Quantum interference and many-body effects in a double donor system

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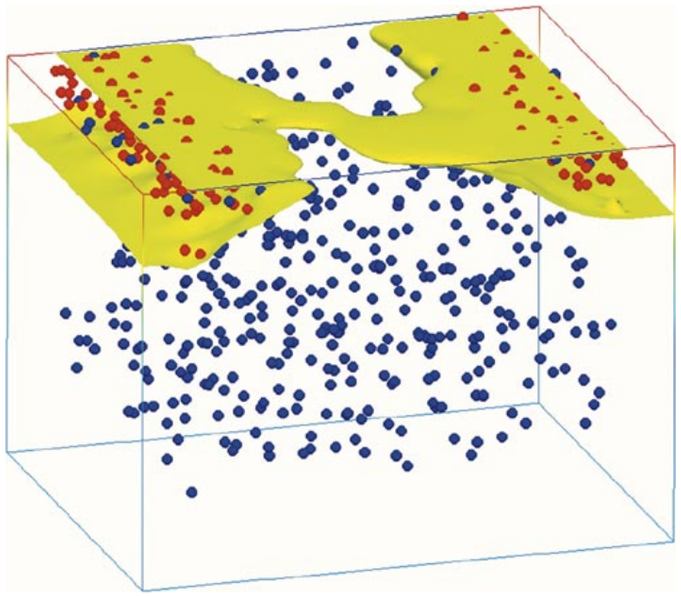
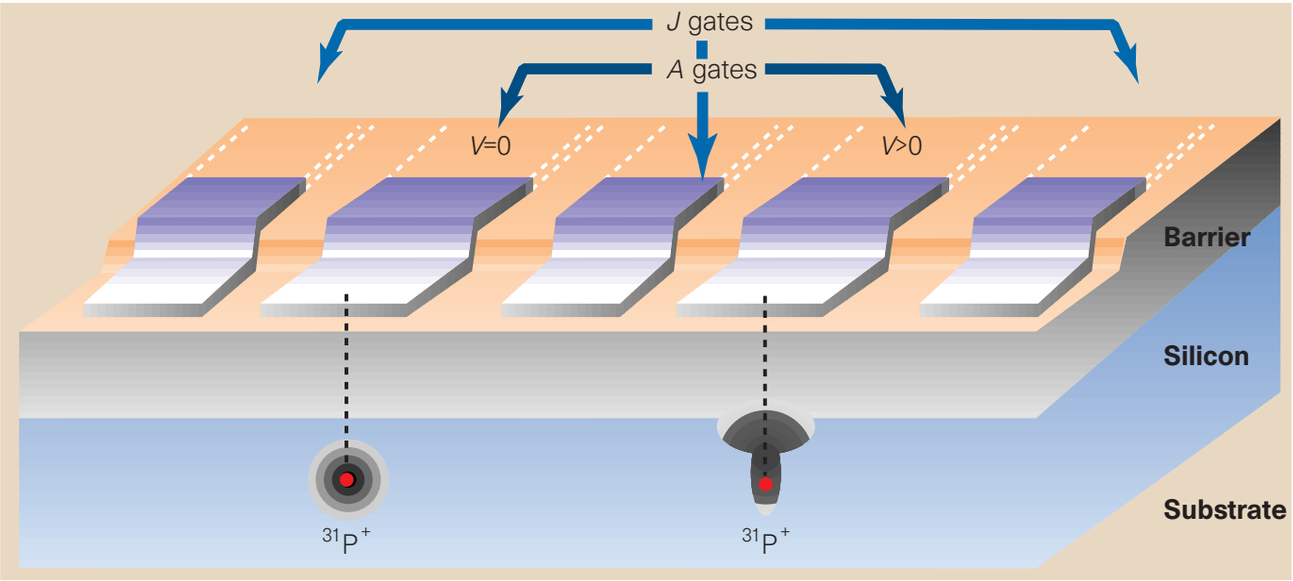
Silicon S&T Quantum Computing Workshop
Monday, August 23, 2010

Platform

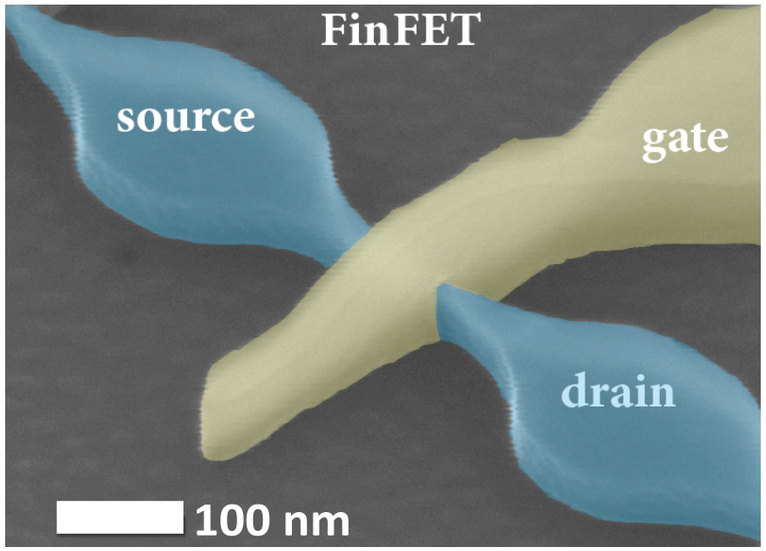
We use commercial prototype devices as a platform to study dopant transport.



