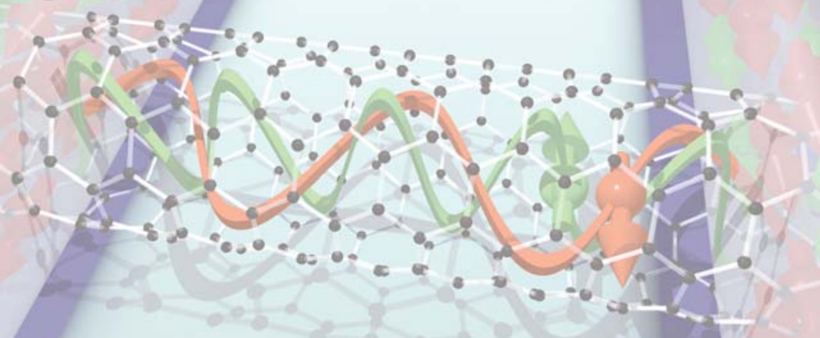
Spin Transport and Double Dots in Carbon Nanotubes



Quantum Phenomena at Low Temperatures
Lammi Biological Station, Finnland, April 2006

Transport in Carbon Nanotube

Sangeeta Sahoo
Takis Kontos
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Matthias Gräber
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D. Loss (Basel)
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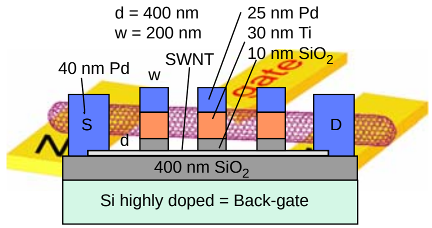
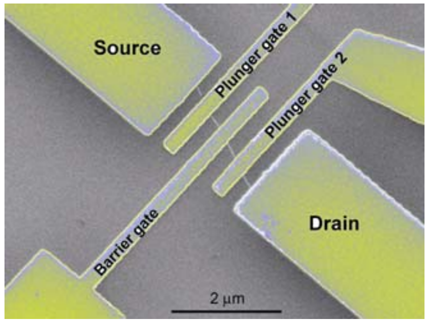
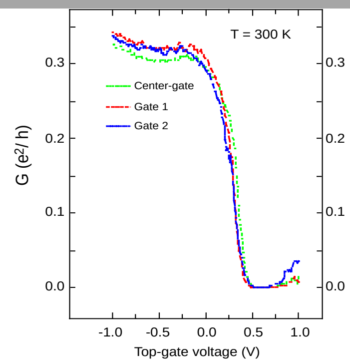
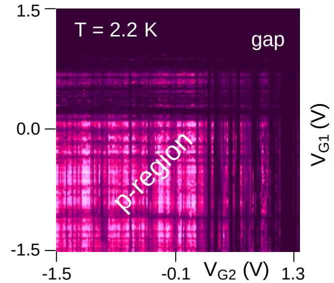
Carbon Nanotube Devices

Carbon Nanotube Devices





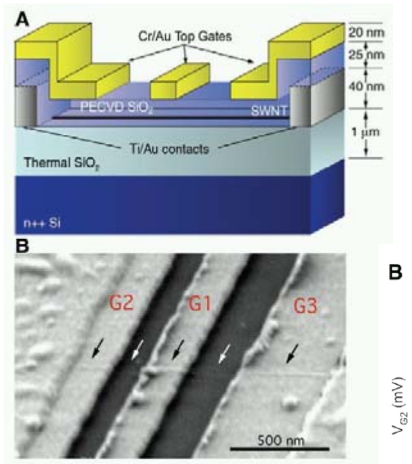


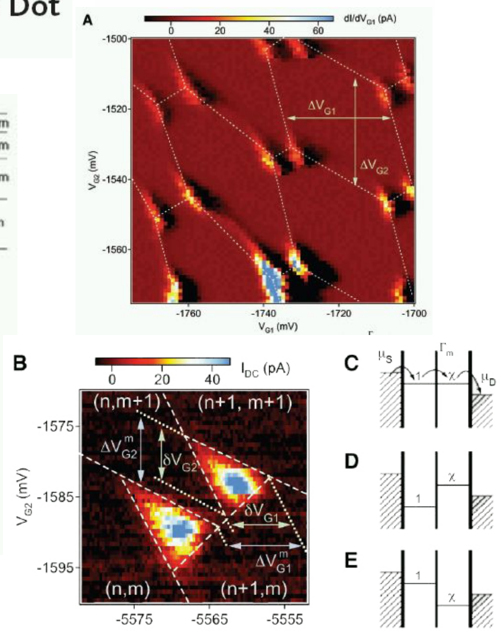


Local Gate Control of a Carbon Nanotube Double Quantum Dot

N. Mason,*† M. J. Biercuk,* C. M. Marcus†

SCIENCE VOL 303 30 JANUARY 2004

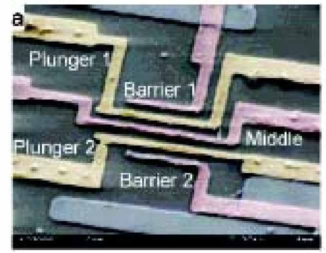


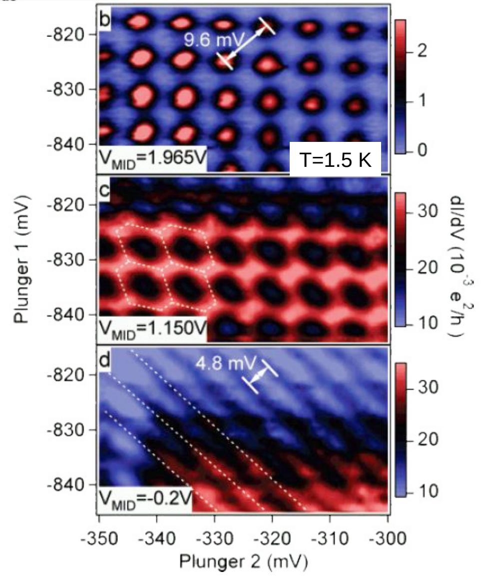


Gate-Defined Quantum Dots on Carbon Nanotubes

M. J. Biercuk, S. Garaj, N. Mason, J. M. Chow, and C. M. Marcus*

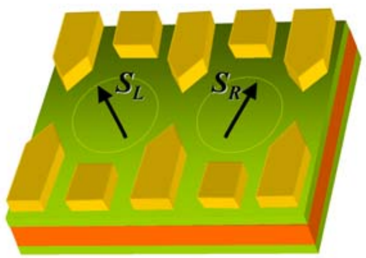
NANO LETTERS
2005
Vol. 5, No. 7
1267−1271





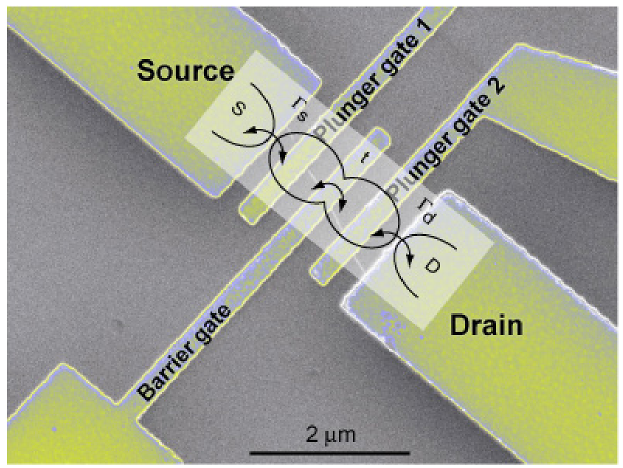
Motivation

- Local gate control of electronic transport in nanotubes
- Probing and controlling quantum effects
- Spin in a quantum dot as quantum bit?
- Long spin dephasing times in nanotubes?

