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Kondo-like zero-bias anomaly in electronic transport through an ultrasmall Si quantum dot

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We have studied charge transport through an ultrasmall Si single electron transistor. We find that at low temperatures, the Coulomb blockade is partially lifted at certain gate voltages. Furthermore, we observed an enhancement of the differential conductance at zero bias. The magnetic field dependence of this zero-bias anomaly is different from that of the Kondo peaks reported in GaAs quantum dots: we observed no splitting of the zero-bias peak with magnetic field. [S0163-1829(99)50948-X]

Quantum dots (QD's) formed in GaAs/Al$_x$Ga$_{1-x}$As heterostructures have been used as model systems to study transport in the Coulomb blockade regime.[1] Following advances in nanolithography, QD size was reduced down to the level where quantum effects started to play a role. As the size became smaller, collective phenomena, such as the Kondo effect, were recently reported.[2,3] To further reduce the QD size for exploring new phenomena, one must abandon the conventional approach of using field-induced barriers. Recently, Si dots with confinement provided by the sharp Si-SiO$_2$ interface have been realized. These dots can be fabricated so small that the single-electron transistor (SET) can operate at room temperature.[4,5] Although an increase of the operating temperature of SET's was the primary driving force behind the development of the Si quantum dot technology, there were some limited studies of electron transport at low temperatures, which provided information about the energy spectrum in these structures[6] and which probed first-order quantum corrections to the conductivity in the Coulomb blockade regime.[7]

In this paper, we report low temperature electron transport in ultrasmall Si quantum dots. We find that at certain range of gate voltages, Coulomb blockade is lifted at $T<1$ K and the differential conductance at zero source-drain bias increases as the temperature is lowered. Although it is appealing to attribute the enhancement to the Kondo effect, we find that the magnetic field dependence of this zero-bias anomaly is inconsistent with such an interpretation.

We have investigated transport in quantum dot samples which are metal-oxide-semiconductor field effect transistors (MOSFET's) with a Si dot connected to the source and drain leads through tunneling barriers (see inset in Fig. 1). The dot is surrounded by 40–50 nm of SiO$_2$ and wrapped by a poly-Si gate (fabrication details can be found in Ref. 8). The gate is also extended over the tunneling barriers and parts of the leads, adjacent to the dot. Outside the gate, the source and drain are *n* type. An inversion layer is formed at the Si-SiO$_2$ interface by applying a voltage to the poly-Si gate. Unlike GaAs dots, there are no separate gates to control the coupling between the dot and the source/drain. In fact, the coupling is a function of the applied gate voltage V_g. We studied more than 30 samples which show Coulomb blockade above 10 K. However, at low temperatures ($T<4$ K) and low source-drain bias ($V_b<100$ μV) the conducting channel under the gate breaks up and the samples have electrical characteristics of multiply connected dots. Wide sweeps of the gate voltage are accompanied by sudden switching, which could be due to charging/discharging of some traps in the oxide. If we restrict the sweeps to <1 V, we can obtain reproducible results for several days.

In Fig. 1 the differential conductance G is plotted as a function of V_g at a source-drain bias $V_b=0$ for six different temperatures from one of the samples. From the device geometry the dot-gate capacitance is estimated to be 1–2 aF. We attribute large peaks at $V_g=3.46$, 3.54, 3.67, and 3.73 V to the main lithographically defined quantum dot. From the analysis of G vs V_b and V_g data we estimate gate voltage to single particle energy conversion coefficient $\alpha\approx 9$ mV/meV.

The G in the valleys between most of the peaks is thermally activated and vanishes rapidly at low T (valleys *A*,*B*,*D*,*E* in Fig. 1). However, in some valleys (for example in valley *C*) the G is almost T independent. Remarkably, in such valleys the G vs V_b data reveal a maximum close to the zero bias in the entire V_g range of the valley. This is in