A. Asenov et al., IEEE Trans. Elec. Dev. 50, 1837, 2003



B.E. Kane, Nature 393, 133, 1998
D.P. DiVincenzo, Nature 393, 113, 1998



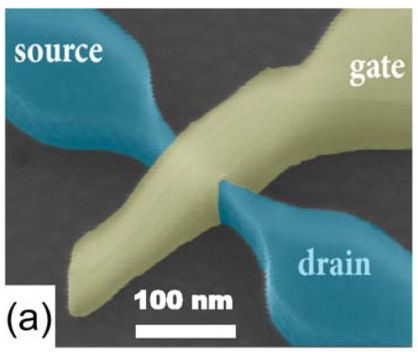
Symp VLSI Tech. p. 108 2005

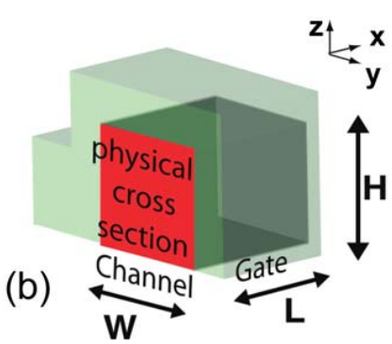
Coupling and Coherence

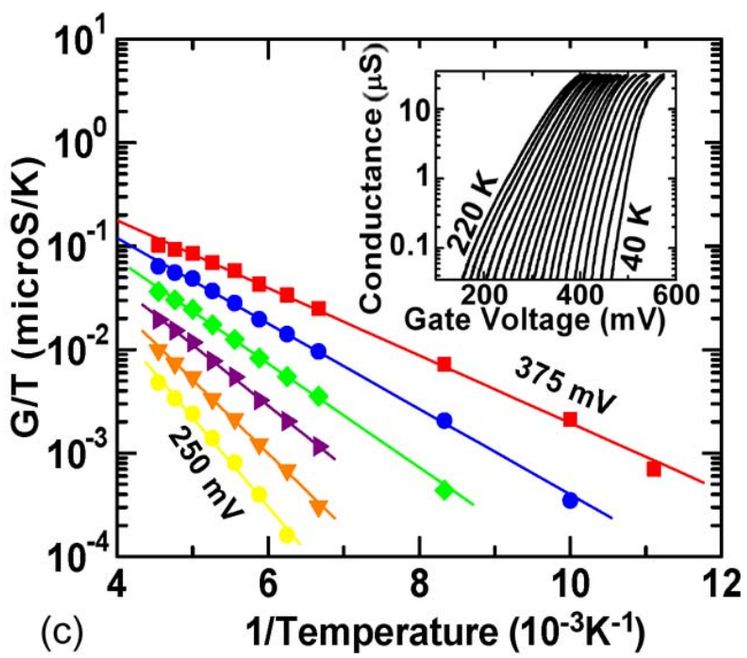
Device Physics

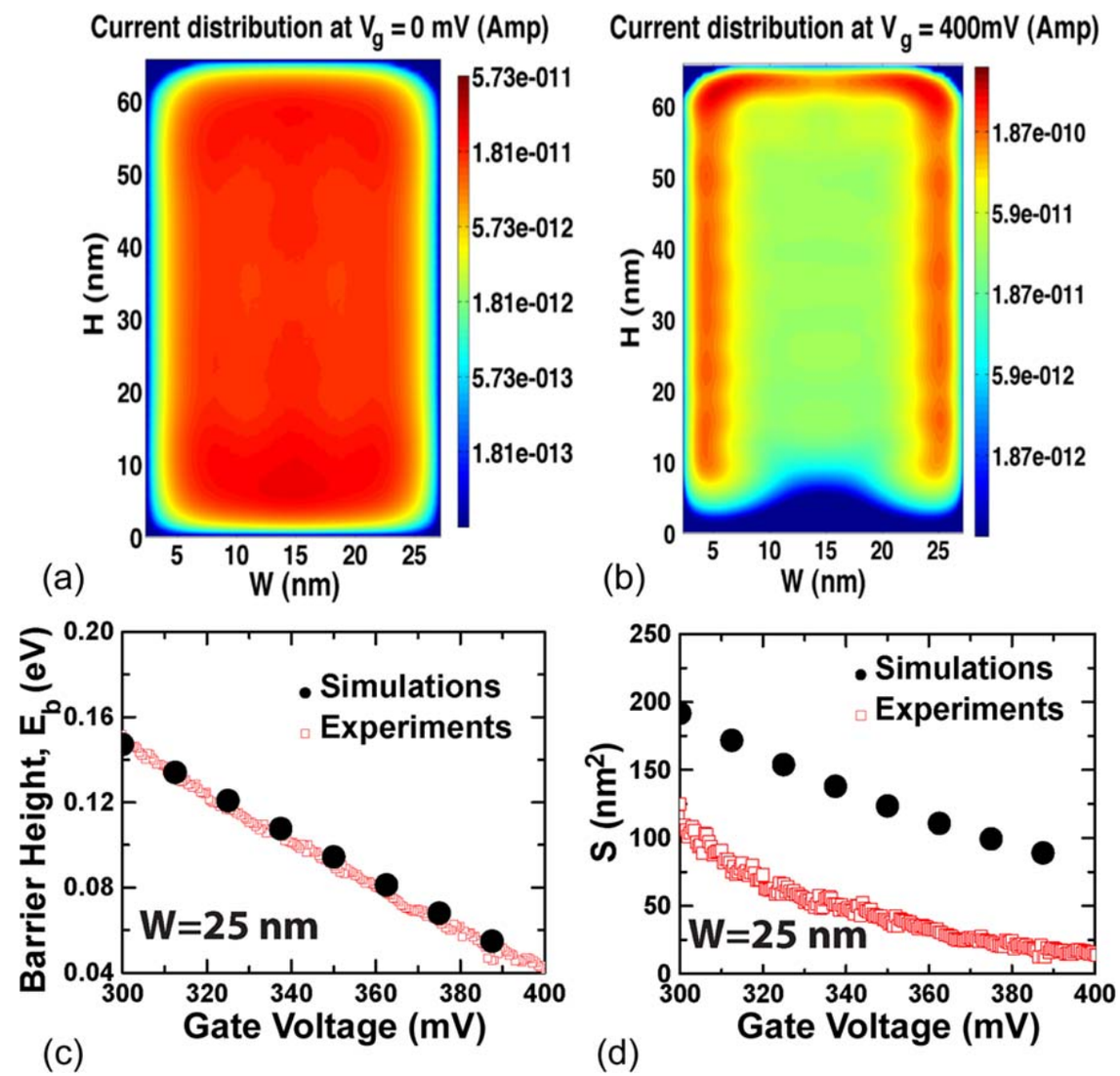
In collaboration with Gerhard Klimeck at Perdue University

Study of the transport in nano-transistors between ~4 Kelvin and room temperature.







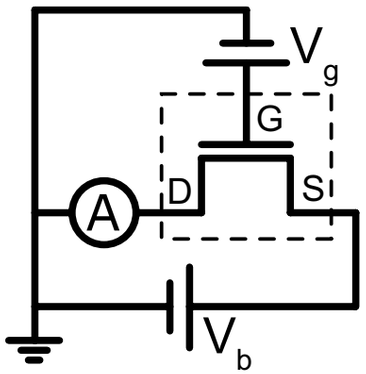


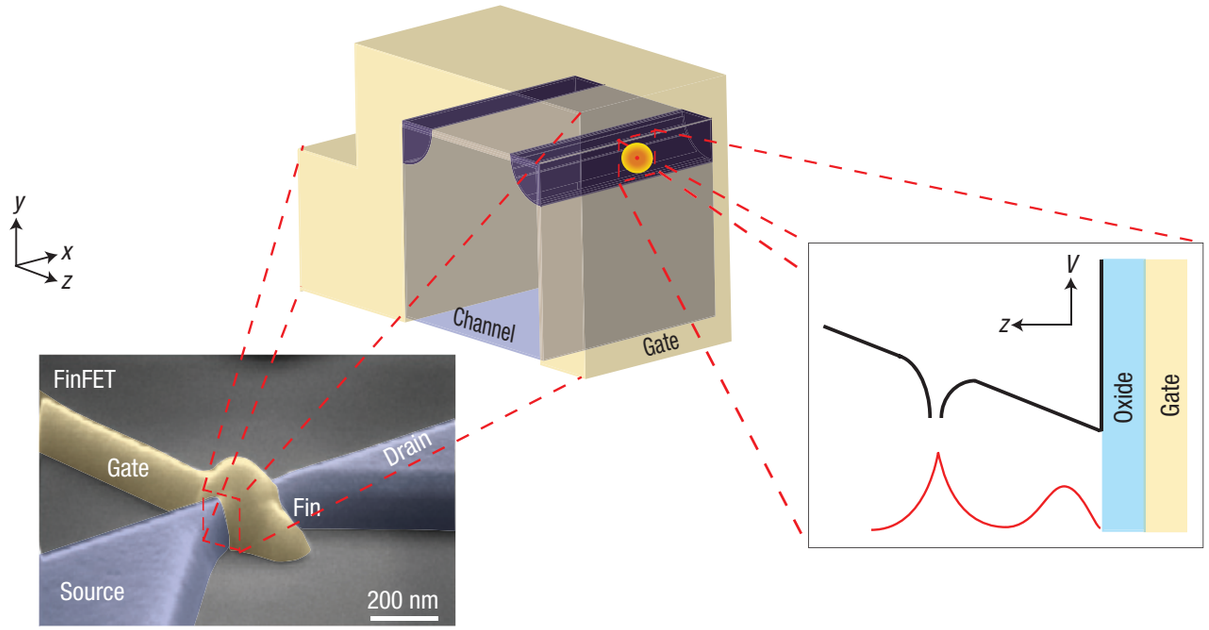
H. Sellier et al., APL 90, 073502, 2007
G.C. Tettamanzi et al., EDL 31, 150, 2010

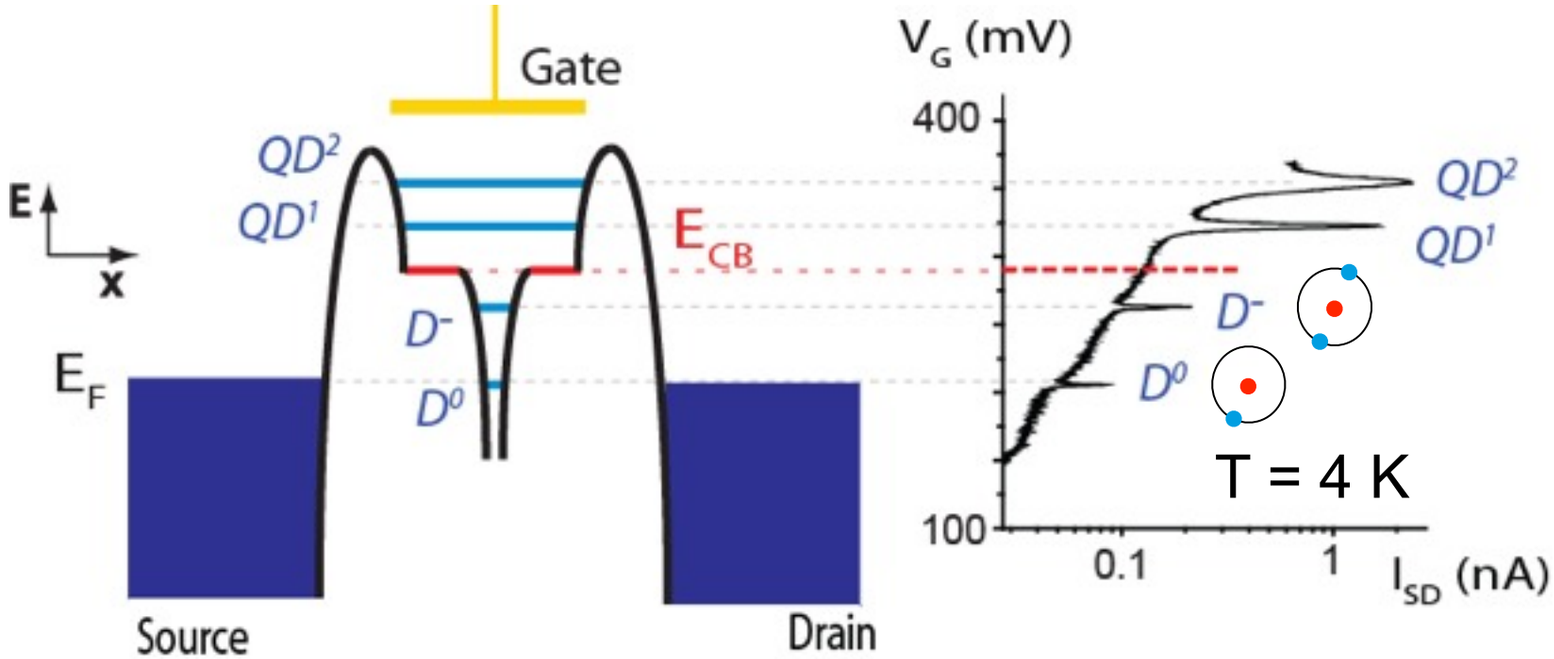
Outline

- Single donor transport
- Fano resonances
- Coherently coupled donors
- Many-body effects
- Outlook

Single Donor Spectroscopy







Characteristics:

- Pair of peaks (D^0, D^-)
- Charging energy 30-35 meV (Reduced by nanostructure)
- Odd/even spin filling