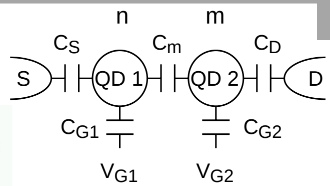


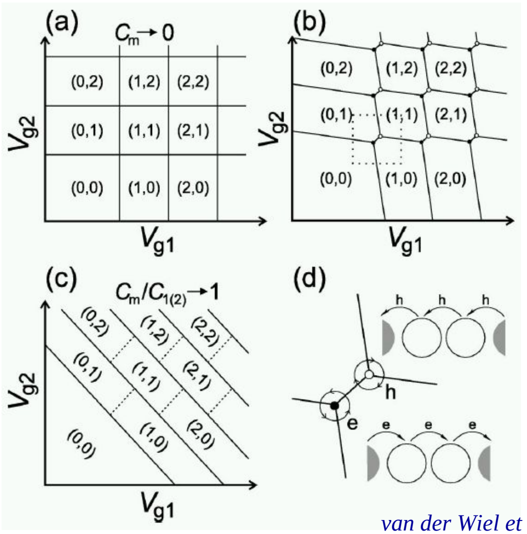
D. Loss and D. P. DiVincenzo Phys. Rev. A ***57****, 120-126 (1998)*

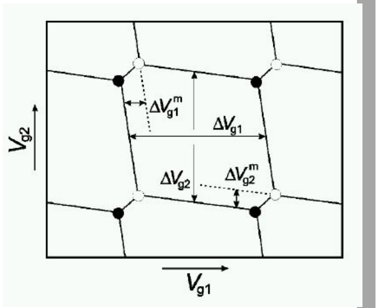
Carbon Nanotube Double Dots



Charge Stability Diagram

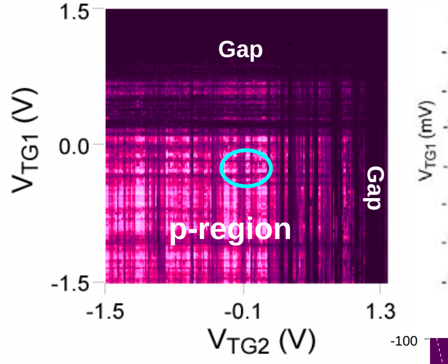


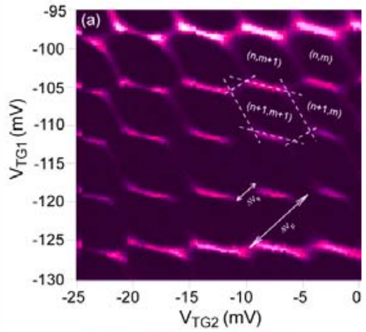




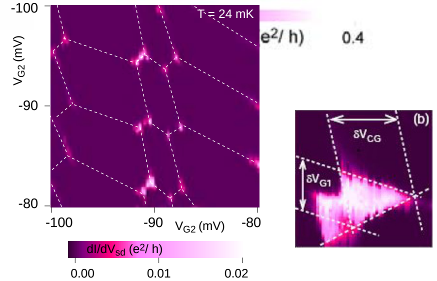
*van der Wiel et al. Rev. Mod. Phys. **75** (2003)*

Carbon Nanotube Double Dot



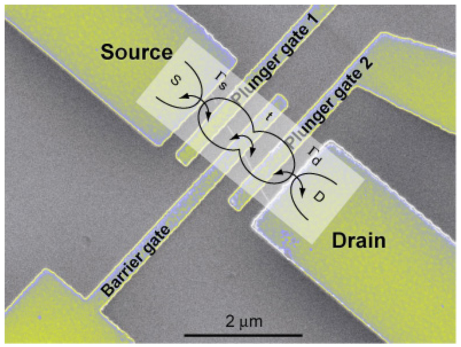


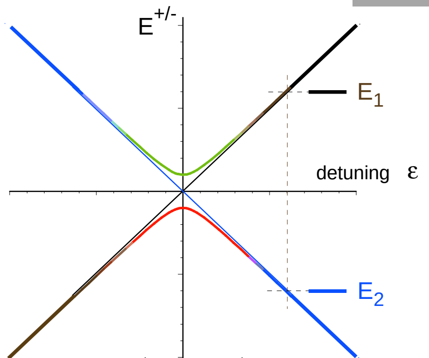
if two dots are weakly coupled



Matthias Gräber et al. cond-mat/0603367

molecular states (hybridization)





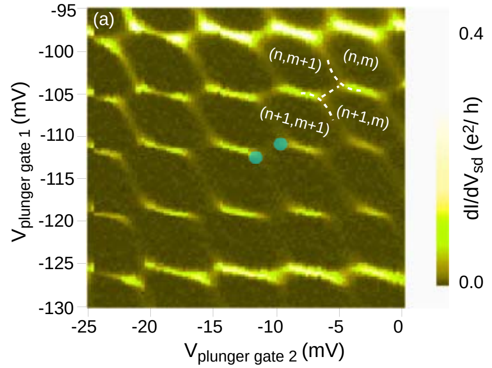
$$H\psi = \begin{pmatrix} E_1 & t \\ t^* & E_2 \end{pmatrix}\psi$$

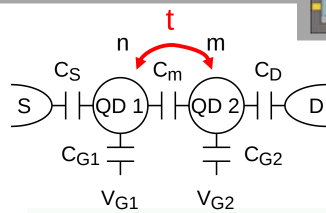
$$\Delta = \frac{E_1 + E_2}{2} \qquad \varepsilon = \frac{E_1 - E_2}{2}$$

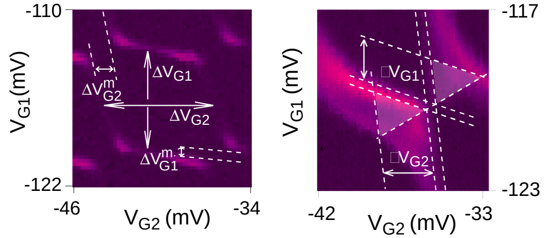
$$E^{+/-} = \Delta \mp \sqrt{\varepsilon^2 + |t|^2}$$

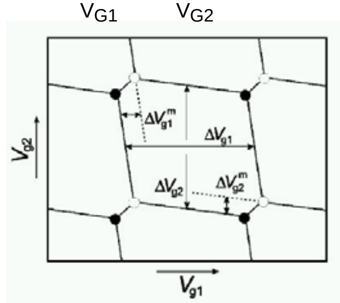
$C_{100'000}$ ➔ $(C_{100'000})_2$

characterization







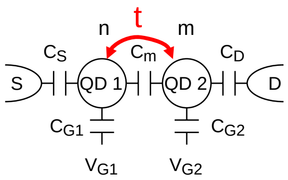


$C_{g1,g2}$ ~ 20 aF

$C_{1=S}$, $C_{2=D}$ ~ 85, 145 aF

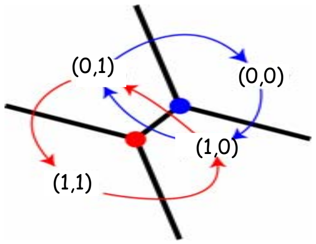
C_m ~ 15 aF

add tunnel coupling

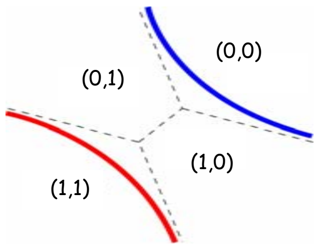


$$E^{+/-} = \Delta \mp \sqrt{\varepsilon^2 + |t|^2}$$

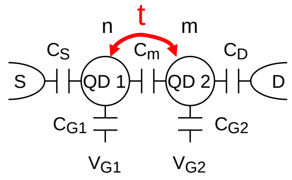
No tunnel-coupling



Tunnel-coupling



add tunnel coupling

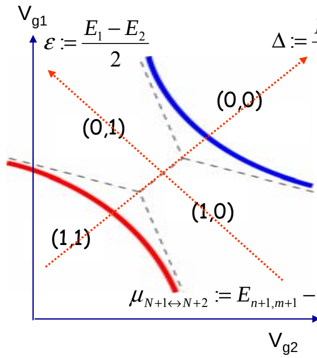


$$E^{+/-} = \Delta \mp \sqrt{\varepsilon^2 + |t|^2}$$

$$E_{n+1,m} - E_{n,m} = Un + U'm + E_1(V_{g1})$$

$$E_{n,m+1} - E_{n,m} = Um + U'n + E_2(V_{g2})$$

$$\psi^{\pm} = \alpha|n+1,m\rangle \pm \beta|n,m+1\rangle$$

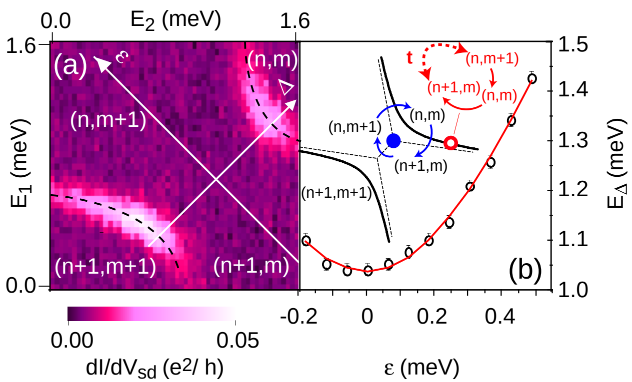


$$\mu_{N\leftrightarrow N+1} := E^+ - E_{n,m} = \frac{1}{2}(U+U')(n+m) + \Delta_{N\leftrightarrow N+1}(\varepsilon) - \sqrt{\varepsilon^2 + |t|^2}$$

