g\mu_B B\hat{\sigma}$$

$$E_n^\sigma(k) = \epsilon(k) + \left(n + \frac{1}{2}\right)\hbar\omega_y + \frac{1}{2}g\mu_B B\sigma$$

$$V_{int}(\mathbf{r}-\mathbf{r}') = \gamma\delta(\mathbf{r}-\mathbf{r}'); \gamma = \frac{\pi\hbar^2}{m^*}$$

$$[H_0 + \gamma n_{-\sigma}(\mathbf{r})]\Psi_i^\sigma = \bar{E}_i^\sigma\Psi_i^\sigma$$

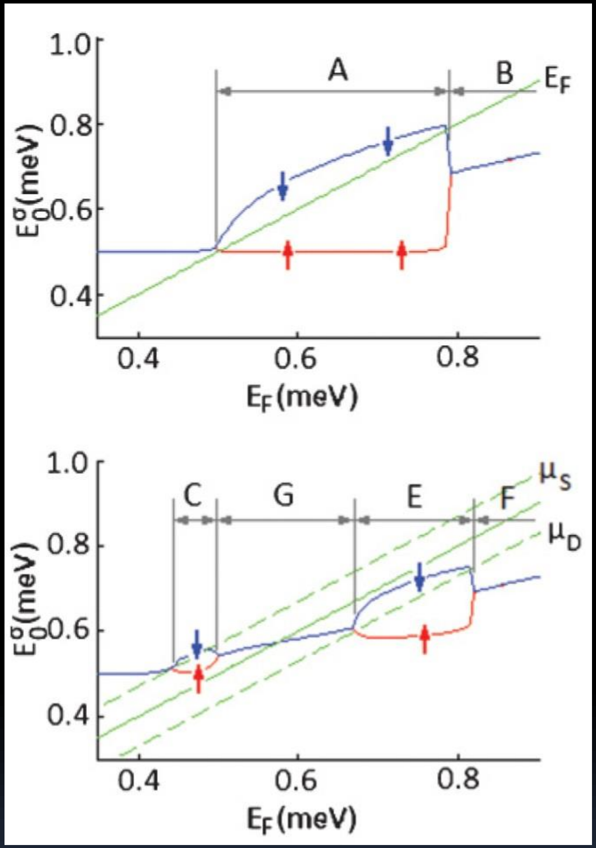
$$\mu_S = E_F + \frac{eV_{SD}}{2}$$

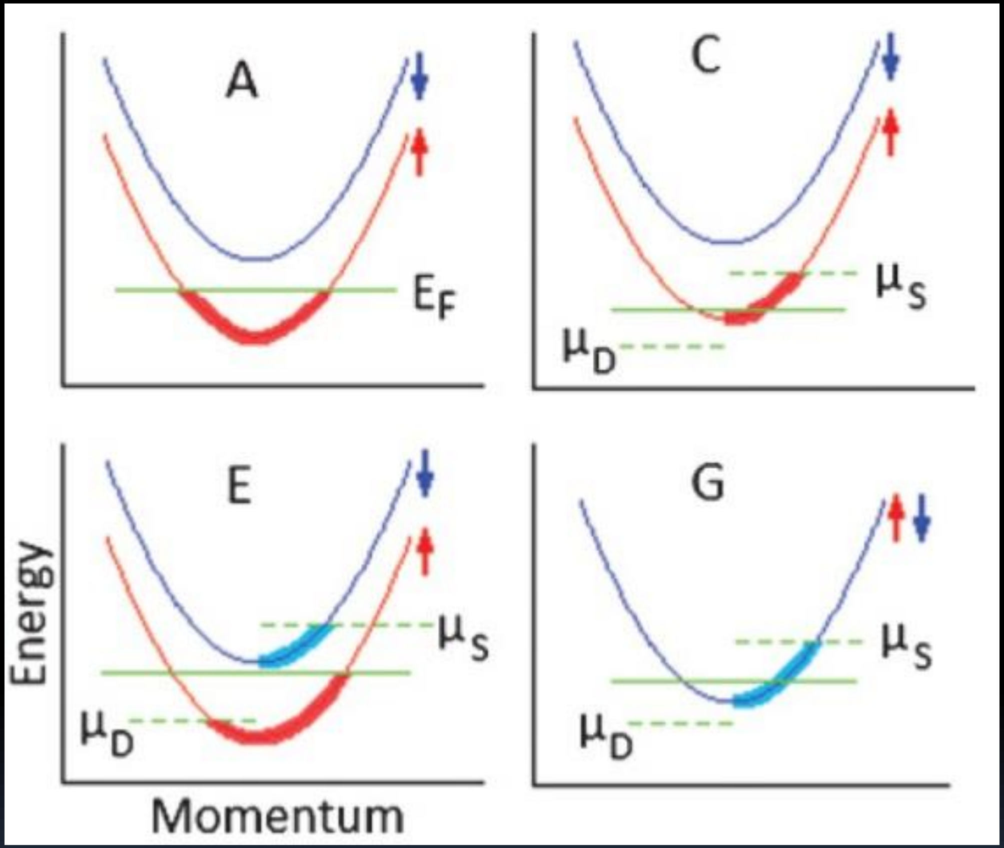
$$\mu_D = E_F - \frac{eV_{SD}}{2}$$