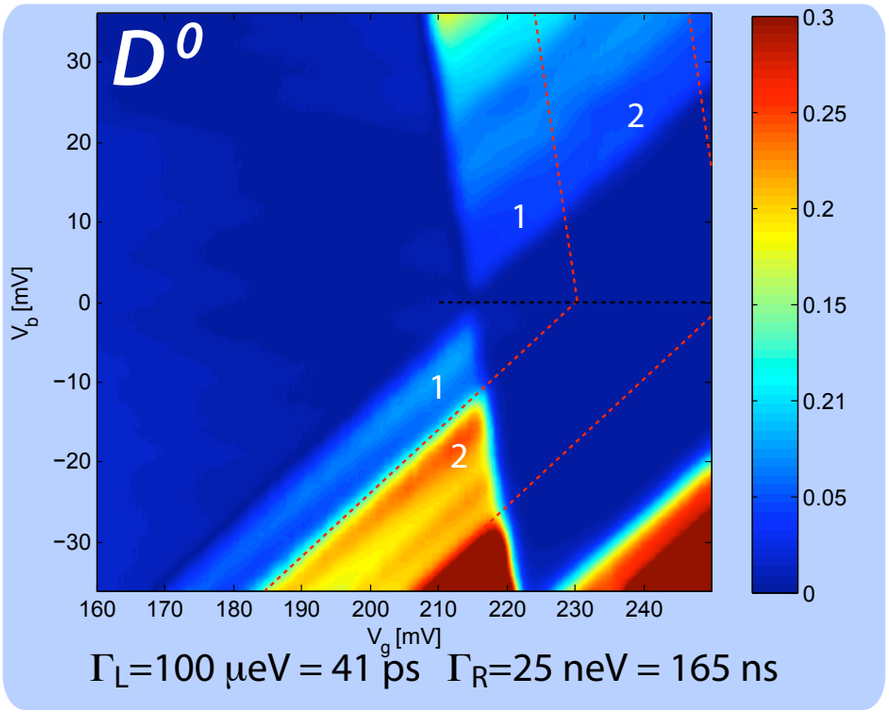
H. Sellier et al., PRL 97, 206805, 2006
G.P. Lansbergen et al., NP 4, 656, 2008

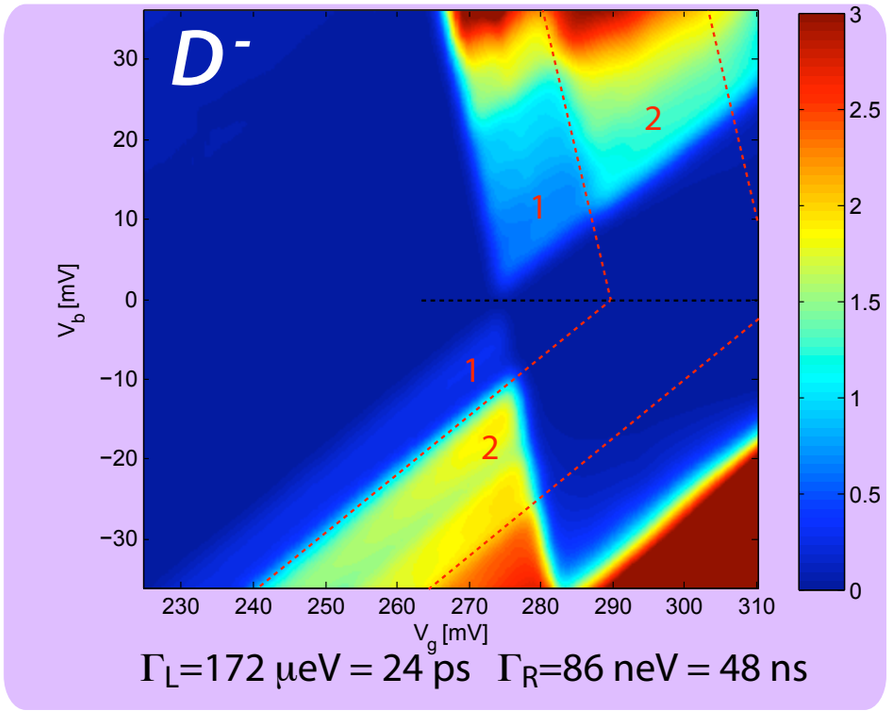
Dopant Transport

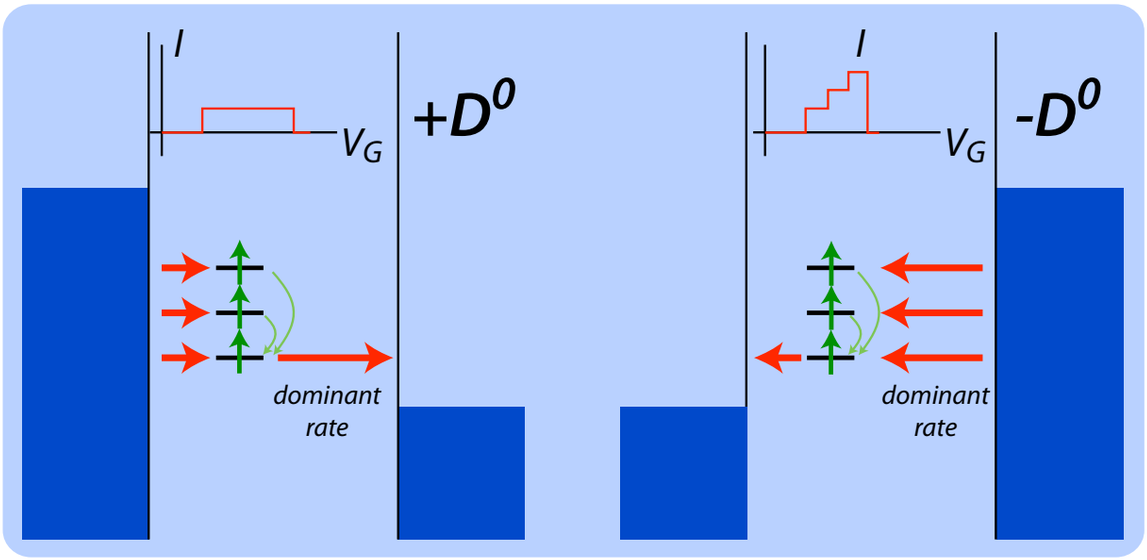
- Learn about intrinsic (uncoupled) properties of dopants
  - Determination of addition energy
  - Excited state spectroscopy
- Interaction in various regimes of coupling to outside world
  - Weak coupling: non-interacting
  - Strong coupling: multi-electron tunneling and many-body effects
- Nature of interactions:
  - Incoherent electron hopping
  - Coherent electron transfer