$$\mu_{N+1\leftrightarrow N+2} := E_{n+1,m+1} - E^+ = \frac{1}{2}(U+U')(n+m) + U' + \Delta_{N+1\leftrightarrow N+2}(\varepsilon) + \sqrt{\varepsilon^2 + |t|^2}$$

$$\mu_{reservoirs} = \mu_{N\leftrightarrow N+1} = \mu_{N+1\leftrightarrow N+2} \;\rightarrow\; \Delta_r(\varepsilon) - \Delta_l(\varepsilon) = U' + 2\sqrt{\varepsilon^2 + |t|^2}$$

level anti-crossing



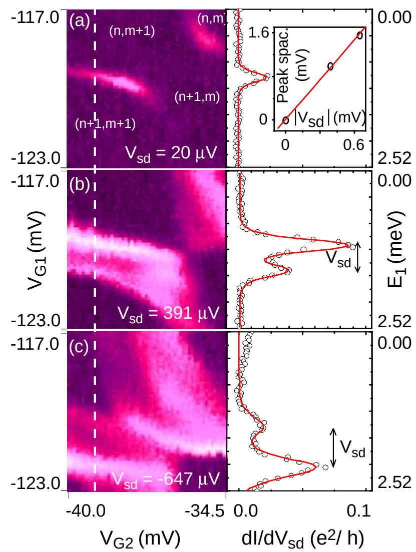
$$E^{+/-} = \Delta \mp \sqrt{\varepsilon^2 + |t|^2}$$

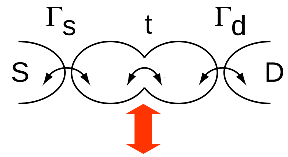
$$E_\Delta := |\Delta_l - \Delta_r| = U' + 2\sqrt{\varepsilon^2 + |t|^2} \qquad U' = \frac{2e^2 C_m}{C_1 C_2 - C_m}$$

t ~ 310-360 µeV

U' < 100 µeV

energy-scale





$$\psi^+ = \alpha|n+1,m\rangle + \beta|n,m+1\rangle$$

$$I = e\Gamma|\alpha\cdot\beta|^2\{f(\mu_{2dot} - \mu_{source}) - f(\mu_{2dot} - \mu_{drain})\}$$

$$\frac{dI}{dV} = -e\Gamma|\alpha\cdot\beta|^2\{(1-r)f'(\Delta\mu_S) + rf'(\Delta\mu_D)\}$$

$$r := \frac{\partial\mu_{2dot}}{\partial\mu_{Source}} = \frac{C_S}{C_\Sigma}$$

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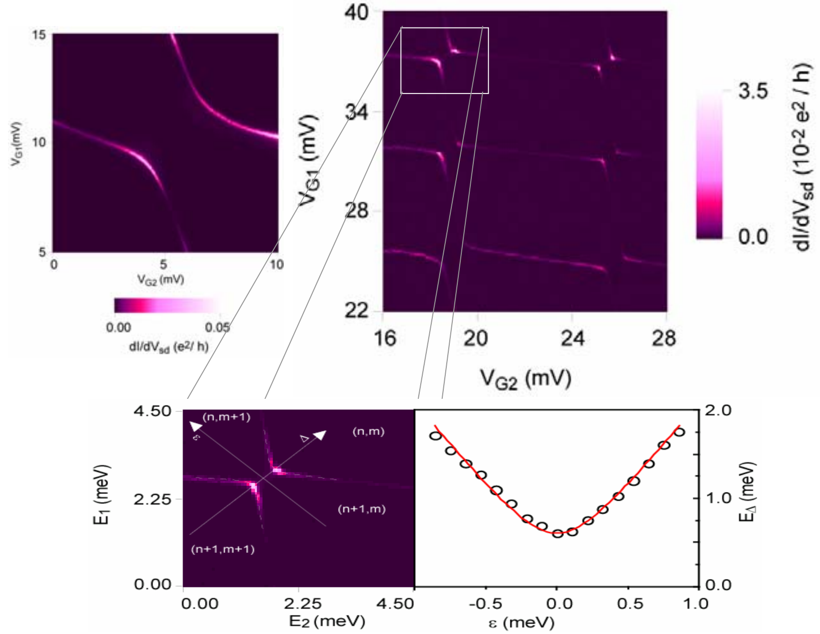
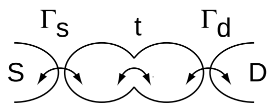
more data



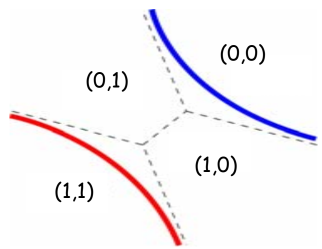
mapping of molecular states

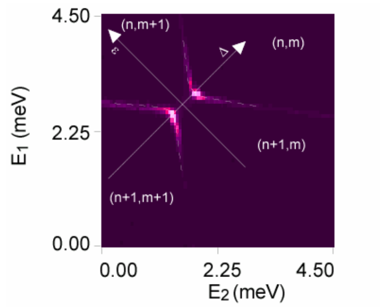


$$\psi = \alpha |n+1, m\rangle + \beta |n, m+1\rangle$$

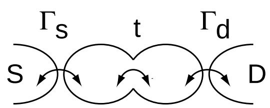
$$\alpha, \beta(\varepsilon) = \frac{|t|^2}{|t|^2 + \left(\varepsilon \pm \sqrt{\varepsilon^2 + |t|^2}\right)^2}$$