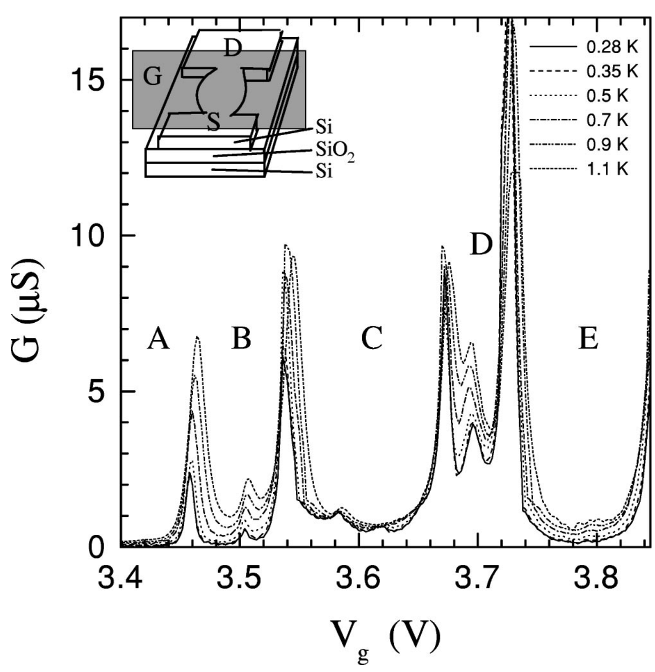

FIG. 1. Differential conductance G in the quantum dot as a function of the gate voltage V_g at six different temperatures. The G is measured with 10 μV ac source-drain bias at a frequency 7.7 Hz, zero dc bias and $B=0$. Letters $A \ldots E$ label Coulomb blockade valleys. Schematic of the device is shown in the inset. Poly-Si gate (G) covers the dot and adjacent regions of source (S) and drain (D).

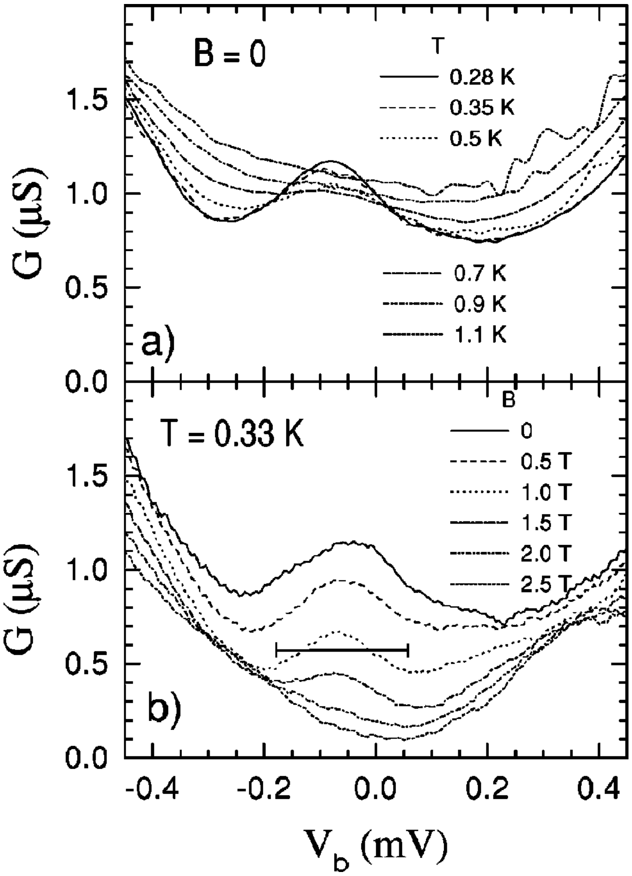

FIG. 2. Differential conductance G as a function of a dc source-drain bias V_b at different (a) temperatures, and (b) magnetic fields at a fixed gate voltage $V_g=3.57$ V. The (a) and (b) data sets were taken one day apart, which resulted in a small difference between $T=0.35$ K data in (a) and $B=0$ data in (b). The bar in (b) indicates twice the Zeeman energy $2E_Z=2g\mu_B B=0.23$ meV $(g=2)$ at $B=1$ T.

striking contrast to the broad minimum around $V_b=0$ observed in the neighboring Coulomb blockade valleys. In Fig. 2(a), we plot a representative G vs V_b curve measured at $V_g=3.57$ V. The peak at $V_b=-0.08$ mV has a weak dependence on the V_g: it shifts from $V_b=-0.06$ mV at $V_g=3.55$ V to $V_b=-0.21$ mV at $V_g=3.66$ V. Similar results which show slightly off-zero bias peaks that shift as a function of the V_g have been reported in GaAs quantum dots.[9,10] In the case of the Kondo regime, the shift of the peak from $V_b=0$ can be qualitatively explained by the energy- and V_g-dependent coupling of the dot to the leads. The maximum at $V_b=-0.08$ mV vanishes at $T>1$ K and becomes a broad minimum.