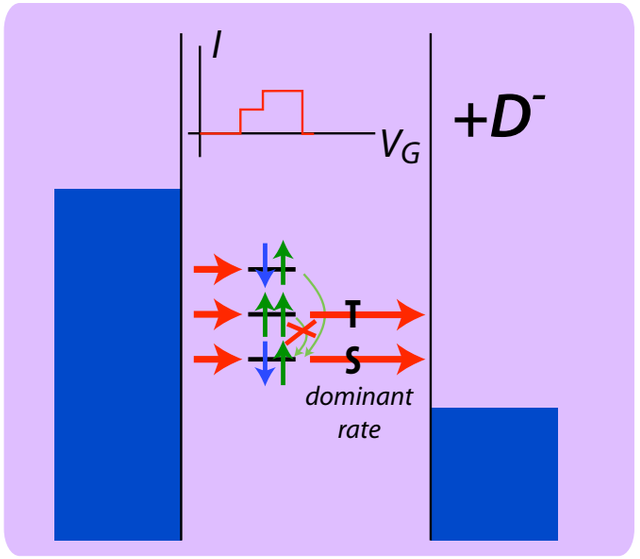
Transport Spectroscopy, example I

Dynamics from time-averaged current







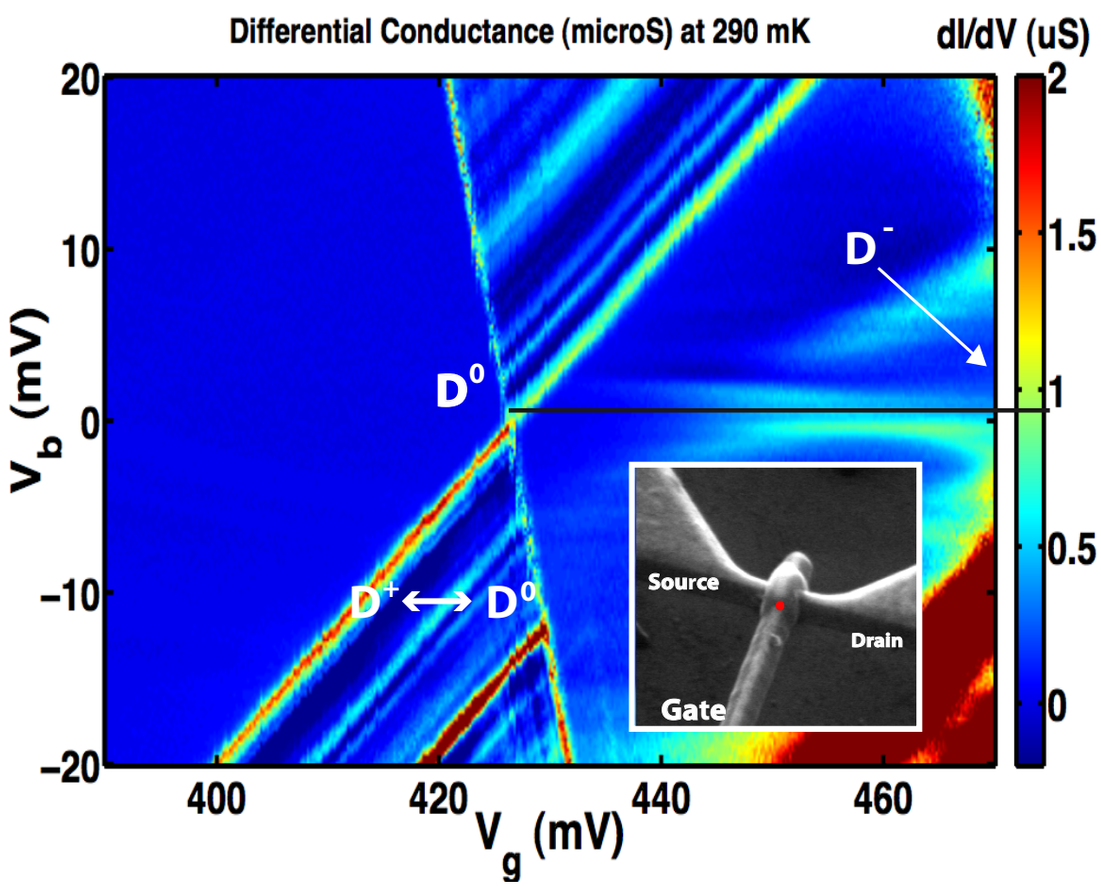


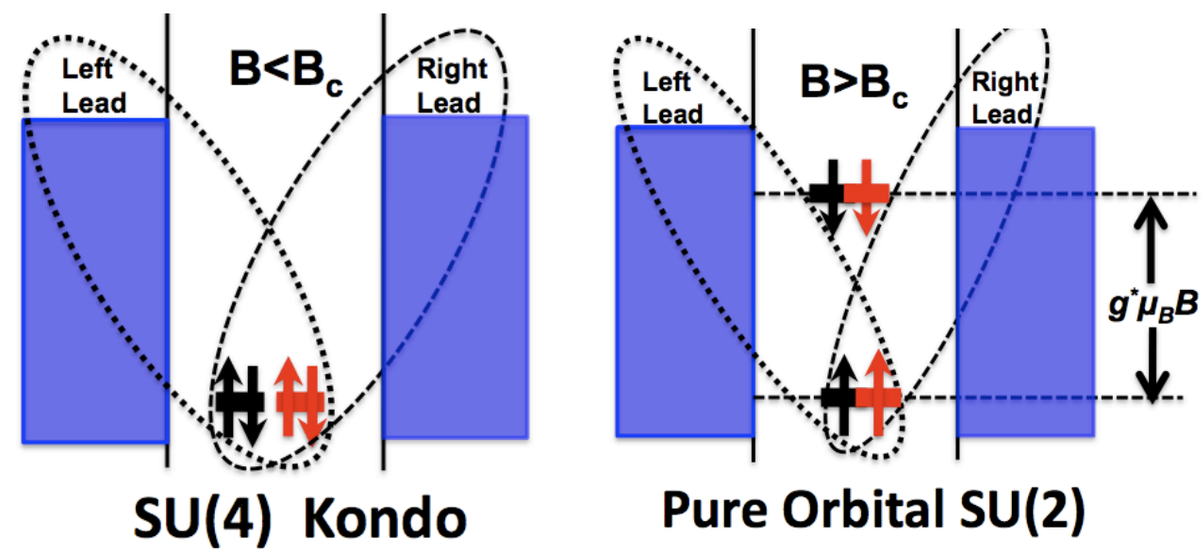
N. Shaji et al., NP 4, 540, 2008
G.P. Lansbergen et al., ArXiv: 1008.1381

Transport Spectroscopy, example II

Coherent interactions

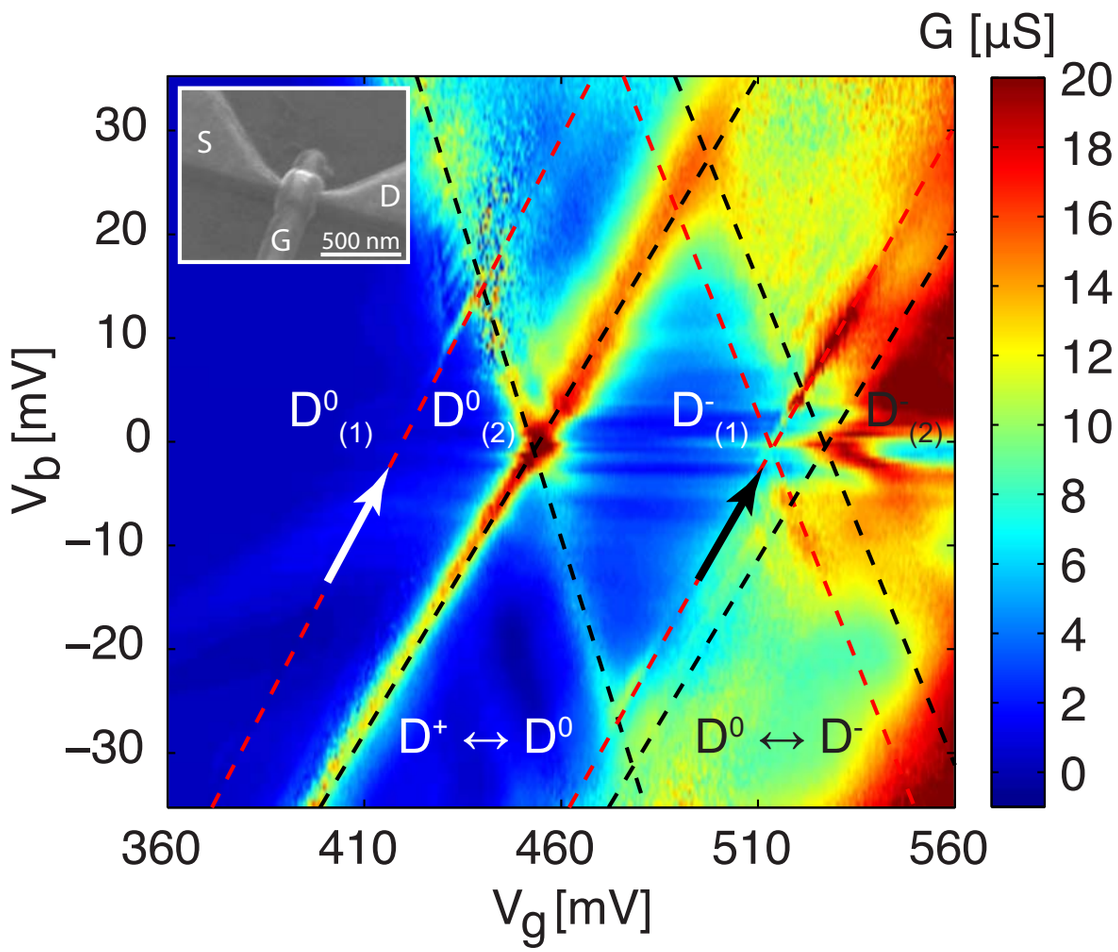
Strongly coupled donor as platform to study coherent interactions, for example a Kondo effect.





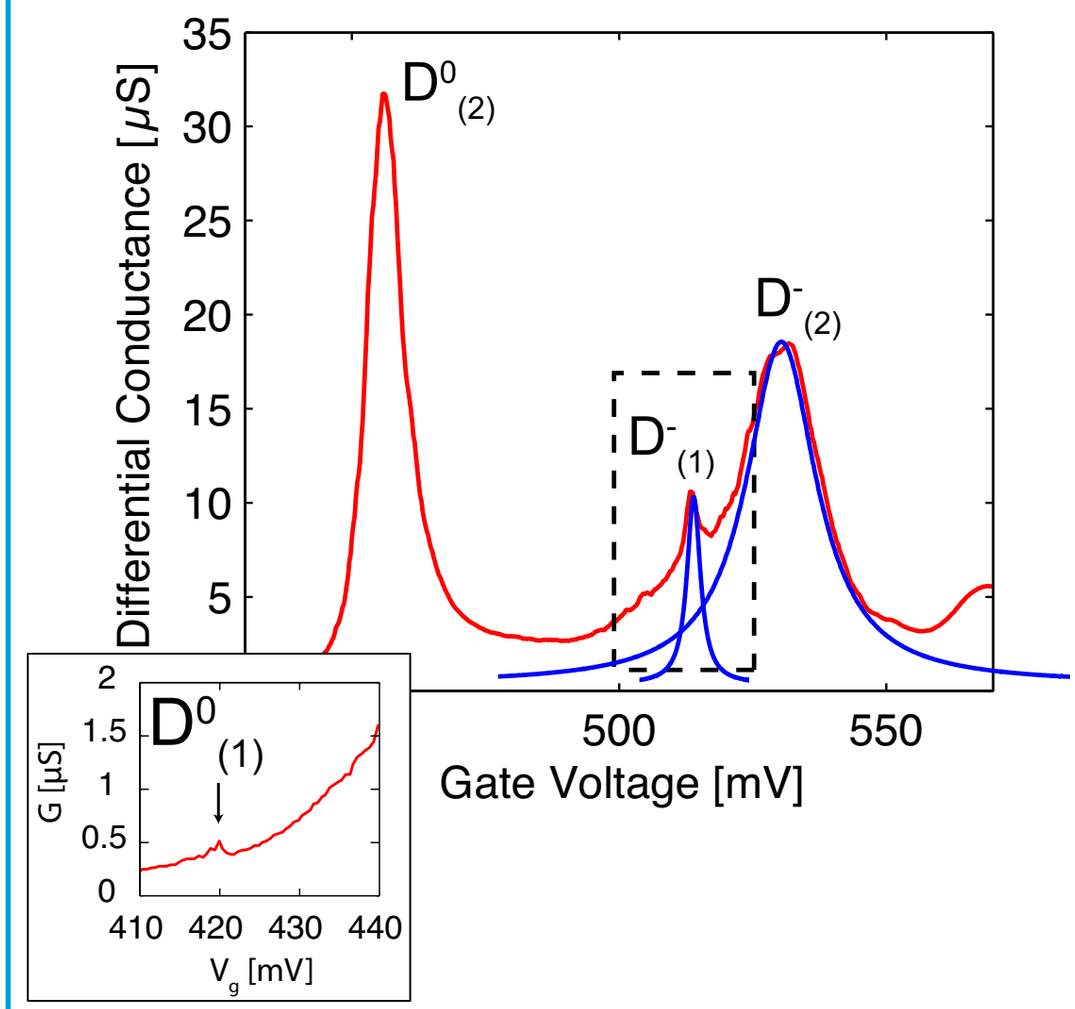
G.P. Lansbergen et al., Nano Letters 10, 455-460, 2010