$$G = e\Gamma |\alpha(\varepsilon) \cdot \beta(\varepsilon)|^2$$

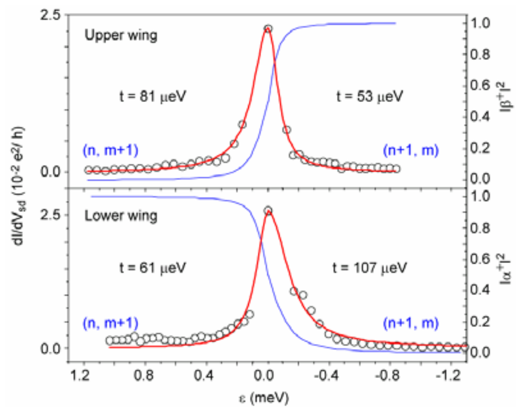


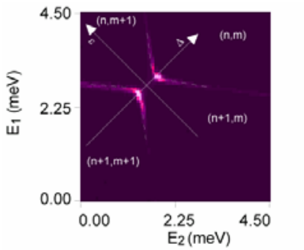


mapping of molecular states

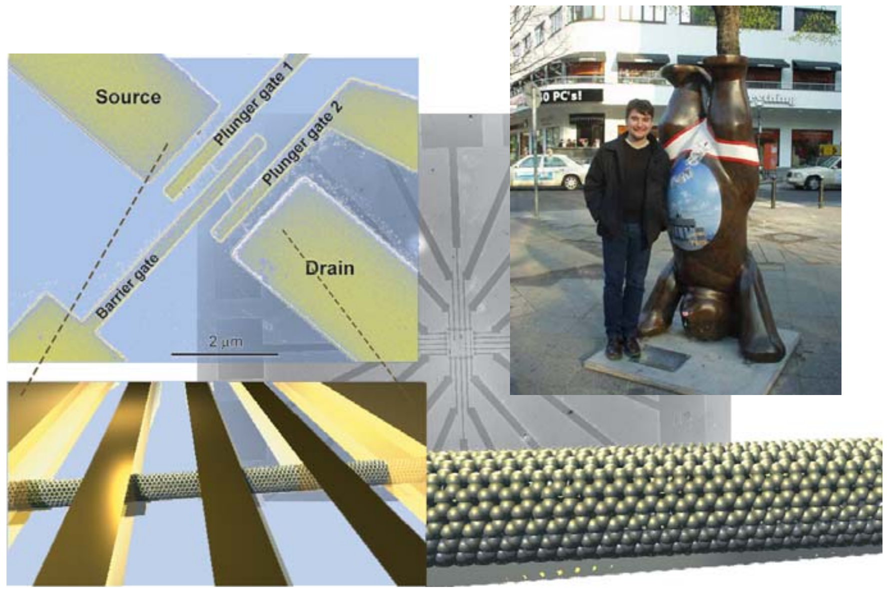


$$\psi = \alpha |n+1, m\rangle + \beta |n, m+1\rangle$$

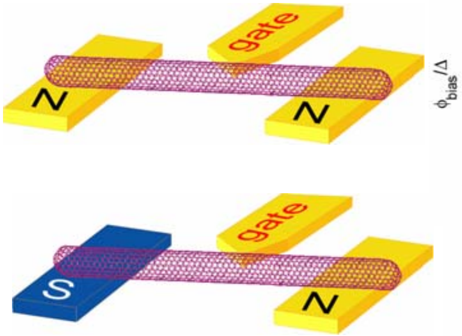


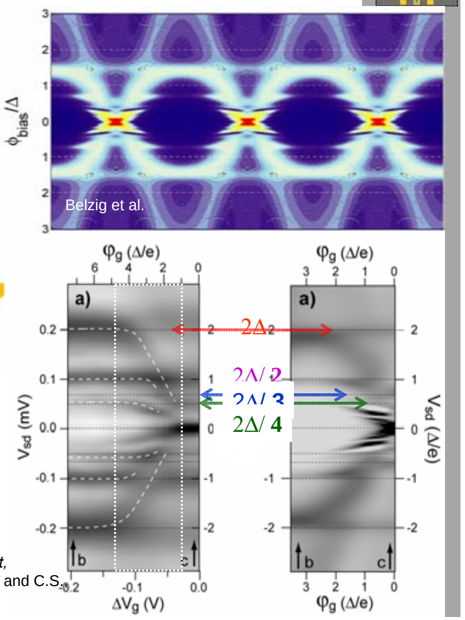


Matthias Gräber



Carbon Nanotube Devices

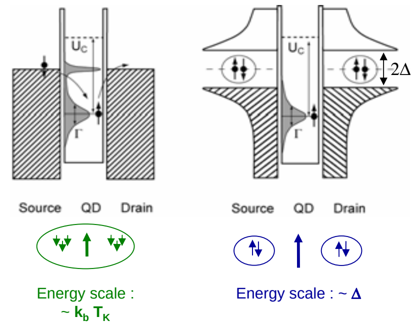




1. *Multi-wall carbon nanotubes as quantum dots*
   M. R. Buitelaar, A. Bachtold, T. Nussbaumer, M. Iqbal and C.S.,
   Phys. Rev. Lett. 88, 156801 (2002).
2. *A quantum dot in the Kondo regime coupled to superconductors*,
   M. R. Buitelaar, T. Nussbaumer, and C. Schönenberger,
   Phys. Rev. Lett. 89(25):256801 (2002).
3. *Multiple Andreev Reflections in a Carbon Nanotube Quantum Dot*,
   M. R. Buitelaar, **W. Belzig**, T. Nussbaumer, B. Babić, B. Bruder, and C.S.,
   Phys. Rev. Lett. 91:057005 (2003).

Carbon Nanotube Hybrid Dots

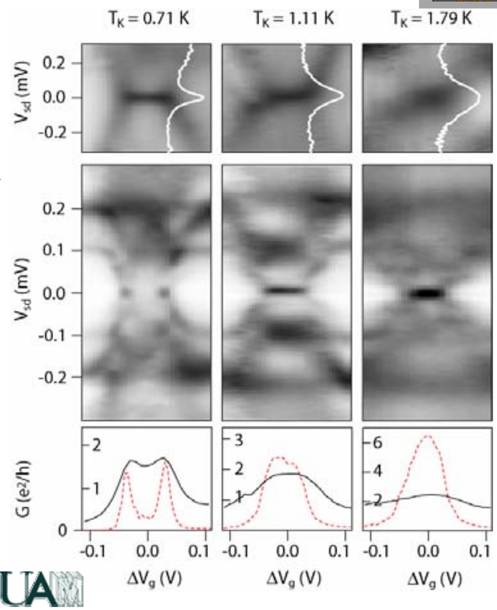
Kondo effect & Superconductivity



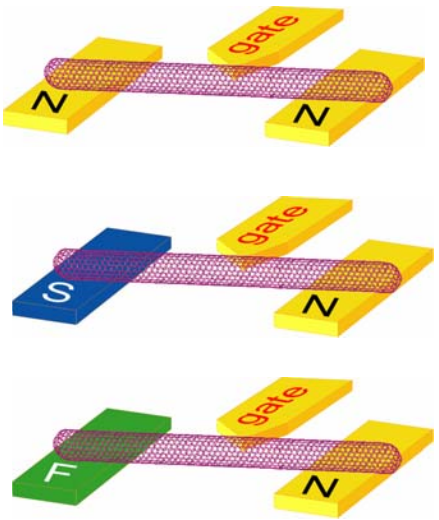
A cross-over at $k_BT_K \sim \Delta$

Phys. Rev. Lett. 89, 256801 (2002)

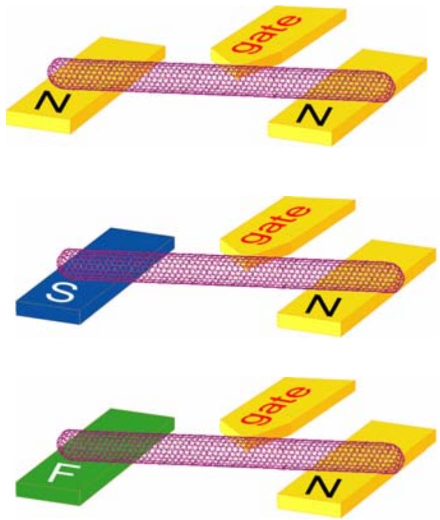
Solid-State Communications ***131****, 625 (2004)*



Carbon Nanotube Devices



Carbon Nanotube Devices



Carbon Nanotubes are great because novel quantum devices (hybrid devices) can be realized

Motivation for F-CNT-F

Spin dependent transport in nanostructures

- Importance of quantum coherence and interference

→ Effect of size quantization on spin transport ?

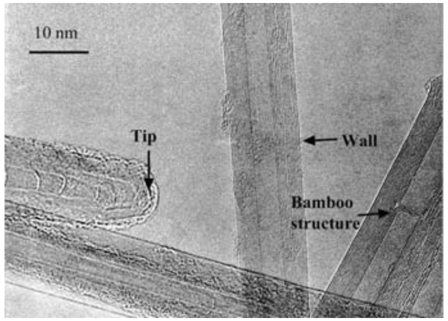
Spin vs Charge in low dimensional conductors

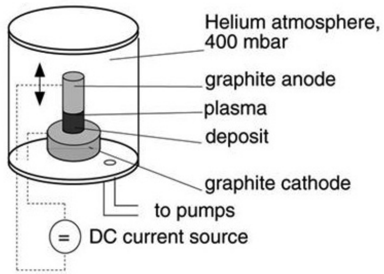
- Importance of electron-electron interactions
- Tunability of electronic transport (weak screening).

→ Manipulation of spins for quantum computing.

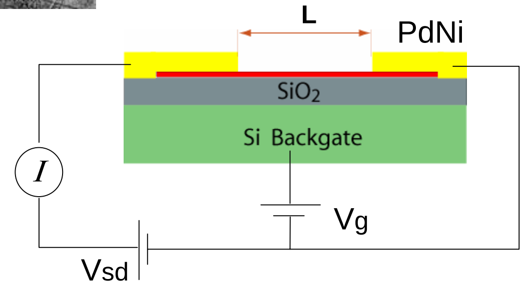
→ Realization of spin FETs.

Multi-Wall Carbon Nanotubes

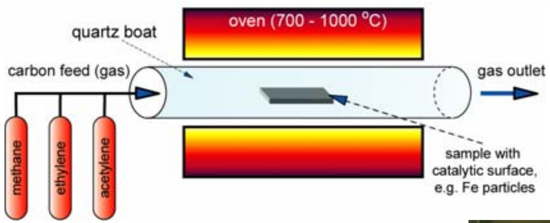




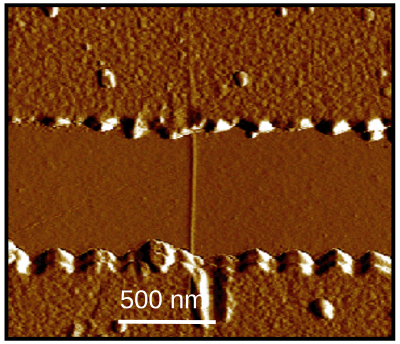
Laszlo Forró EPFL



Single-Wall Carbon Nanotubes



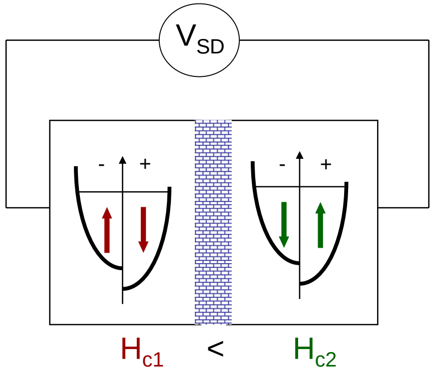
Bakir Babic

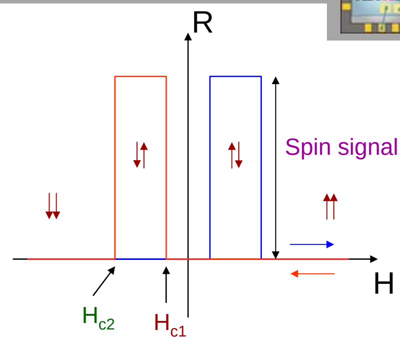


Jürg Furer

acknowledgment:
Jing Kong and
Herre van der Zant !