This zero-bias anomaly is sensitive to an external magnetic field B. At $B>2$ T, applied parallel to the conducting channel, the enhanced conductivity is suppressed and the Coulomb blockade is restored in the entire range 3.55 V $<V_g<3.66$ V. At $B>2$ T, the conductance shows a broad minima near $V_b=0$. In Fig. 2(b) we plotted G vs V_b at $V_g=3.57$ for different B. There is no apparent dependence of the peak position on B, while the peak magnitude decreases as B is increased. The peak is completely suppressed by $B\approx 2$ T.

There are striking differences between the Kondo effect reported in GaAs dots and the zero-bias anomaly in our data. One of the signatures of the Kondo effect is that at $B>0$ the zero bias peak in G is split into two peaks separated by twice the Zeeman energy, $\Delta V_b=2E_Z/e$. Such a splitting was reported in GaAs quantum dots[2,3,9] as well as in metallic grains.[11] $E_Z=g\mu_B B=0.12$ meV at $B=1$ T (assuming $g=2$ in Si)[12] and the splitting is expected to be $\Delta V_b=0.23$ mV [indicated by a bar in Fig. 2(b)]. The width of the zero-bias peak in our data is ≈ 0.15 mV at $B=1$ T, half the expected Kondo splitting. However, we have seen no splitting of the zero-bias maximum as a function of B in our data up to $B=2$ T, the highest field at which the maximum is still observed. Also, the position of this maximum is not affected by magnetic field.

An underlying physics for the Kondo effect requires the highest occupied level in the dot to be at least doubly degenerate. Adding an extra electron to the dot costs just the charging energy $U_c=e^2/2C$, where C is the total capacitance from the dot to the gate and leads. Adding a second electron should cost $U_c+\Delta E$, where ΔE is due to the size quantization in the dot (or it can be the same U_c if the level is more than twofold degenerate). Thus, the Kondo effect is expected to be observed in the narrower valley between two adjacent charge-degenerate peaks which are separated by $\Delta V_g=\alpha U_c$, while neighboring valleys are expected to be wider with gate voltage separation of $\Delta V_g=\alpha(U_c+\Delta E)$. However, we observed zero-bias anomaly in the widest valley with $\Delta V_g=170$ mV, while the neighboring valleys with widths 80 and 60 mV have no zero-bias anomalies at $B=0$. There is also a characteristic shift of the charge-degenerate peaks as a function of temperature in the Kondo regime.[13] As temperature decreases, valley conductance is enhanced, which results in the shift of the charge-degenerate peaks toward each other. Instead, we observed that the peak at $V_g=3.54$ V shifts to the lower gate voltages as the temperature is decreased, while the position of the peak at $V_g=3.67$ V is almost temperature independent.

Dependence of the conductance of the zero-bias peak G^P on T, B and V_b is shown in Fig. 3. The temperature range $0.3<T<1$ K, where zero-bias anomaly is observed, is not sufficient to extract the functional dependence $G^P(T)$ with certainty, although it is close to being logarithmic. The zero-bias peak is superimposed on a parabolic V_b-dependent background, thus we cannot unambiguously conclude what is the functional dependence of G^P on the bias voltage. In contrast, G^P is a strong function of the magnetic field. As shown in the inset in Fig. 3, magnetic field exponentially suppresses the conductance by more than an order of magnitude. Note, that one expects a weak logarithmic suppression of G by magnetic field at $V_b=0$ in the Kondo regime.

Another striking result is that in some Coulomb blockade valleys the zero-bias anomaly appears only at nonzero magnetic field. These valleys may group around the valley where the zero-bias anomaly is observed at $B=0$. For example, at $B=0$ we observe a peak in G at $V_b\approx 0$ in valley C (Fig. 2), while there are broad minima at $V_b=0$ in the neighboring valleys. The zero-bias anomaly peak in valley C is destroyed by $B\approx 2$ T, and G has a broad minimum centered at $V_b=0$ at higher magnetic field. However, at $B=3$ T, G has a maximum in valley B. In Fig. 4(a), the V_b dependence of G is shown in the center of that valley at $V_g=3.49$ V. While