Coherence Experimentally



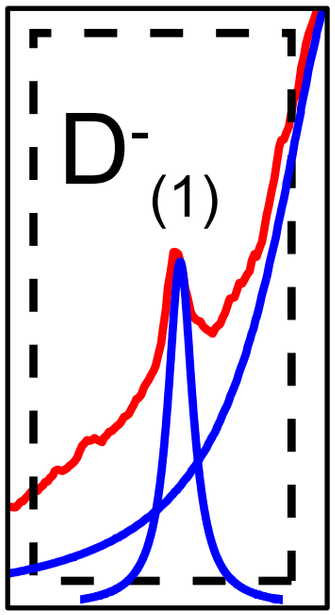
- Transport through two coupled donors
- Fano resonances, i.e. coherence

Resonance with a Fano line shape



H. Sellier et al., PRL 97, 206805, 2006
J. Verduijn et al., APL 96, 072110, 2010

Fano resonance: A Model



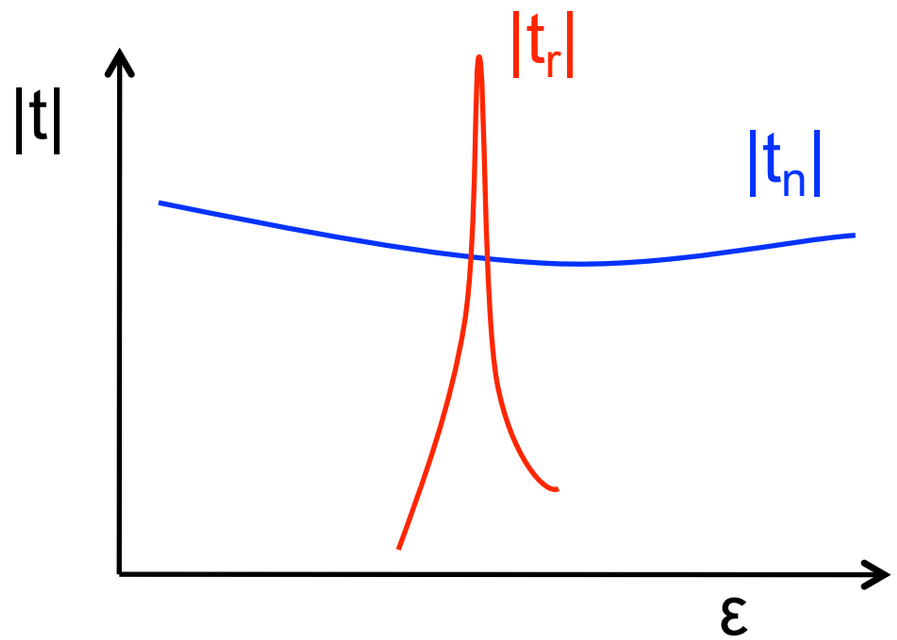
$$t_n = \sqrt{T_n} e^{i\phi}$$

+

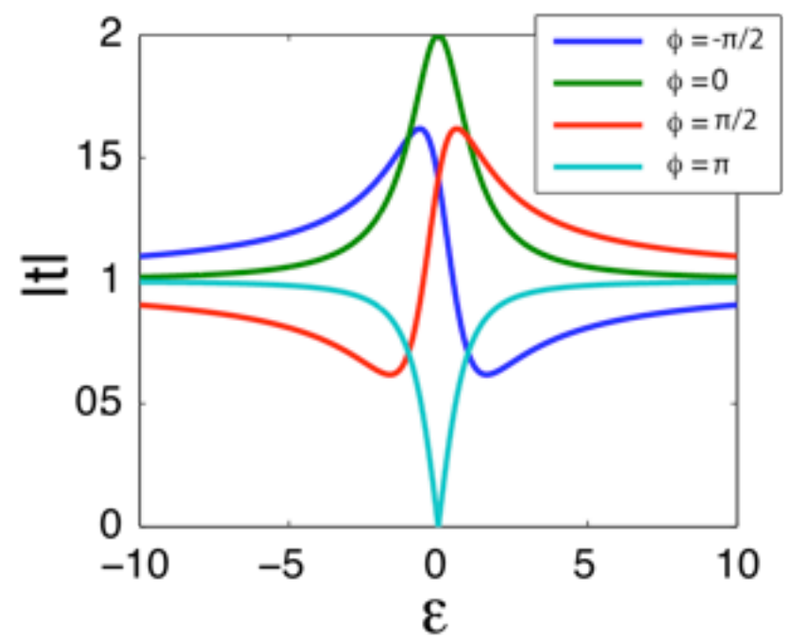
$$t_r = \sqrt{T_r} \frac{i}{\epsilon + i}$$

=

$$|t| = |t_n + t_r| = \left| \sqrt{T_n} e^{i\phi} + \sqrt{T_r} \frac{i}{\epsilon + i} \right|$$

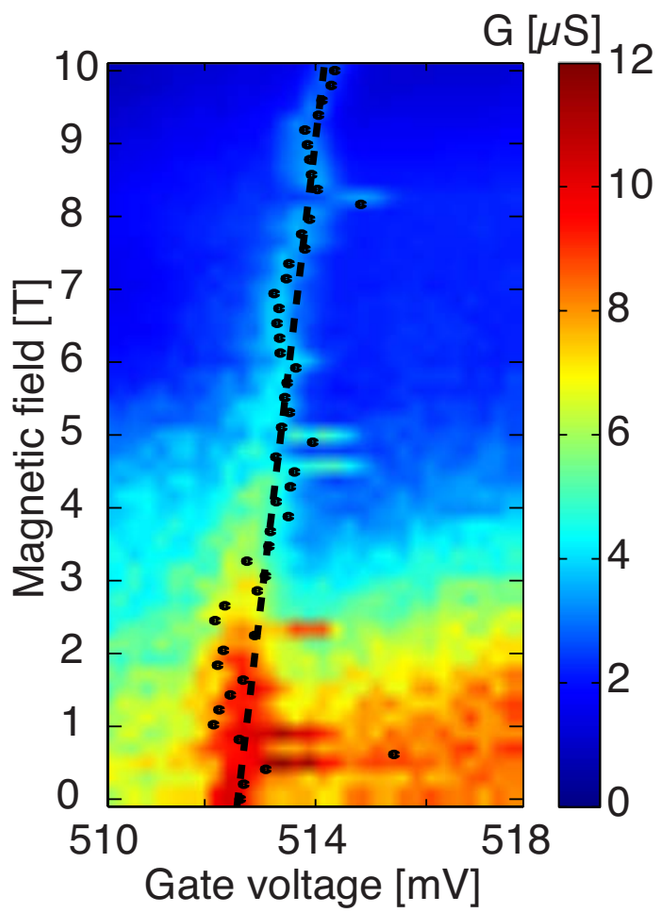


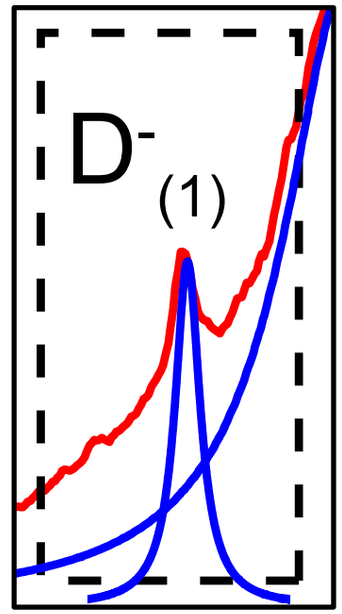
$$G(\epsilon) = \frac{e^2}{h} T(\epsilon) = G_F \frac{|\epsilon + q\Gamma/2|^2}{\epsilon^2 + (\Gamma/2)^2}$$