Introduction: Spin Valve Effect





assume spin and energy independent transmission ➔ Jullière's model

$$G_P \propto |t|^2 \left(N_+^2 + N_-^2\right)$$

$$G_{AP} \propto |t|^2 2N_+N_-$$

$$G_P > G_{AP} \quad because \quad N_+^2 + N_-^2 > 2N_+N_-$$

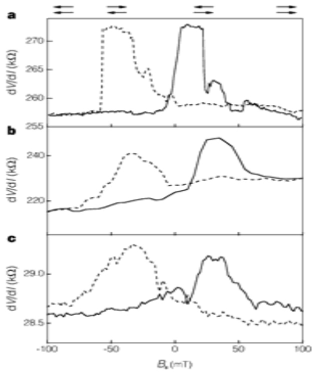
$$P = \frac{N_+ - N_-}{N_+ + N_-}$$

$$TMR = 2\frac{G_P - G_{AP}}{G_P + G_{AP}} = 2P_L P_R$$

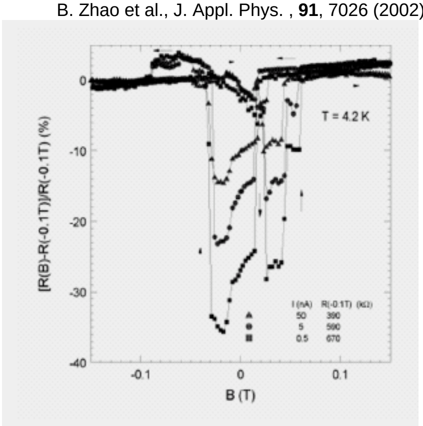
Previous work

Co contacts

K. Tsukagoshi et al., Nature, **401**, 572 (1999)



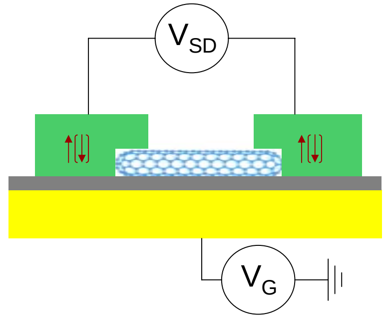
B. Zhao et al., J. Appl. Phys. , **91**, 7026 (2002)



- Positive TMR ~5%
- No gate !
- Negative TMR ~ -30%
- No gate !

Normal as well as anomalous TMR...?

Spin Injection in NTs

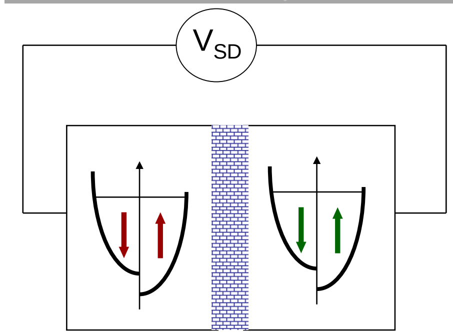


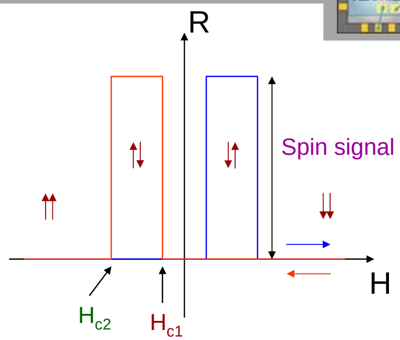
Spin valve geometry (2 terminal)

- Injection and detection of spins with ferromagnetic electrodes.
- Study as a function of V_{SD} and V_G.

*S. Sahoo, T. Kontos, J. Furer, C. Hoffmann, M. Gräber, A. Cottet and CS, Nature Physics **1**, 99 (2005)*

Introduction: Spin Valve Effect





H_{c1} < H_{c2}

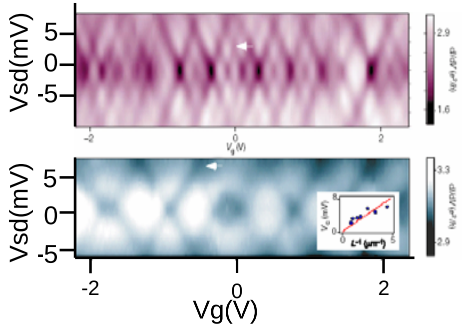
Jullière's model $P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$

$$G_{AP} \propto |t|^2 2N_\uparrow N_\downarrow$$
$$G_P \propto |t|^2 (N_\uparrow^2 + N_\downarrow^2)$$
$$TMR = 2\frac{G_P - G_{AP}}{G_P + G_{AP}} = 2P_L P_R$$
$$G_P > G_A \quad because \quad N_\uparrow^2 + N_\downarrow^2 > 2N_\uparrow N_\downarrow$$

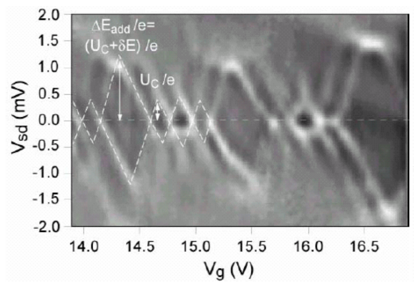
Assumes spin and energy independent transmission !

quantum interference and charging

W. Liang et al., Nature **411**, p 665 (2001)



Mark Buitelaar et al., PRL **88**, 156801 (2002)

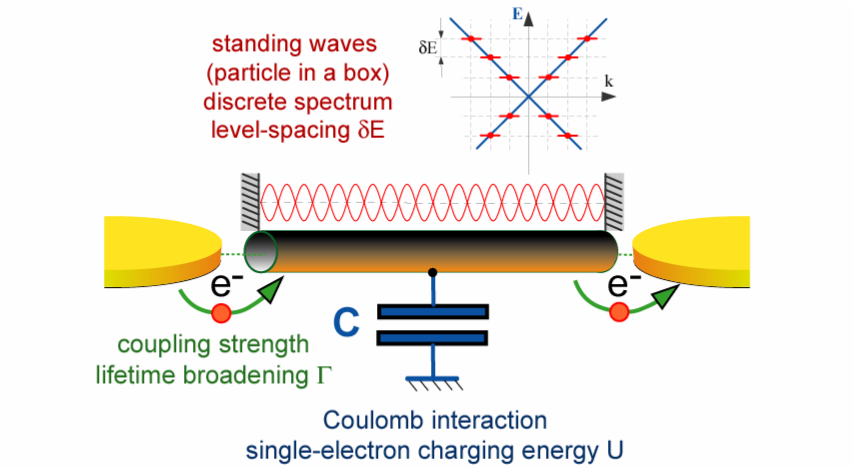


- Fabry-Perot in SWNTs
- Quantum dot in MWNTs

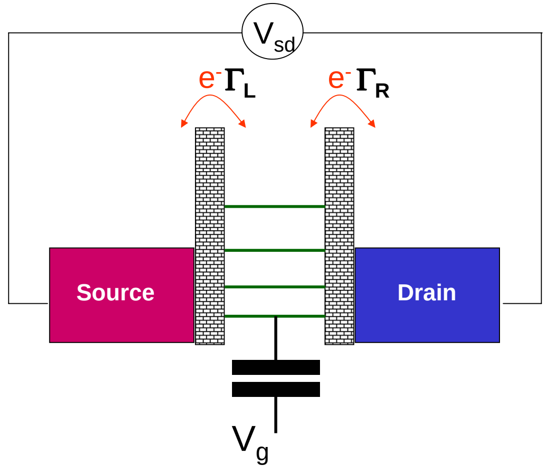
$E=hv_F/2L$ ⟶ 1.67 meV/µm

Energy dependent transmission in NTs…

Nanotubes as quantum dots

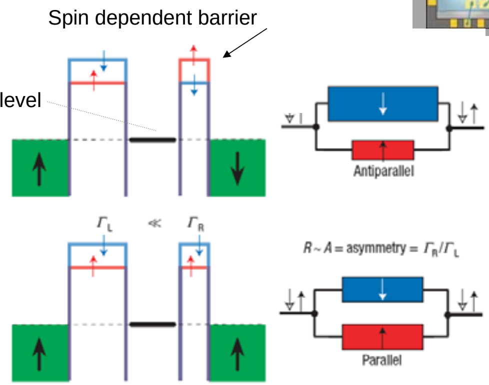


Nanotubes as quantum dots



Energy dependent transmission in NTs…

TMR and quantum interference



$$T(E) = \frac{\Gamma_L \Gamma_R}{(E - E_0)^2 + ((\Gamma_L + \Gamma_R)/2)^2}$$

$$\Gamma_L = \Gamma_L (1 \pm P_L)$$

$$\Gamma_R = \Gamma_R (1 \pm P_R)$$

Off-resonance,

$$T(E) \propto \Gamma_R \Gamma_L, TMR = \frac{2P_L P_R}{1 - P_L P_R}$$

On resonance with asymmetry,

$$\Gamma_R >> \Gamma_L \Rightarrow T(E) = 4\Gamma_L / \Gamma_R, TMR = \frac{-2P_L P_R}{1 + P_L P_R}$$

