Chapter 1. Single-Electron Electronics

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1.1 Goals and Objectives

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When electrons are confined to a small particle of metal or a small region of semiconductor both the energy and charge of the system are quantized. In this way, such nanometer-sized systems behave like artificial atoms.[3] When the channel of a transistor is made very small and isolated from its leads by tunnel barriers, an artificial atom is created and the transistor behaves in an unusual way. Whereas a conventional field-effect transistor turns on only once when electrons are added, the single-electron transistor (SET) turns on and off again every time a single electron is added. This increased functionality may eventually make SETs technologically important. The overall goal of our research is to better understand the physics of these devices in order to determine how they can be optimally applied.

1.2 Summary of Recent Work

How localized electrons interact with delocalized electrons is a question central to how SETs operate and also to many forefront problems in solid state physics. The simplest example is the Kondo effect, which occurs when an impurity atom with an unpaired electron is placed in a metal. At low temperatures a spin singlet state is formed between the unpaired localized electron and delocalized electrons at the Fermi energy. An SET contains a confined droplet of electrons coupled by quantum mechanical tunneling to the delocalized electrons in the transistor's leads.

Several theoretical papers[4] have predicted that a Kondo singlet could form in an SET, which would make it possible to study aspects of the Kondo effect inaccessible in conventional systems. With an SET, the number of electrons on the droplet can be changed from odd to even; the difference in energy between the localized state and the Fermi level can be tuned; the coupling to the leads can be adjusted; voltage differences can be applied revealing non-equilibrium Kondo phenomena[5]; and a single localized state can be studied rather than a statistical distribution of many impurity states.

However, for SETs fabricated previously, the binding energy of the spin singlet has been too small to observe Kondo phenomena. Ralph and Buhrman[6] have observed the Kondo singlet at a single accidental impurity in a metal point contact, but, with only two electrodes and without control over the structure, they have not been able to observe all the features

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[1] Weizmann Institute of Science, Rehovot, Israel.

[2] Ibid.

[3] R.C. Ashoori, “Electrons in Artificial Atoms,” *Nature* 379: 413 (1996); M.A. Kastner, “Artificial Atoms,” *Phys. Today* 46: 24 (1993).

[4] T.K. Ng and P.A. Lee, “On-Site Coulomb Repulsion and Resonant Tunneling,” *Phys. Rev. Lett.* 61: 1768 (1988); L.I. Glazman and M.E. Raikh, “Resonant Kondo Transparency of a Barrier with Quasilocal Impurity States,” *JETP Letters* 61: 1768 (1988); Y. Meir, N.S. Wingreen, and P.A. Lee, “Low-Temperature Transport Through a Quantum Dot: the Anderson Model Out of Equilibrium,” *Phys. Rev. Lett.* 70: 2601 (1993); N.S. Wingreen and Y. Meir, “Anderson Model Out of Equilibrium: Noncrossing-Approximation Approach to Transport Through a Quantum Dot,” *Phys. Rev. B* 49: 11040 (1994).

[5] N.S. Wingreen and Y. Meir, “Anderson Model Out of Equilibrium: Noncrossing-Approximation Approach to Transport Through a Quantum Dot,” *Phys. Rev. B* 49: 11040 (1994).

predicted. We have recently reported[7] measurements on a new generation of SETs that exhibit all the aspects of the Kondo effect.