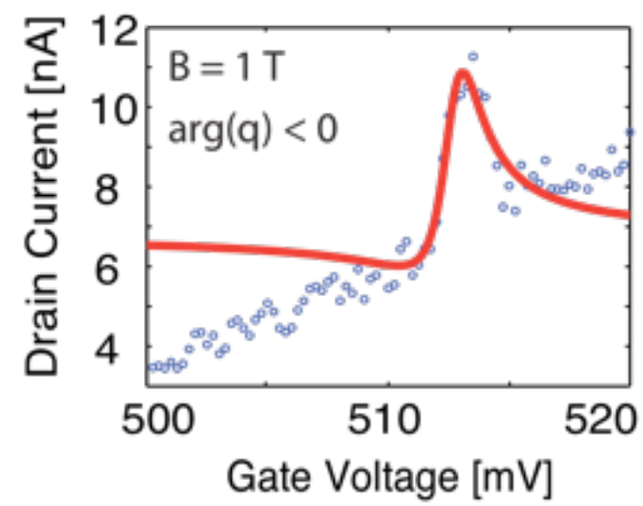
U. Fano, Nuovo Cimento 12, 154, 1935

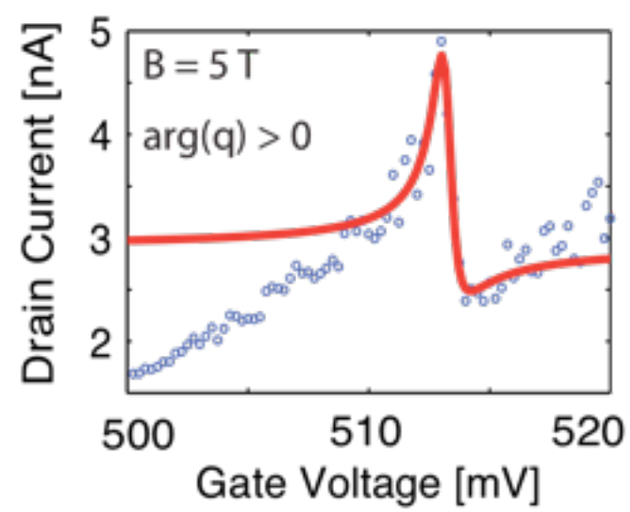
Magnetic field dependence





$$G(\epsilon) = G_F \frac{|\epsilon + q\Gamma/2|^2}{\epsilon^2 + (\Gamma/2)^2}$$



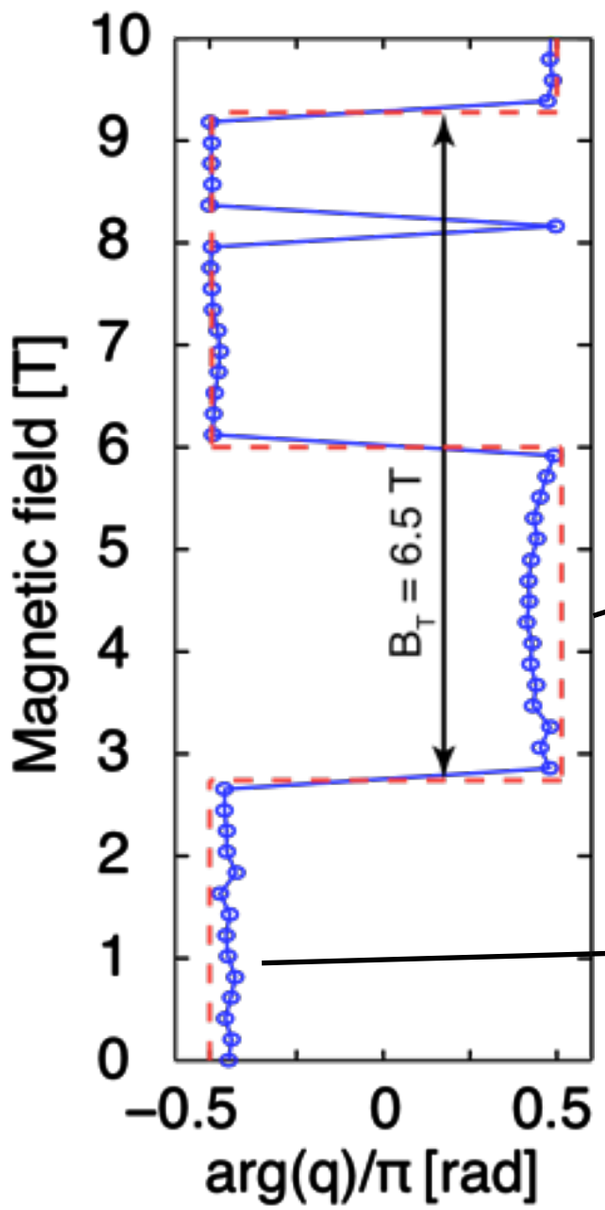


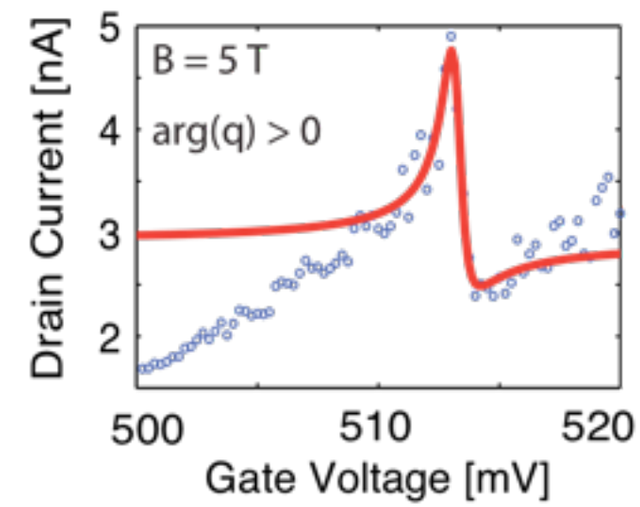
Zeeman shift →
D^- resonance, spin up

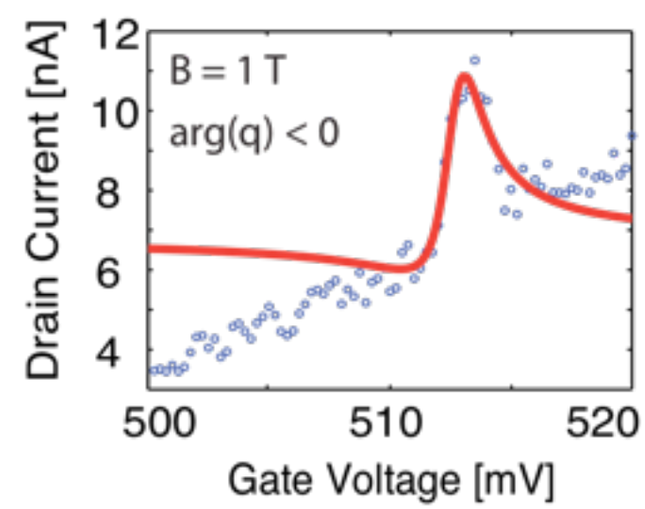
J. Verduijn et al., APL 96, 072110, 2010

Symmetry changes

$$G(\epsilon) = G_F \frac{|\epsilon + q\Gamma/2|^2}{\epsilon^2 + (\Gamma/2)^2}$$

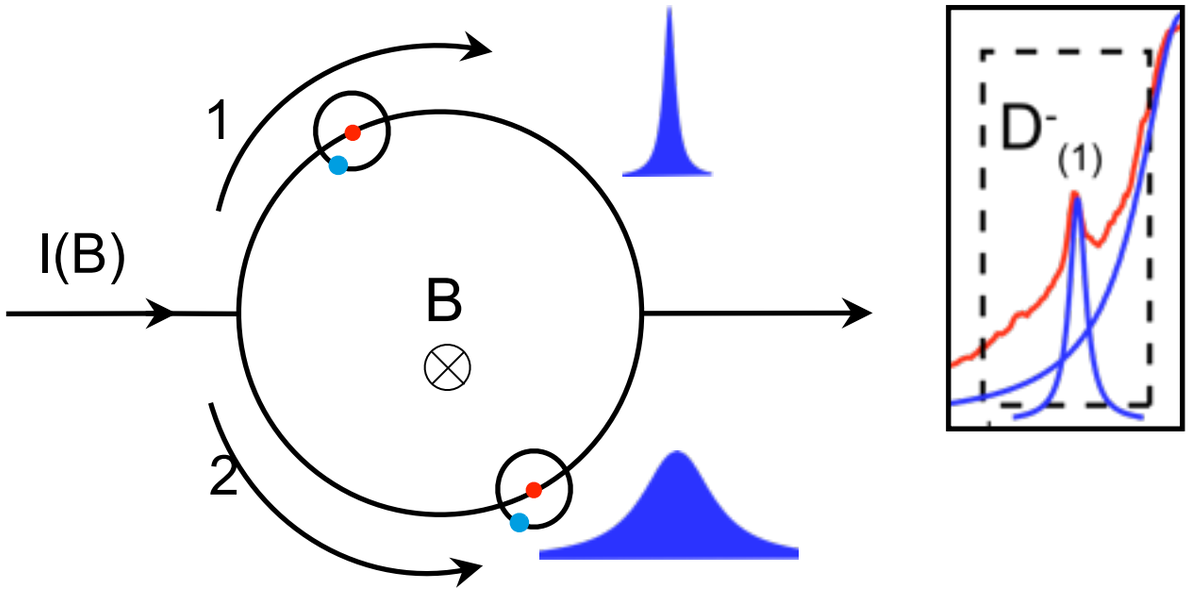




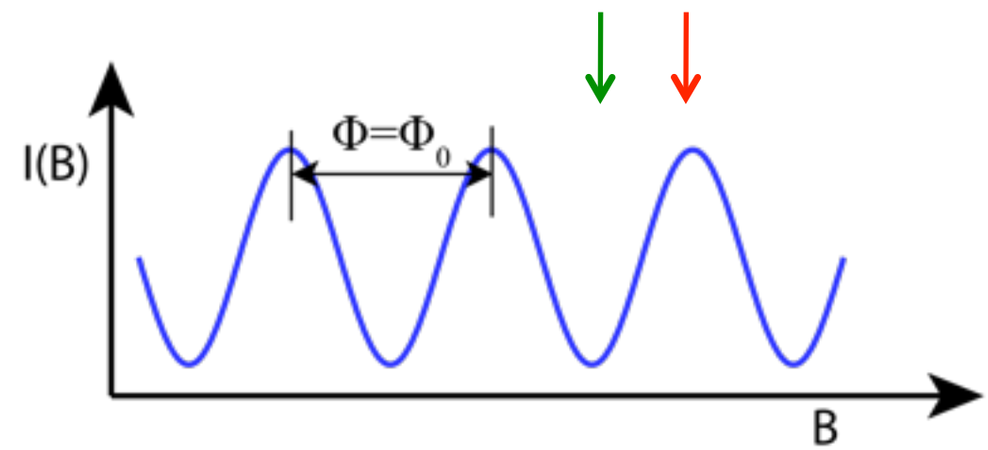


J. Verduijn et al., APL 96, 072110, 2010

Magnetic field dependence



Constructive and destructive interference



Two paths contribute in a different way due to the presence of the magnetic field.