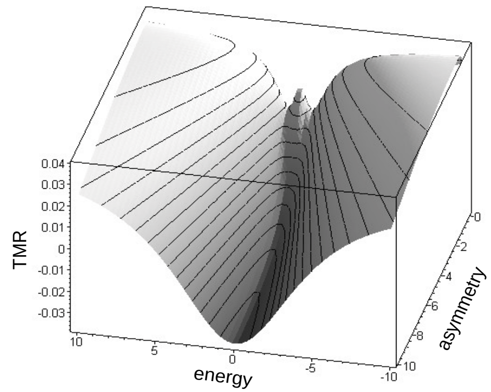
SpinFET behavior because E_0 controlled by gate.

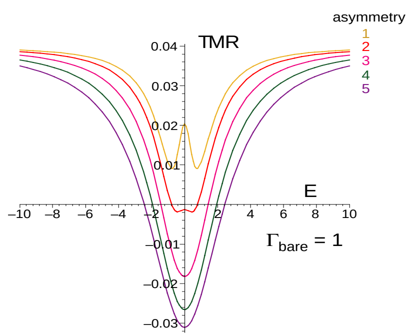
*S. Sahoo, T. Kontos, J. Furer, C. Hoffmann, M. Gräber, A. Cottet and CS, Nature Physics **1**, 99 (2005)*

See also E.Y. Tsymbal et al. PRL 90, 186602 (2003) in Ni/NiO/Co nanojunctions

RT yields a symmetric TMR

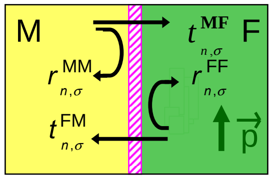
Γ=1 and P=0.2, one resonance





Description of spin injection

Spin-Dependence of Interfacial Phase Shifts (SDIPS)



n : channel index
σ : spin

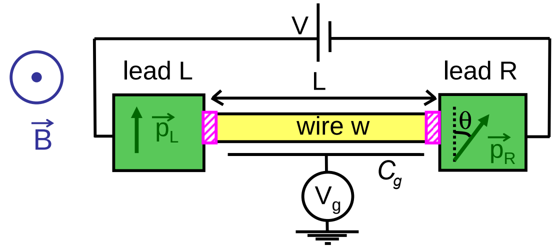
Transmission amplitude $t_\sigma^{FM(MF)} = \sqrt{T_\sigma}\, e^{i\varphi_\sigma^{FM(MF)}}$

Reflexion amplitude $r_\sigma^{FF(MM)} = \sqrt{1-T_\sigma}\, e^{i\varphi_\sigma^{FF(MM)}}$

SDIPS

A. Cottet, T. Kontos, W. Belzig, C.S and C. Bruder, Eur. Phys. Lett. ***74****, 320 (2006)*

Ballistic channel with F-leads



Assumptions :

- interactions neglected
- single channel wire
- $e\kappa V_g, g\mu_B B << E_F^W$

  $\kappa = C_g / C_W$

Scattering description with parameters:

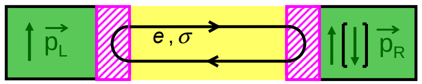
$\delta_0 = L(k_F^W + (e\kappa V_g - E_F^W)/\hbar v_F^W)$ Phase acquired by carriers along w at B=0

$T_{L(R)} = (T^{\uparrow}_{L(R)} + T^{\downarrow}_{L(R)})/2 \qquad P_{L(R)} = (T^{\uparrow}_{L(R)} - T^{\downarrow}_{L(R)})/(T^{\uparrow}_{L(R)} + T^{\downarrow}_{L(R)})$

$\varphi^{WW}_{\sigma,L(R)} \longrightarrow \Delta\varphi_{L(R)} = \varphi^{WW}_{\uparrow,L(R)} - \varphi^{WW}_{\downarrow,L(R)} \neq 0$ SDIPS parameters

A. Cottet, T. Kontos, W. Belzig, C.S and C. Bruder, Eur. Phys. Lett. ***74****, 320 (2006)*

Bound states are spin-dependent



Resonance condition for θ=0 [θ= π] :

$$2\delta_0 + \varphi^{WW}_{\sigma,L} + \varphi^{WW}_{[-]\sigma,R} = 2\pi j,\ j \in \mathbf{Z}$$

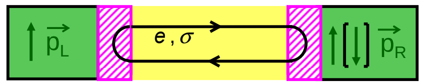
tunneling limit

$$T_\sigma^{m_1,m_2} = \frac{4\Gamma_{1\sigma}^{m_1}\Gamma_{2\sigma}^{m_2}}{4\varepsilon^2 + (\Gamma_{1\sigma}^{m_1} + \Gamma_{2\sigma}^{m_2})^2}$$ (no **SDIPS**)

$$T_\sigma^{m_1,m_2} = \frac{4\Gamma_{1\sigma}^{m_1}\Gamma_{2\sigma}^{m_2}}{4\left(\varepsilon_\sigma^{m_1,m_2}\right)^2 + (\Gamma_{1\sigma}^{m_1} + \Gamma_{2\sigma}^{m_2})^2}$$

$$\varepsilon_\sigma^{m_1,m_2} := \varepsilon_0(V_g) + \kappa\sigma\left(P_1 m_1 + P_2 m_2\right)$$

extended model allows for asymmetric TMR



Resonance condition for θ=0 [θ= π] :

$$2\delta_0 + \varphi^{WW}_{\sigma,L} + \varphi^{WW}_{[-]\sigma,R} = 2\pi j,\ j \in \mathbf{Z}$$

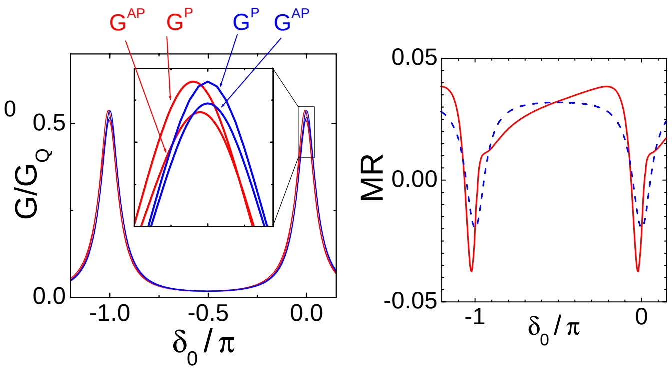
$T_L = 0.5$, $T_R = 0.05$,

$P_{L(R)} = 0.3$, $\varphi^{WW}_{\downarrow,L(R)} = 0$

$\varphi^{WW}_{\uparrow,L(R)} = 0$

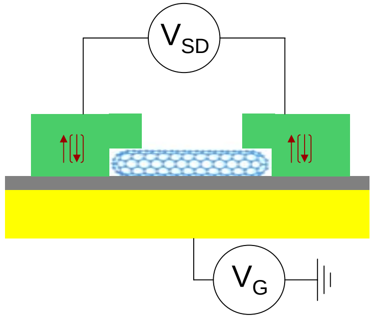
$\varphi^{WW}_{\uparrow,L(R)} = 0.05$

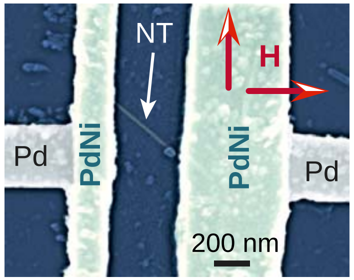
weak SDIPS



A. Cottet, T. Kontos, W. Belzig, C.S and C. Bruder, Eur. Phys. Lett. ***74****, 320 (2006)*

an actual device (MWNT)

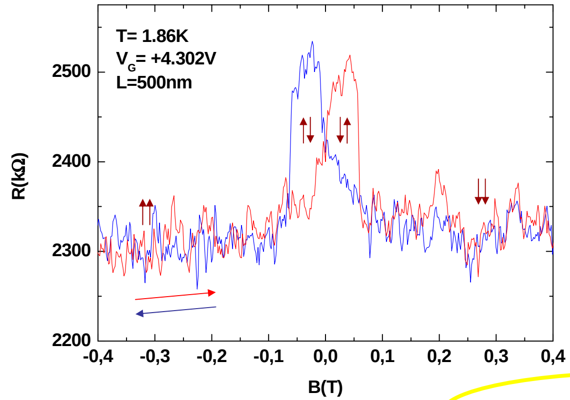




Spin valve geometry

- Transparent contacts using a new contacting scheme with $Pd_{0.3}Ni_{0.7}$
- Shape anisotropy to control switching of magnetizations.