We have fabricated SETs using multiple metallic gates (electrodes) deposited on a GaAs/AlGaAs heterostructure containing a two-dimensional electron gas (see Figure 1). First, the electrons are trapped in a plane by differences in the electronic properties of the heterostructure's layers. Second, they are excluded from regions of the plane beneath the gates when negative voltages are applied to those gates. This creates a droplet of electrons separated from the leads by tunnel junctions. To make our SETs smaller than earlier ones, we have fabricated shallower 2DEG heterostructures as well as finer metallic gate patterns by electron-beam lithography. The smaller size of the SETs is critical to our observation of the Kondo effect. Several important energy scales and their relative sizes determine the behavior of an SET. At low temperature, the number of electrons N in the droplet is a fixed integer (roughly 50 for our samples). This number may be changed by raising the voltage of a nearby gate electrode which lowers the energy of electrons in the droplet relative to the Fermi level in the leads. The change in energy necessary to add an electron is called U, and in a simple model is the charging energy $e^2/2C$, where C is the capacitance of the droplet. Since U is determined by the Coulomb repulsion between pairs of electrons in the droplet, it scales approximately inversely with the droplet's radius.

For small droplets, the quantized energy difference between different spatial electronic states becomes important. We call the typical energy spacing between spatial states $\Delta\varepsilon$. Another important energy Γ is the coupling of electronic states on the artificial atom to those on the leads, resulting from tunneling. When Γ is made greater than $\Delta\varepsilon$, the electrons spread from the artificial atom into the leads, and quantization of charge and energy is lost, even at temperature T=0. Finally, the energy that determines whether Kondo physics will be visible is $k\,T_K$, which is always smaller than Γ. (k is Boltzmann's constant and T_K is called the Kondo temperature.)[8] By making smaller SETs, we have made $\Delta\varepsilon$ relatively large, which permits large Γ and thus T_K comparable to accessible temperatures. In semiconductor SETs, Γ can be tuned by changing the voltage on the gates that create the barriers between artificial atom and leads. We find that with our new SETs we can vary Γ slowly as it approaches $\Delta\varepsilon$, and thus optimize T_K.

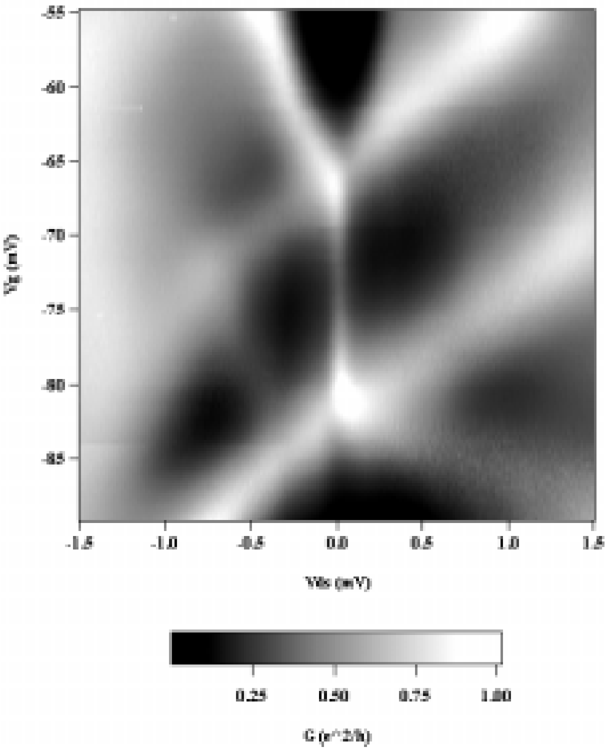

Figure 1. Differential conductance on a grey scale as a function of both V_g and V_{ds}. The white vertical line between the two maxima indicates that there is a zero-bias peak for odd N only.

In our experiment, we make two types of measurements. In the first, we apply a voltage of a few µV between the two leads of the SET, the source and drain, and measure the current that flows through the droplet as a function of the voltage V_g on one of the SET's gates. For such small applied voltage (< kT/e), the current varies linearly with voltage, and the zero-

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[6] D.C. Ralph and R.A. Buhrman, “Kondo-Assisted and Resonant Tunneling Via a Single Charge Trap: a Realization of the Anderson Model Out of Equilibrium,” *Phys. Rev. Lett.* 72: 3401 (1994).