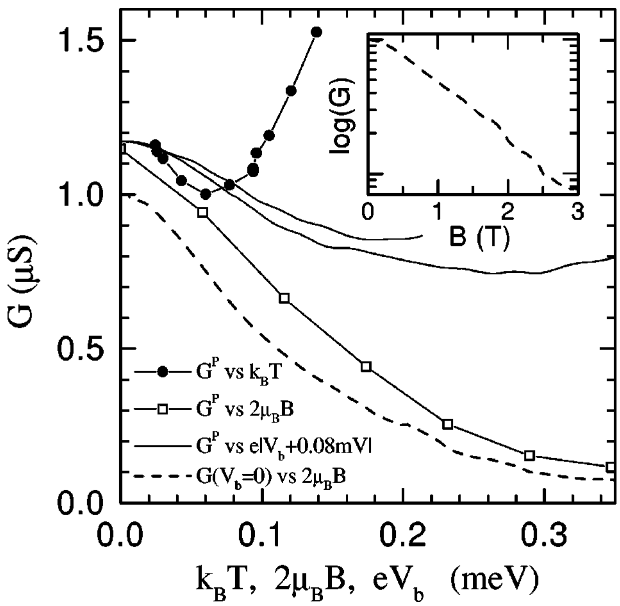

FIG. 3. Peak differential conductance G^P at $V_b=-0.08$ mV is plotted as a function of temperature k_BT at $B=0$ (●), magnetic field $2\mu_BB$ at $T=0.3$ K (□). The two solid curves are G^P vs bias $e|V_b-V_b^P|$ at $B=0$ and $T=0.28$ K, where $V_b^P=-0.08$ mV is the peak position. Dashed line is G vs B at $V_b=0$ and $T=0.3$ K. Inset: G at $V_b=0$ falls almost exponentially as a function of B.

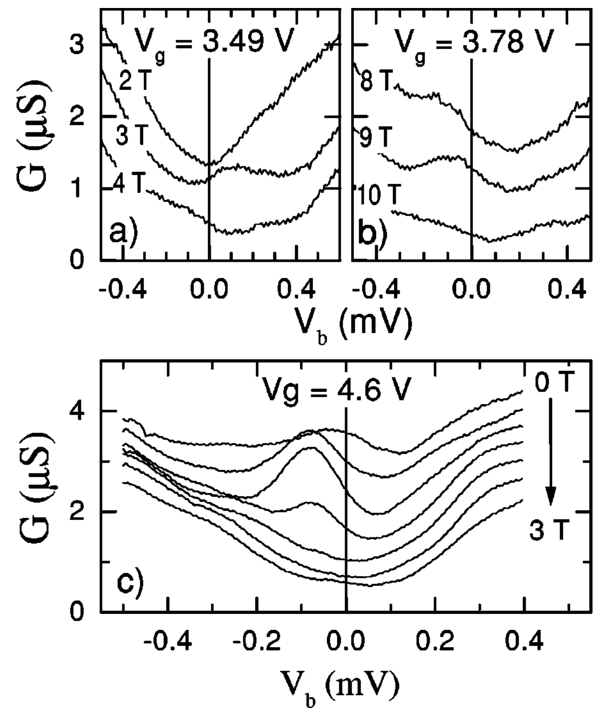

FIG. 4. Differential conductance G as a function of dc bias V_b in three different Coulomb blockade valleys. In these valleys, peaks in G are observed at $B\neq 0$. Curves are offset by 0.5 μS in (a) and (b) and by 0.25 μS in (c), except for the bottom curves in each plot.

there is a minimum around $V_b=0$ at $B<2$ T and $B>4$ T, there is a pronounced peak at $V_b=0.1$ mV at $B=3$ T. In the neighboring valley D we observed a peak at $V_b=-0.3$ mV at $B=5$ T. At yet higher $B=9$ T, there is a maximum at $V_b=-0.1$ mV in valley E, as shown in Fig. 4(b). These maxima are observed over a limited B range of $\Delta B\approx 1$ T.

In some Coulomb blockade valleys, zero bias anomaly is observed at $B=0$, although the strongest zero-bias peak is found at $B>0$. As shown in Fig. 4(c), at $V_g=4.6$ V the strongest zero-bias peak is at $B=0.6$ T; the peak becomes a broad minimum at $B>2.5$ T. There are no zero-bias anomalies developed in the adjacent valleys in the experimental range of $0<B<10$ T.

To summarize our findings, we observed a suppression of the Coulomb blockade and an enhancement of the differential conductance at low temperatures at certain gate voltages. This anomaly is destroyed by (i) raising the temperature, (ii) increasing the bias, or (iii) applying a magnetic field. Unlike in the Kondo effect reported in GaAs quantum dots, the zero-bias anomaly in our experiment is not split by the magnetic field but, instead, the magnetic field suppresses it exponentially. Also, at certain gate voltages we observed a zero-bias anomaly at $B>0$.

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