$$n_\sigma = \sum_n \int \frac{dk}{2\pi} f_{FD}(k,n,\sigma)|\Psi_n^\sigma|^2$$

$$I = \frac{e\hbar^2}{m^*}\sum_n\sum_\sigma \int \frac{dk}{2\pi} k f_{FD}(k,n,\sigma)$$

SUBBANDS AND CHEMICAL POTENTIALS FOR NONZERO SOURCE-DRAIN BIAS





H. Lind, I.I. Yakimenko, K.-F. Berggren, Phys. Rev. B, 83, 075308 (2011).

CONDUCTANCE

In C region:

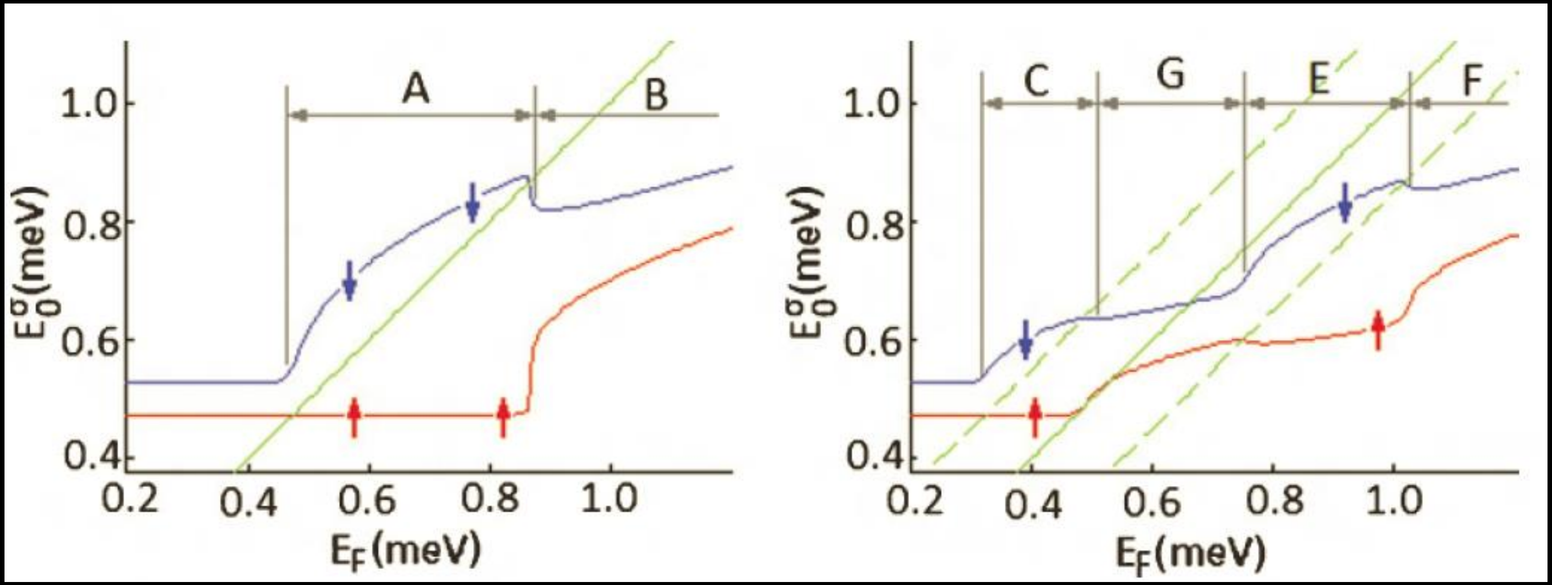
$$G_{AC} = \frac{d}{dV_{SD}}\frac{e}{h}\left(E_F + \frac{eV_{SD}}{2} - E_0^{\uparrow}\right) = 0.25\,\frac{2e^2}{h}$$

In G region:

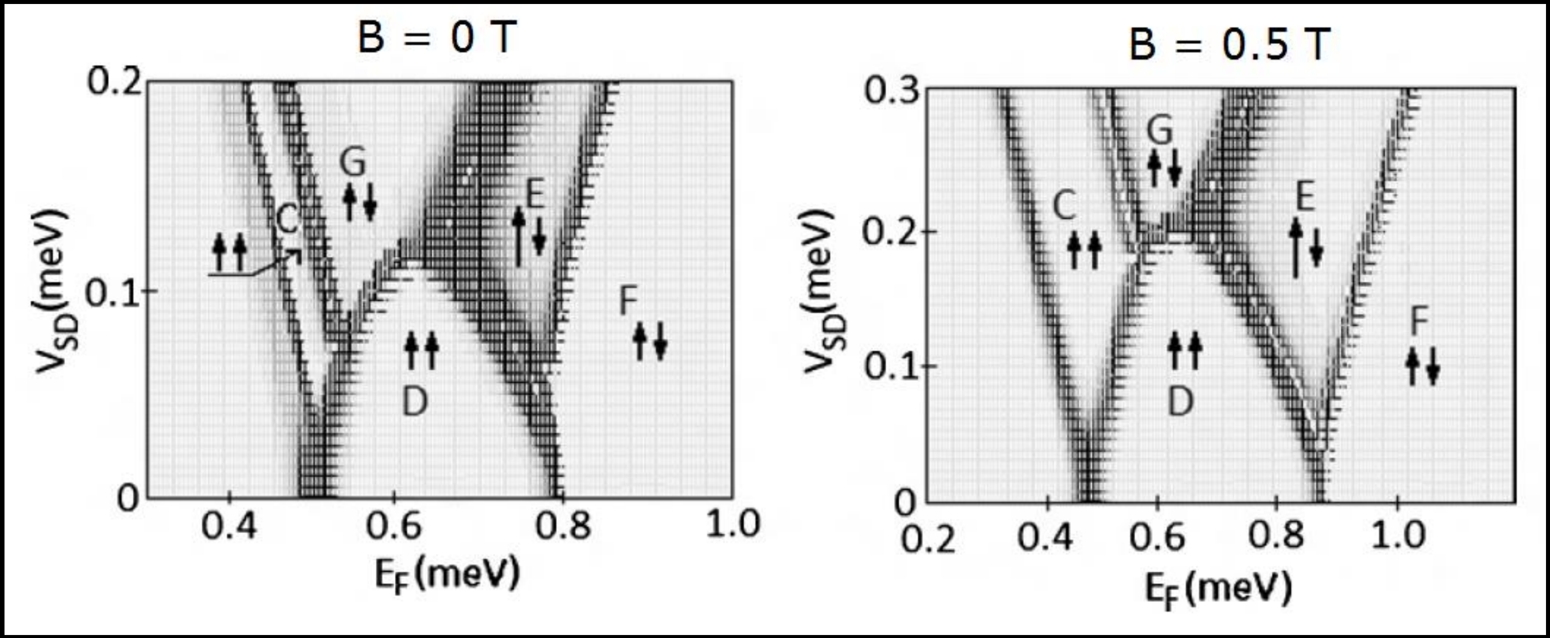
$$G_{AC} = \frac{d}{dV_{SD}}\frac{e}{h}\left(E_F + \frac{eV_{SD}}{2} - E_0^{\uparrow} + E_F + \frac{eV_{SD}}{2} - E_0^{\downarrow}\right) = (0.5 - \zeta)\,\frac{2e^2}{h}$$

$$\zeta = \frac{dE_0^{\uparrow}}{d(eV_{SD})} = \frac{dE_0^{\downarrow}}{d(eV_{SD})}$$