[7] D. Goldhaber-Gordon, D. Mahalu, H. Shtrikman, D. Abusch-Magder, U. Meirav, and M.A. Kastner, “Kondo Effect in a Single Electron Transistor,” *Nature* 391: 156 (1998).

[8] N.S. Wingreen and Y. Meir, “Anderson Model Out of Equilibrium: Noncrossing-Approximation Approach to Transport Through a Quantum Dot,” *Phys. Rev. B* 49: 11040 (1994).

bias conductance can be measured. In the second class of measurements, we add a variable DC offset V_{ds} (up to several mV) to a μVAC excitation and use lock-in detection of the current to obtain differential conductance dI/dV_{ds} versus V_{ds}.

Varying V_g on an SET typically results in adding an electron to the droplet each time the voltage is increased by a fixed increment proportional to U. Since current can flow through the SET only when the occupancy of the island is free to fluctuate between N and N+1, conductance versus V_g shows a series of sharp, periodically-spaced peaks when Γ is made relatively small. When Γ is large, however, we find that these peaks form pairs, with large inter-pair spacing and small intra-pair spacing. The two peaks within a pair have comparable widths and heights, while between pairs the widths vary significantly. These observations are direct evidence that two electrons of different spin are occupying each spatial state. Between paired peaks N is odd, while between adjacent pairs it is even. Since two electrons corresponding to the pair of peaks are added to the same spatial state, the intra-pair spacing is determined by U. However, when N is even (between pairs) the next electron must be placed in a different spatial state, so the interpair spacing is determined by $U + \Delta\varepsilon$.

We observe an enhancement of linear conductance at low temperature for odd but not even N, a clear manifestation of Kondo physics. If N is odd, there is an unpaired electron with a free spin which can form a singlet with electrons at the Fermi level in the leads. This coupling results in an enhanced density of states at the Fermi level in the leads, and hence an enhanced conductance.[9] Raising the temperature destroys the singlet and attenuates the conductance.

Another aspect of the Kondo effect is the sensitivity of the excess conductance between the pair of peaks to the difference in Fermi levels in the two leads. The extra electron in the droplet couples to electrons in both leads, giving an enhanced density of states at both Fermi levels. When the applied voltage is large, separating the Fermi levels in the two leads, the electrons at the Fermi level in the higher energy lead can no longer resonantly tunnel into the enhanced density of states in the lower energy lead, so the extra conductance is suppressed.

A magnetic field also alters the Kondo effect. Applying a magnetic field splits the unpaired localized electron state into a Zeeman doublet. This also splits the enhanced density of states at the Fermi level resulting in a splitting of peaks in differential conductance.

We have seen all the predicted features of the Kondo effect. Figure 1 shows the differential conductance at low temperature and zero magnetic field as a function of both V_{ds} and V_g. This range of V_g spans one pair of peaks as well as the valleys on either side of it. The bright diagonal lines result from strong peaks in dI/dV_{ds} marking the values of V_{ds} and V_g where N can change to N+1 or N-1. The slopes of these lines contain information about the relative capacitances of gates and leads to the droplet of electrons. A narrow, bright, vertical line at $V_{ds} = 0$ in Figure 1 shows that the zero-bias conductance is enhanced everywhere between the paired peaks but not outside the pair. The sharpness of the Kondo peak compared with other features is a dramatic illustration that we have, indeed, observed the Kondo effect in our SET.

1.3 Publication

Goldhaber-Gordon, D., D. Mahalu, H. Shtrikman, D. Abusch-Magder, U. Meirav, and M.A. Kastner. "Kondo Effect in a Single Electron Transistor." *Nature* 391: 156 (1998).

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[9] T.K. Ng and P.A. Lee, "On-Site Coulomb Repulsion and Resonant Tunneling," *Phys. Rev. Lett.* 61: 1768 (1988); L.I. Glazman and M.E. Raikh, "Resonant Kondo Transparency of a Barrier with Quasilocal Impurity States," *JETP Letters* 61: 1768 (1988).