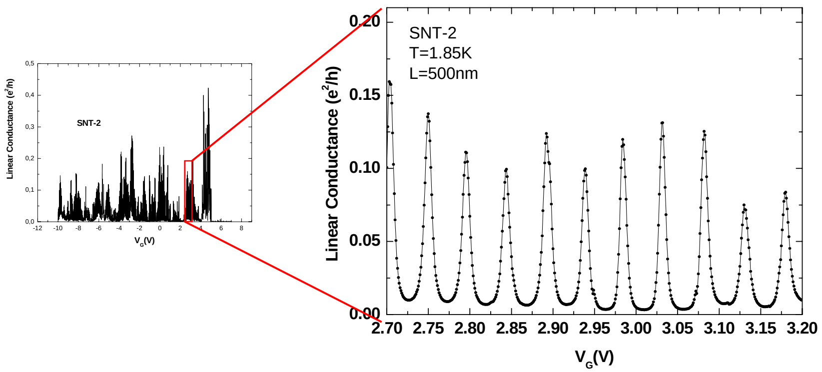
Spin signal for a SWNT-device



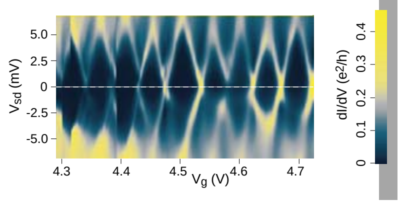
$TMR=(R_{AP}-R_P)/R_P$

- Hysteresis ~ 5-10 %
- Sharp switching for ~ 100mT
- TMR ~ $2P^2$ with P~0.2

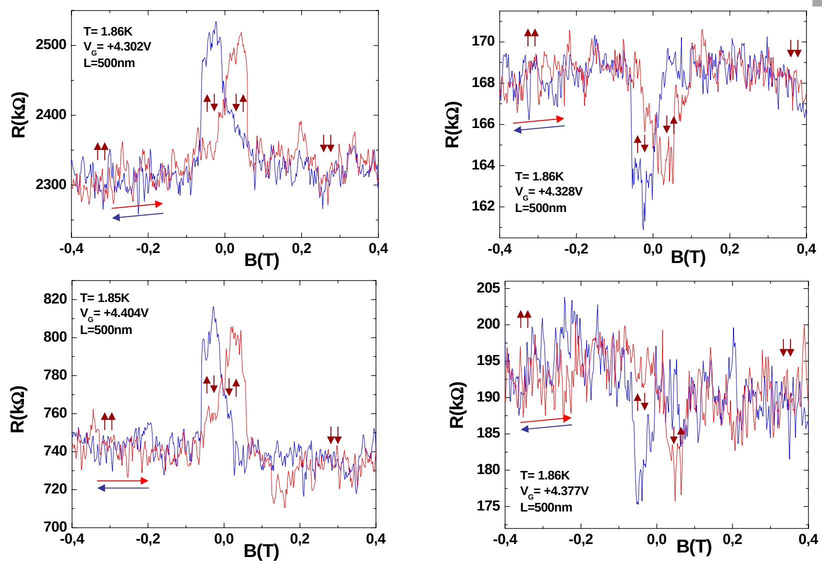
Linear conductance



- Resonances in conductance at 1.85K
- Peaks always symmetric about maximum

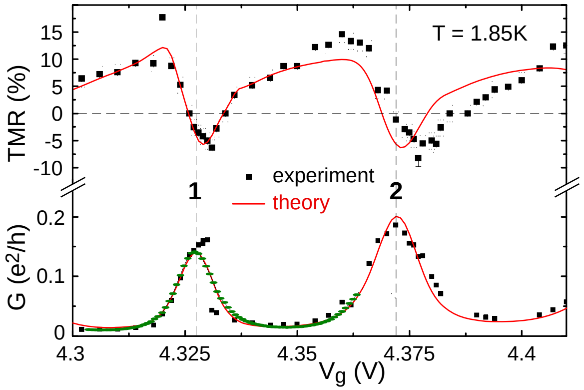


Gate dependence of TMR



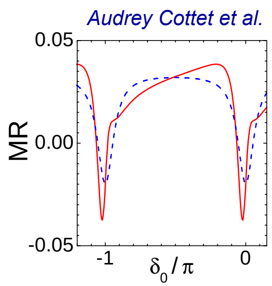
- Sign and amplitude of TMR gate controlled.

Comparison G and TMR vs Gate



Asymmetry in TMR

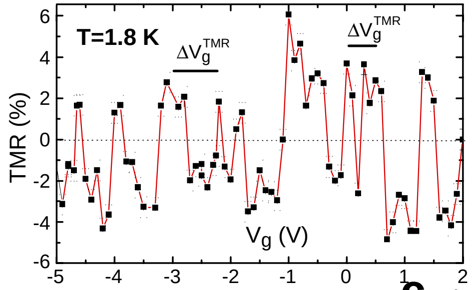
$$E_{\uparrow} - E_{\downarrow} = 0.26meV$$

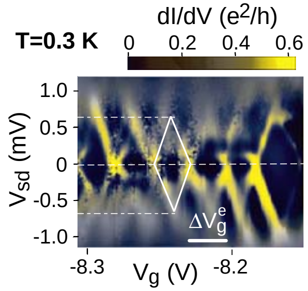


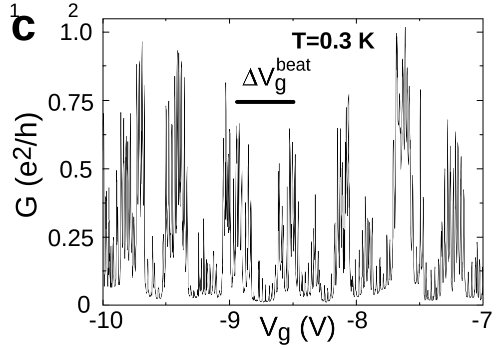
- Oscillations of TMR between -8% and +17%.
- Spin dependent resonant tunneling mechanism.
- Direct measurement of spin imbalance ~ 2.2 T.

S. Sahoo, T. Kontos, J. Furer, C. Hoffmann M. Gräber, A. Cottet and C.S., Nature Phys., **2,** 99 (2005)

„universial", also seen in MWNTs







Problems...artefacts...?

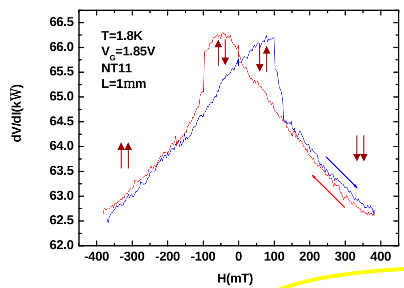
1. stray field
2. magneto-Coulomb effect
3. magnetostrictive effects very locally on the contacts

1. magnetic **stray-field** may change R via some „background" MR of CNT (other than spin-valve)

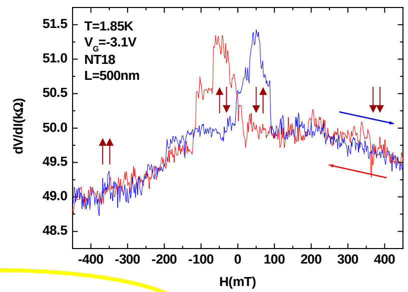
   ➔ have a look at background

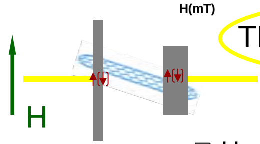
Background and MR

H parallel to leads axis

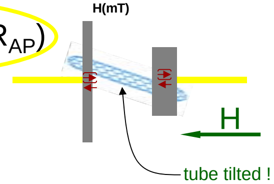


H perpendicular to leads axis



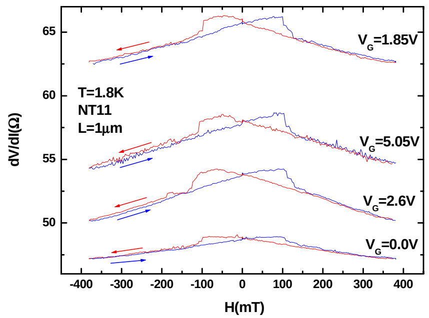


TMR=2(R$_{AP}$-R$_P$)/(R$_P$+R$_{AP}$)