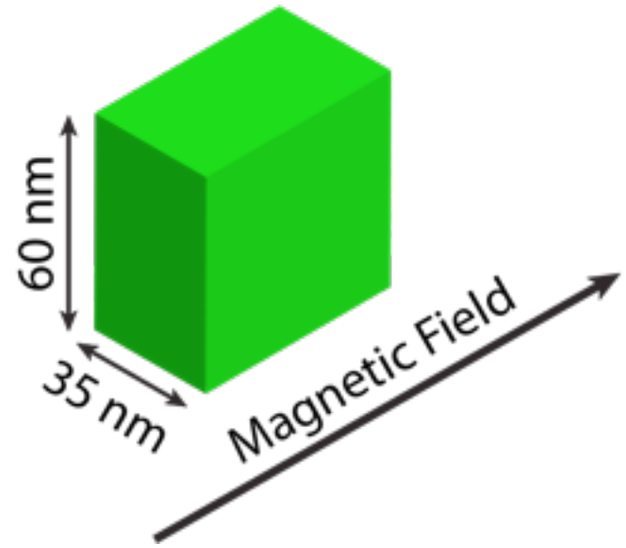
$$\varphi = \varphi_1 - \varphi_2 = k(l_1 - l_2) - \frac{e}{\hbar}\oint \vec{A}\cdot \mathrm{d}\vec{l}$$
$$= \Delta\varphi_0 - 2\pi\frac{\Phi}{\Phi_0},\ \ \Phi_0 = \frac{h}{e}$$

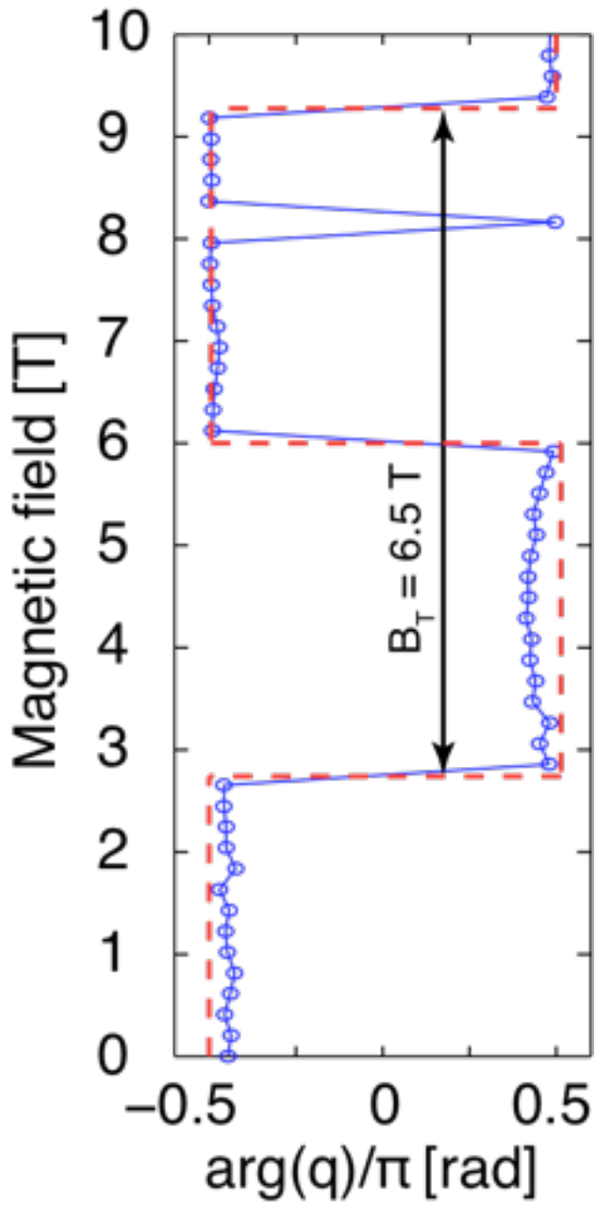
Experimental situation:

Two donors in parallel coupled to the leads, with a phase coherent conduction path between them

Aharonov and Bohm, Phys. Rev. 115, 485, 1959

Surface area loop



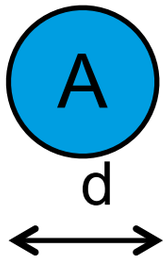


$$\Delta\varphi = 2\pi \frac{\Phi}{\Phi_0}$$

$$\Delta\varphi = 2\pi \rightarrow A = \frac{h}{e}\frac{1}{B_T}$$

A ≈ (4,125 / 6.5) nm²

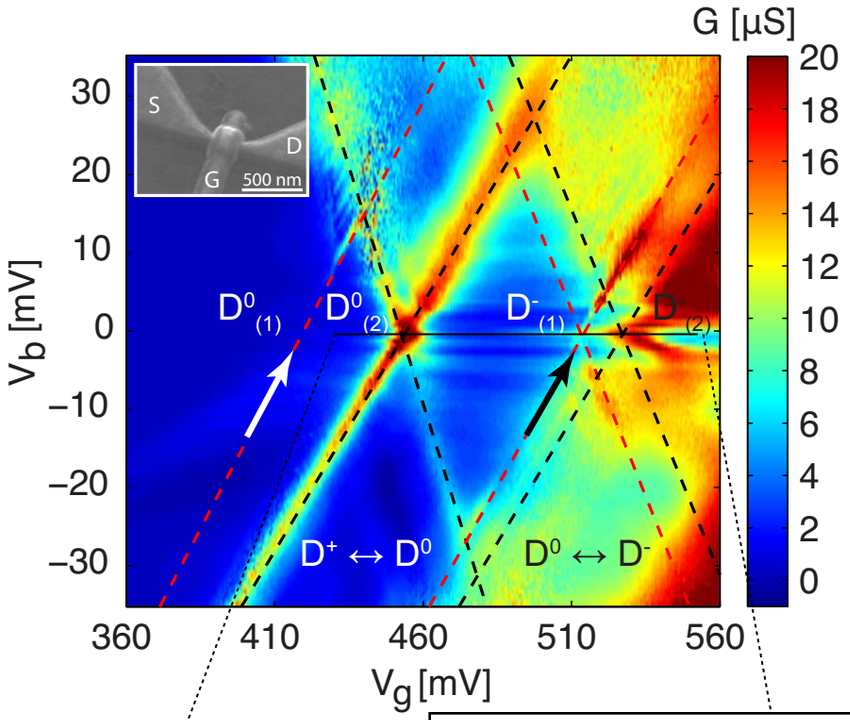
d ≈ 28 nm



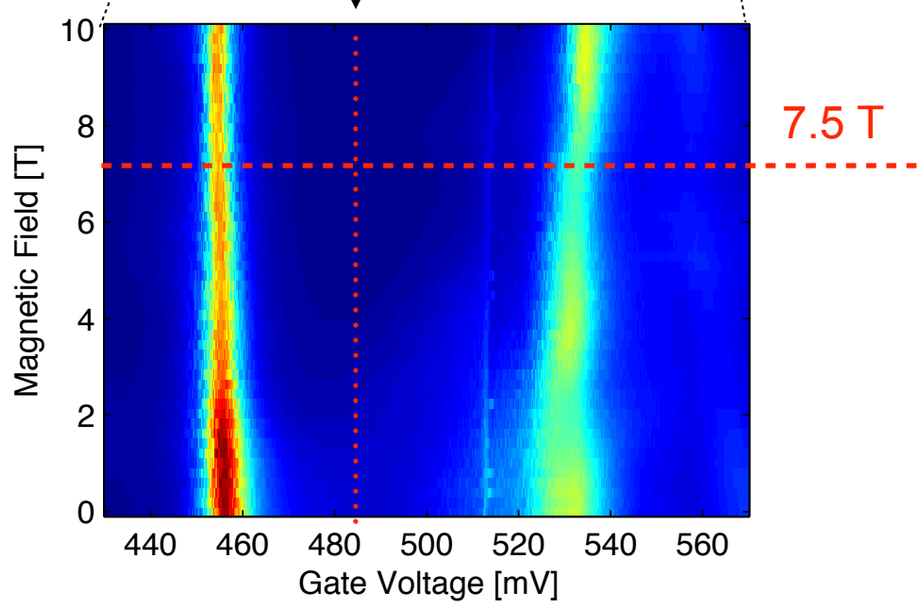
- Loop size consistent with device dimensions!