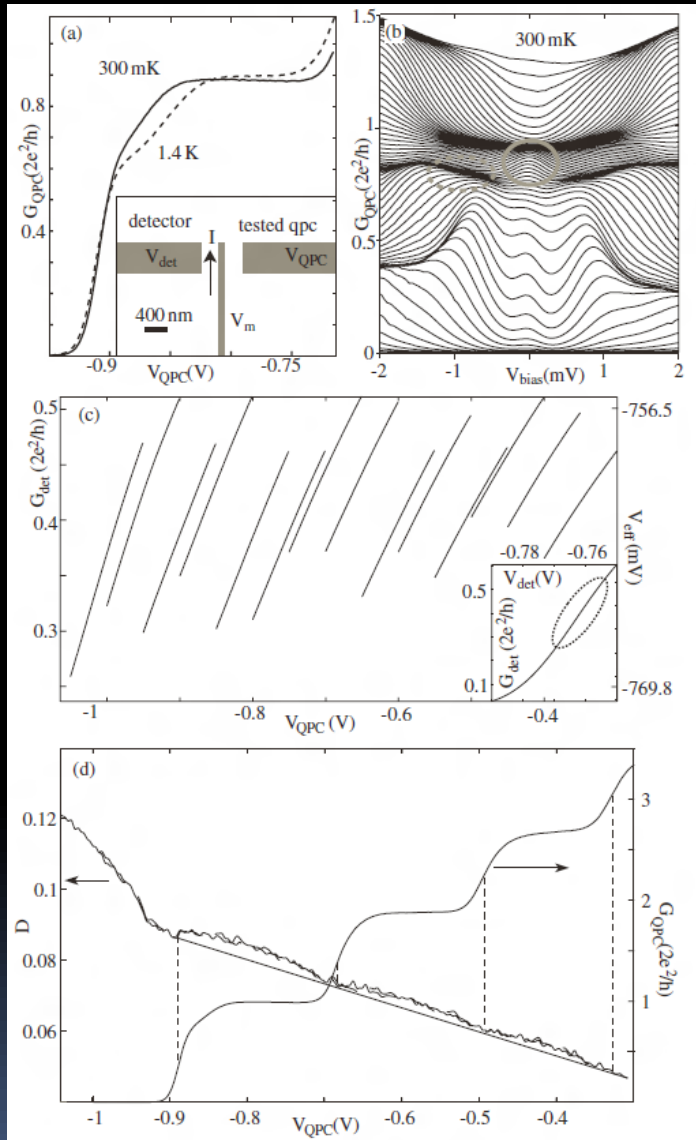
BIASED QUANTUM WIRE IN A MAGNETIC FIELD

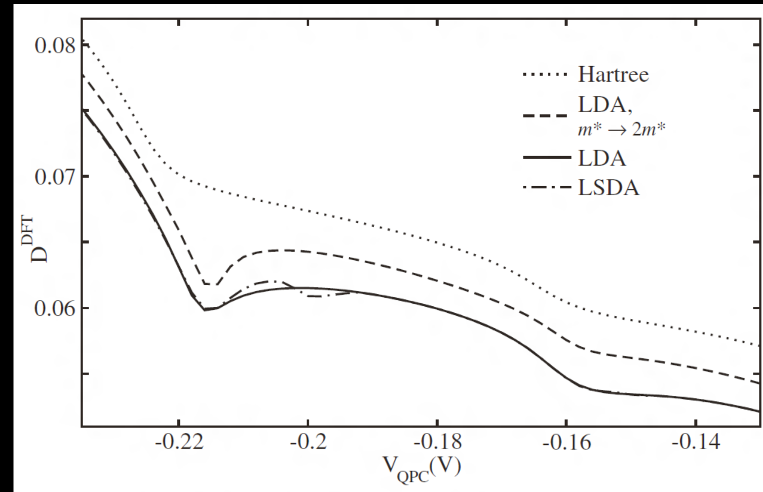


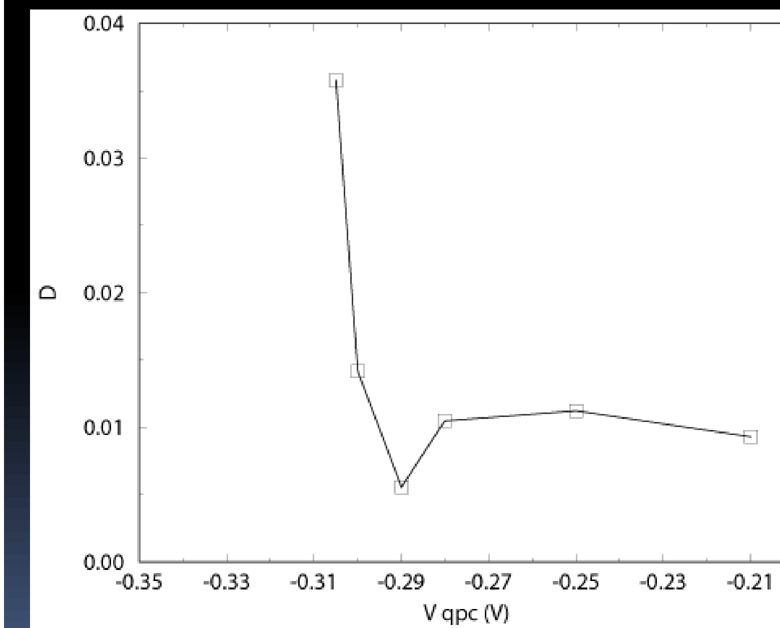
TRANSCONDUCTANCE



COMPRESSIBILITY MEASUREMENTS

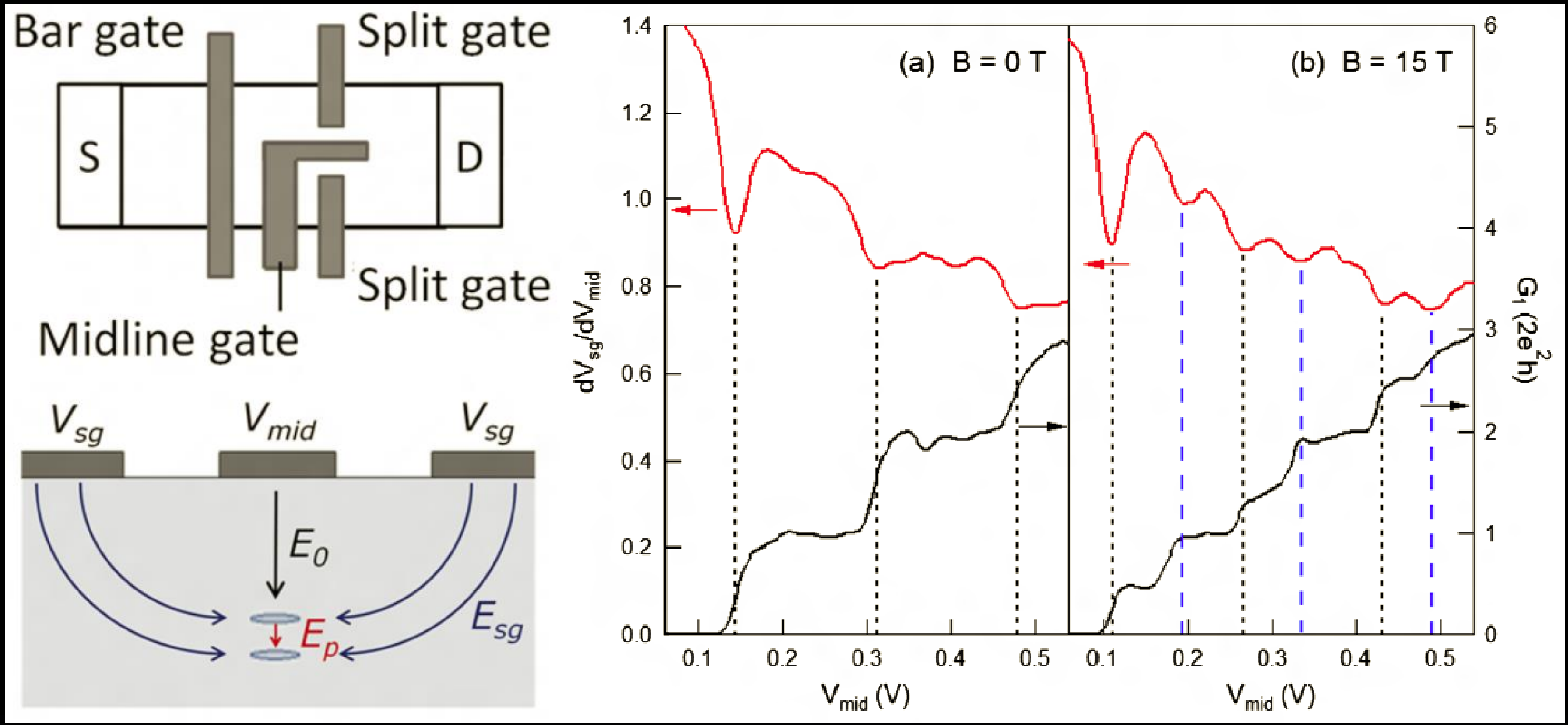






S. Lüscher, *et al.*, Phys. Rev. Lett. 98, 196805 (2007).

COMPRESSIBILITY MEASUREMENTS



L.W. Smith, *et al.*, Phys. Rev. Lett. 107, 126801 (2011).

APPLICATIONS

- In SPINTRONICS: for implementation of the spin-filter and all-electric spin-polarizer based on the effect of spin polarization in quantum point contacts
- In QUANTUM COMPUTING: for qubit and quantum gate implementation using nanomagnetism in quantum point contacts
- In NANOELECTRONICS: for magnetic memory devices using localized electrons in quantum point contacts and quantum wires