

# Chapter 5. Coulomb Blockade in Narrow MOSFETs

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## 5.1 Project Description

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We are investigating the conductance through a quantum dot where the discrete nature of the electron charge on the dot and the Coulomb energy  $U$  associated with the addition or removal of a charge dominate the physics. This theoretical work is inspired by the experimental work of Professor Kastner's group, which discovered periodic structures in the conductance as a function of gate voltage in a narrow MOSFET structure with two constrictions. These constrictions create a quantum dot through which the electron must tunnel. There are two energy scales in the problem: (1) the energy spacing  $\Delta\epsilon$  between energy levels in the quantum dot which we estimate to be  $\Delta\epsilon \approx 0.1$  meV for a  $50$  nm  $\times$   $1$   $\mu$ m quantum dot in GaAs and (2) The Coulomb interaction energy between electrons  $U$  which is approximately equal to the capacitive charging energy of the quantum dot  $e^2/C$  where  $C$  is the capacitance and we estimate  $e^2/C \approx 1$  meV, so that  $U \gg \Delta\epsilon$ . Under these conditions, an electron must overcome the Coulomb energy in order to tunnel, a phenomenon known as the Coulomb blockade.

We treat a model consisting of two ideal leads coupled to a site with  $n$  energy levels and a Coulomb interaction energy  $U$  every time an extra electron is added to the site. This model is reminiscent of the Anderson model of magnetic impuri-

ties, in which electrons of either up or down spin ( $n = 2$ ) can occupy a site, and there is an on-site repulsion  $U$  for double occupation. The present problem is richer because the Fermi level in the right and left ideal leads can be separately adjusted.

Earlier we had examined the low temperature limit of this model,<sup>1</sup> and we found important correlation between the electron state on the quantum dot and the electrons in the lead when the temperature  $T$  is less than  $T_K$ , the Kondo temperature. However, in most cases  $T_K$  is very low, and we have recently developed a formalism to describe the high temperature limit<sup>2</sup> when  $T \gg T_K$ . We note that  $\Delta\epsilon$  can be comparable to  $kT$ , and there are interesting changes in the lineshape of the conductance peaks as  $kT$  goes from  $kT \ll \Delta\epsilon$  to  $kT \gg \Delta\epsilon$ . For  $kT \ll \Delta\epsilon$ , the lineshape is a Lorentzian broadened by the derivative of the Fermi function. As  $kT$  is increased through  $\Delta\epsilon$ , this is no longer the case, and we find that the peak height can increase or decrease with temperature, depending on the way the levels couple to the leads. This feature, which was observed experimentally, has been a puzzle for some time.

According to our theory, the observed temperature dependence is explained by simultaneous transport through multiple levels whose coupling to the leads increases rapidly with energy near the top of the tunnel barriers. Our theory gives a satisfactory account of the temperature dependence of the periodic structure in conductance, thus providing strong support for the validity of the Coulomb blockade model.

<sup>1</sup> T.-K. Ng and P.A. Lee, "On Site Coulomb Repulsion and Resonant Tunnelling," *Phys. Rev. Lett.* 61:1768 (1988).

<sup>2</sup> Y. Meir, N. Wingreen, and P. Lee, "Transport Through a Strongly Interacting Electron System: Theory of Periodic Conductance Oscillations," submitted to *Phys. Rev. Lett.*

### 5.1.1 Publications

Kinaret, J., and P.A. Lee. "Exchange Interaction in a Quantum Wire in a Strong Magnetic Field." *Phys. Rev. B* 42(18): 768-773 (1990).

Kinaret, J., and P.A. Lee. "Conductance of a Disordered Narrow Wire in a Strong Magnetic Field." *Phys. Rev. B*. Forthcoming.

Meir, Y., N. Wingreen, and P.A. Lee. "Transport Through a Strongly Interacting Electron System: Theory of Periodic Conductance Oscillations." Submitted to *Phys. Rev. Lett.*



*Professor Patrick A. Lee's recent work is focused on the effect of Coulomb repulsion on the tunneling probability through a quantum dot.*