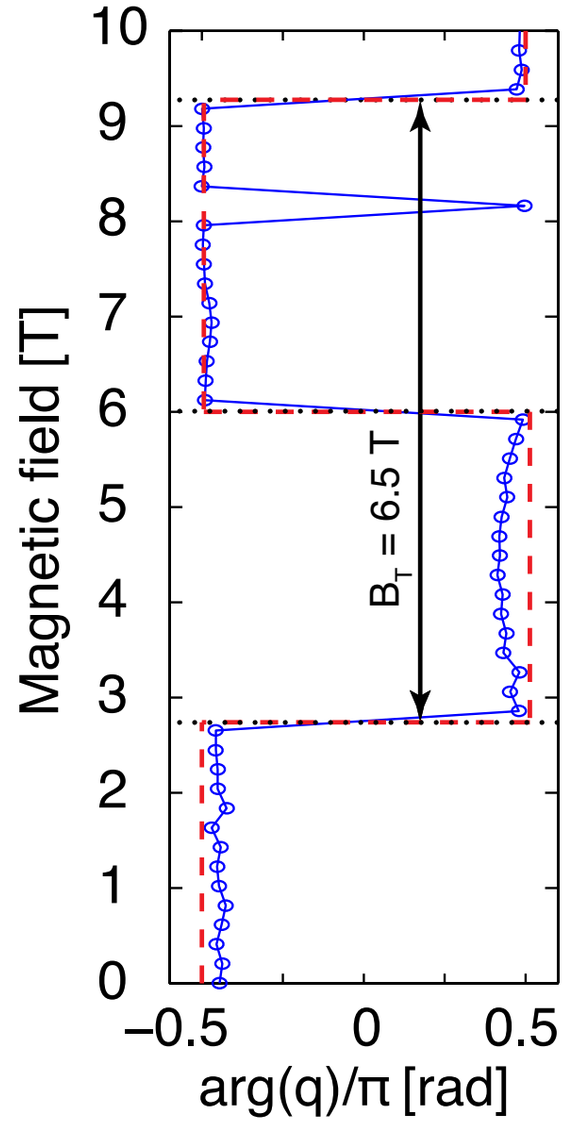
J. Verduijn et al., APL 96, 072110, 2010

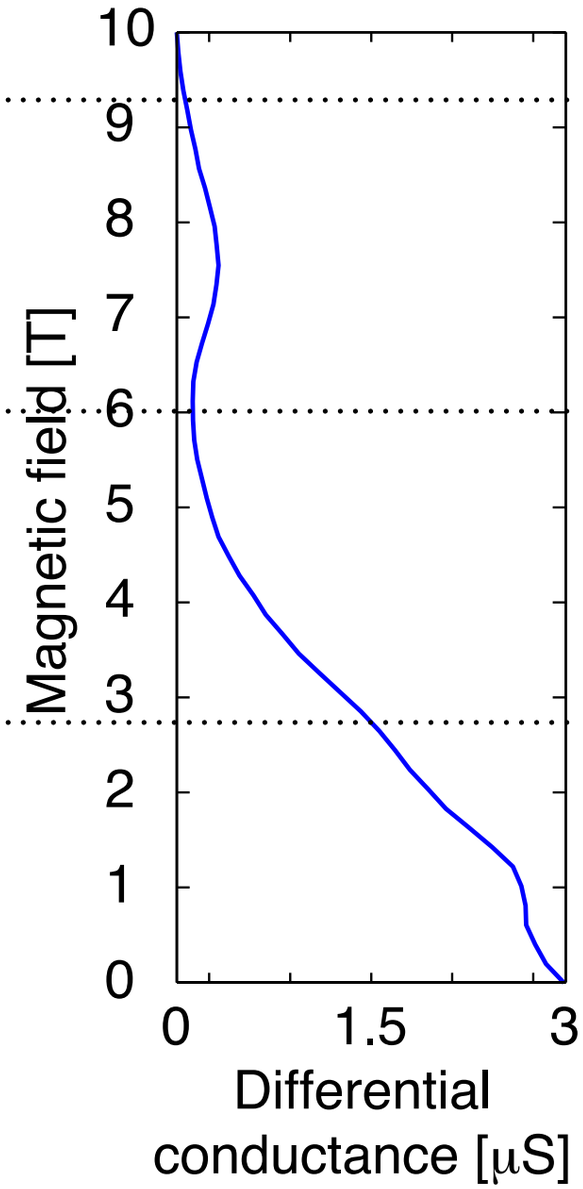
Correlation effects



Correlation effects are enhanced





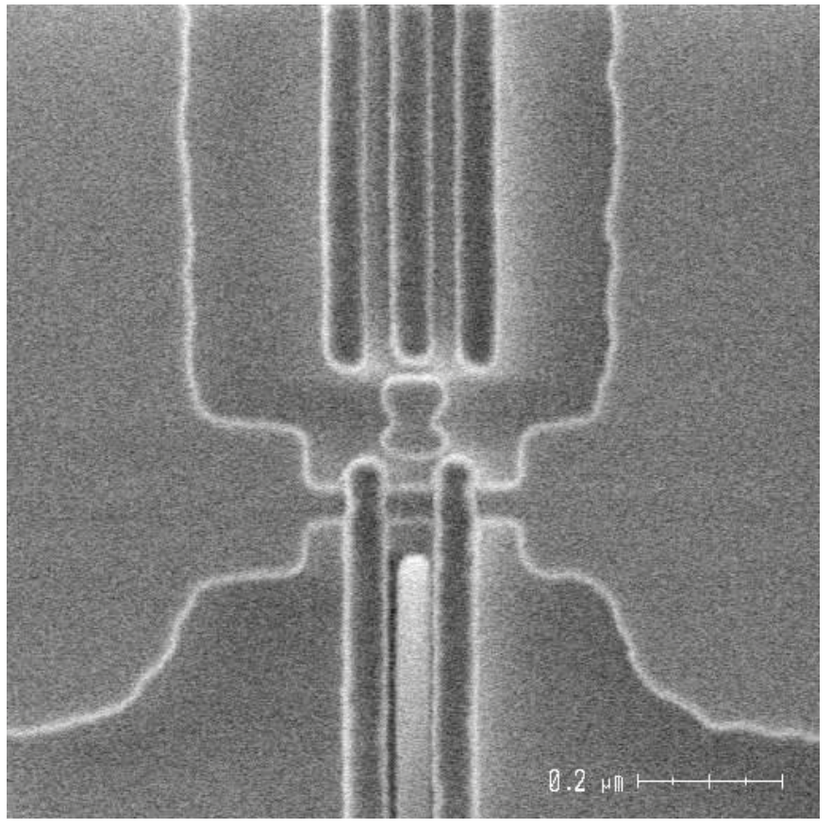


J. Wen *et al.*, PRB 75, 155327, 2007
R. Yoshii *et al.*, Physica E 42, 856, 2009

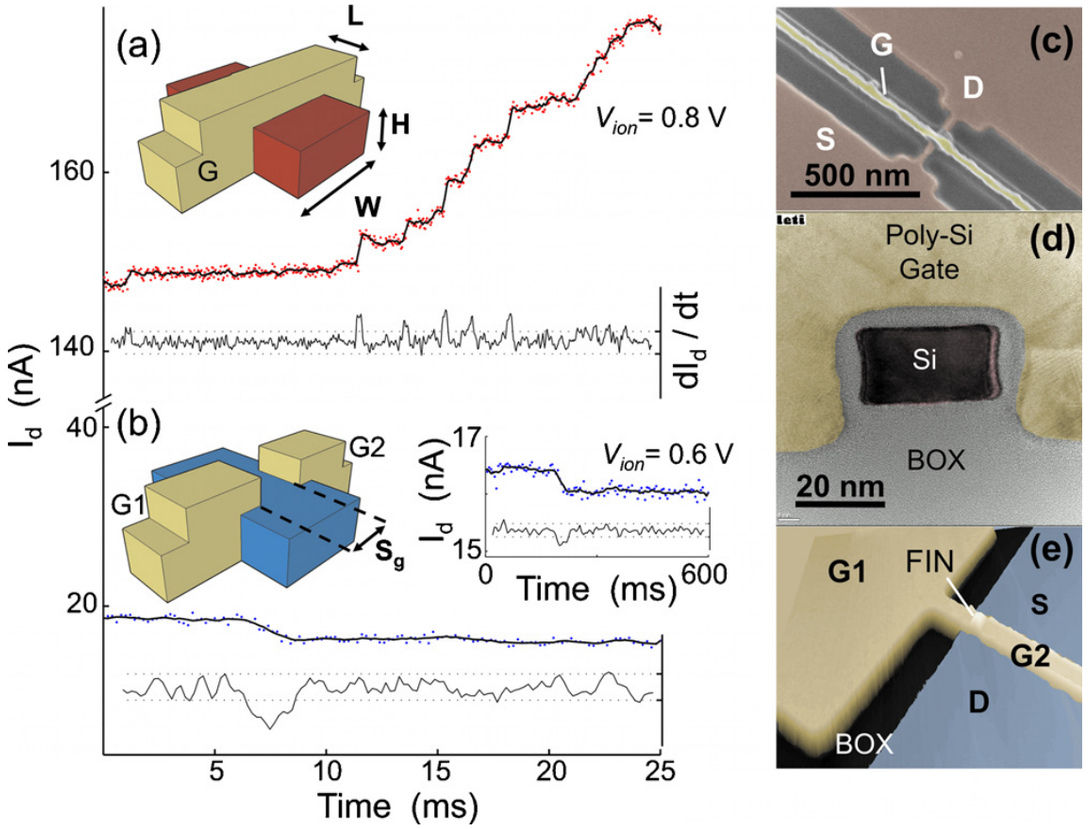
Fabrication routes

In collaboration with David Jamieson at University of Melbourne

Compact complex structures fabricated on a large scale



Nano-scale single ion implantation



B. Johnson et al., APL 69, 264102, 2010

Conclusions

- Phase coherent exchange of electrons between two coupled donors;
  - Magnetic field phase tuning by the Aharonov-Bohm effect
  - AB loop size consistent with the device dimensions
- Future directions: Coherence in more complex devices

We have open positions for PhDs and Postdocs!