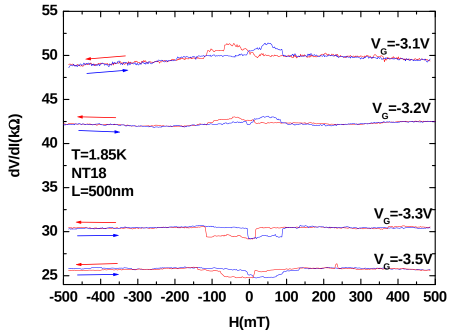


- Hysteresis with TMR ~ +3%
- Sharp switching for ~ 100mT
- Sharper switching for ~ 0mT for perpendicular H

Background and MR



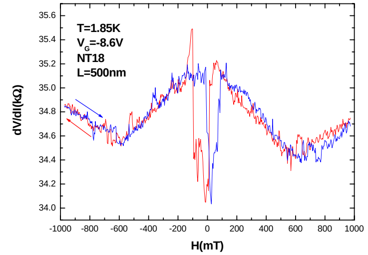
NT11



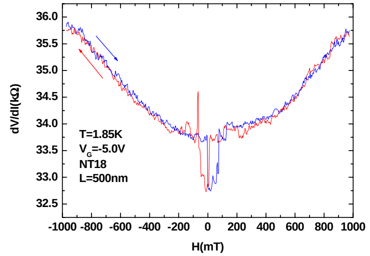
NT18

Background and MR

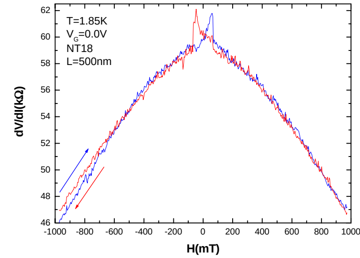
Back < 0 TMR < 0

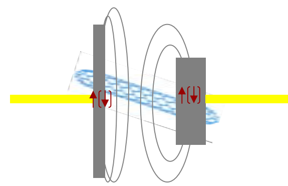


Back > 0 TMR < 0



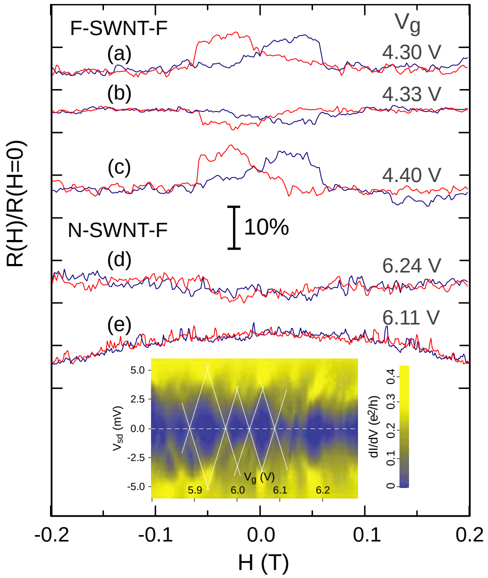
Back < 0 TMR > 0





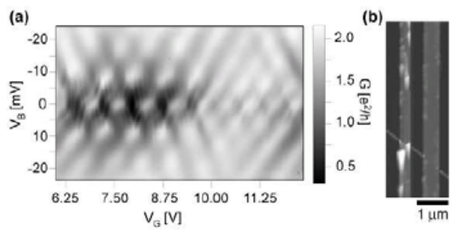
- No stray field effect...

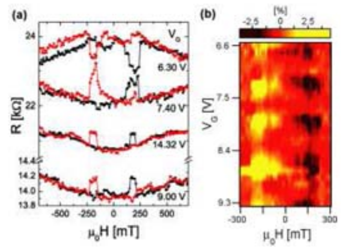
Control Experiment

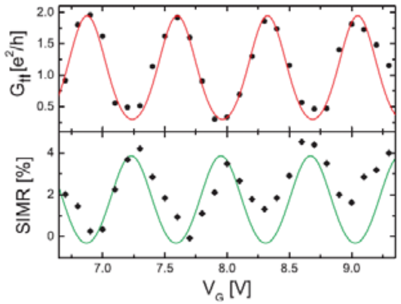


Morpurgo et al.

H.T. Man, I.J.W. Wever, and A.F. Morpurgo, condmat 0512505







Alphenaar et al.

APPLIED PHYSICS LETTERS 88, 023503 (2006)

Gated spin transport through an individual single wall carbon nanotube

B. Nagabhirava, T. Bansal, G. U. Sumanasekera, and B. W. Alphenaar[a]
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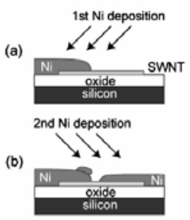
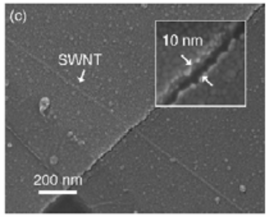
(Received 19 October 2005; accepted 21 November 2005; published online 10 January 2006)

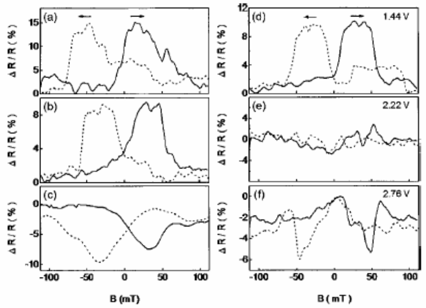
Hysteretic switching in the magnetoresistance of short-channel, ferromagnetically contacted individual single wall carbon nanotubes is observed, providing strong evidence for nanotube spin transport. By varying the voltage on a capacitively coupled gate, the magnetoresistance can be reproducibly modified between +10% and −15%. The results are explained in terms of wave vector matching of the spin polarized electron states at the ferromagnetic / nanotube interfaces. © 2006 American Institute of Physics. [DOI: 10.1063/1.2164367]

some non-trivial gate-effect, but not (yet) periodic





very short channel

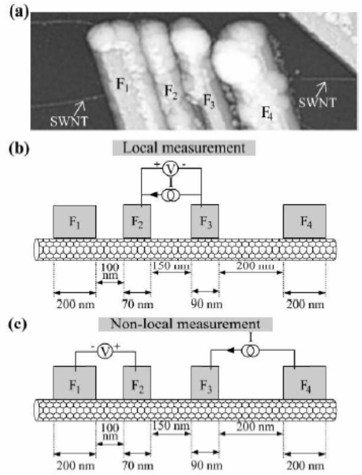


Comment by van Wees et al.

Separating spin and charge transport in single wall carbon nanotubes

We demonstrate spin injection and detection in single wall carbon nanotubes using a 4-terminal, non-local geometry. This measurement geometry completely separates the charge and spin circuits. Hence all spurious magnetoresistance effects are eliminated and the measured signal is due to spin accumulation only. Combining our results with a theoretical model, we deduce a spin polarization at the contacts, α_F, of approximately 25 %. We show that the magnetoresistance changes measured in the conventional two-terminal geometry are dominated by effects not related to spin accumulation.

- no gate
- all contacts ferro (rather than N-F-F-N)
- contact transparency may be critical



Conclusion

- Spin injection in carbon nanotubes TMR ~10% (SWNTs)
- Spin FET-like behavior in spin valves with nanotubes due to quantum dot behavior

→ Importance of spin dependent quantum interference

- Can one make effective spin FETs ?
- Direct control of spin possible ?
- Effect of e-e interactions ?

Refs:
*S. Sahoo, T. Kontos, CS and C. Sürgers, Appl. Phys. Lett. **86**, 112109 (2005)*
*S. Sahoo, T. Kontos, J. Furer, C. Hoffmann, M. Gräber, A. Cottet and CS, Nature Phys. **2,** 99 (2005)*
*A. Cottet, T. Kontos, W. Belzig, C.S and C. Bruder, Eur. Phys. Lett. **74**, 320 (2006)*

H.T. Man, I.J.W. Wever, and A.F. Morpurgo, cond-mat 0512505

B. Nagabhirava, T. Bansal, G. U. Sumanasekera, B. W. Alphenaar, Appl. Phys. Lett. 88, 023503 (2006)

N. Tombros, S.J. van der Molen, B.J. van Wees, cond-mat/0506538