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Strong cotunneling suppression in a single-electron transistor with granulated metal film island

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Macroscopic quantum tunneling (cotunneling) is a major source of errors in single-electron devices that require the transfer of a precise number of electrons. The authors present a single-electron transistor (SET) where the suppression of cotunneling is achieved by using a granulated metal film as the material of the SET island. In this device a characteristic charging energy is defined by the Al/AlO_x junctions while the cotunneling is suppressed by electron scattering in the granulated metal island. The authors discuss possible applications of this solution for single-electron latches and pumps. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2243341]

Devices based on the precise transfer of single electrons using the Coulomb blockade effect [Coulomb coupled single-electron logic such as quantum-dot cellular automata (QCA), single-electron pumps, and single-electron memories] attract significant attention as the scaling progresses down to nanoscale. However, the operation of these devices is impaired by cotunneling,[1] a macroscopic quantum process, which opens a classically prohibited channel for charge transfer under the Coulomb barrier. Theory[1] shows that the cotunneling current in the array of N tunnel junctions scales with the number of junctions as $I \sim V^{2N-1}$. By increasing the number of junctions one can, for small biases, significantly reduce the cotunneling current. Unfortunately, in practice, the need to compensate for the presence of random offset charges on each island in the array drastically complicates the operation of the devices.[2] Another way to reduce cotunneling is to embed a linear (Ohmic) resistor $R > R_Q = h/e^2$ which represents an electromagnetic environment with large dissipation capable of absorbing a significant part of the electron energy in series with tunnel junctions.[3] As a result the cotunneling current changes with the applied bias as $I \sim V^{2(N+z)-1}$, where N is the number of junctions and $z = R/R_Q$. The experiments[4] showed that Ohmic microstrips with resistance $n \times R_Q$ act as n extra tunnel junctions in the array, strongly suppressing the cotunneling. A single-electron transistor (SET) with two granulated film CrO_x strips connecting an Al island to Al wires was studied in Ref. 5. However, the microstrips used in Ref. 5 were not linear resistors as in Ref. 4, but rather have strongly nonlinear *I-V* characteristics. A strong suppression of cotunneling was identified by high power factor of the *I-V* characteristic measured in the valleys of the Coulomb blockade oscillations (CBOs): $I \sim V^{\alpha}$, $\alpha \approx 10$, a value far greater than for a regular SET with two junctions ($\alpha \approx 3$). Luo *et al.*[6,7] showed that observation of CBOs in such devices is due to the formation of random junctions connecting the island to granulated metal strips. The low yield of the devices showing CBOs and strong variations in charging energy rule out this fabrication method as unreliable.

In this letter we report an experimental demonstration of a SET with suppressed cotunneling where a granulated metal is used for the island material, while conventional Al/AlO_x tunnel junctions provide SET island isolation.

The devices are fabricated using the Dolan bridge technique[8] utilizing e-beam lithography and metal deposition with *in situ* oxidation. First, a 20 nm layer of Al is evaporated then oxidized for 10 min at 60 mtorr of pure O_2 and then a second metal, Cr, 20 nm thick, is evaporated in an oxygen ambient ($p \approx 5 \times 10^{-5}$ torr) at a different angle. The desired sheet resistance of the CrO_x film, $R \sim h/4e^2$, close to a metal-insulator transition, is achieved by adjusting the oxygen content in the chamber during the evaporation.[5–7] The schematic of the device pattern design is shown in Fig. 1(a). The area of the junctions is about 30×30 nm^2. To analyze

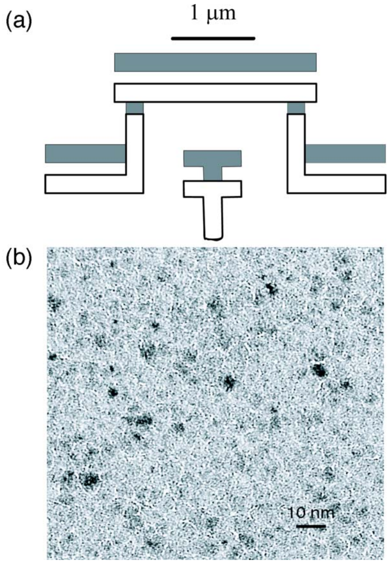

FIG. 1. (Color online) (a) The sketch of the device. Solid gray bars—underlying Al with thin layer of Al_2O_3 on top. White bars—CrO_x top layer which forms the SET island. Two shifted images are the results of Dolan bridge technique. (b) TEM micrograph of the CrO_x film. The dark particles are unoxidized Cr particles, based on lattice images and the clear identification of Cr rings in the diffraction pattern. The white "lacey" structure is due to Fresnel contrast, which occurs due to a difference in inner potential. The image reveals a nanocrystalline Cr film, with 2–10 nm Cr grains surrounded by oxidized grain boundaries that show up white.

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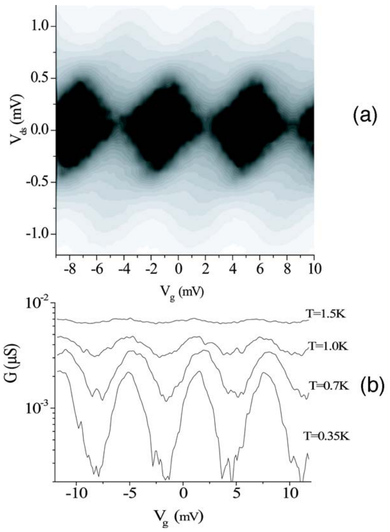

FIG. 2. (Color online) (a) Charging diagram of the device "A" measured at 60 mK. Darker color corresponds to the lower conductance. Note that we use a logarithmic scale to plot a gray scale map. (b) Coulomb blockade oscillations at different temperatures for $V_{\text{ds}}=0$.

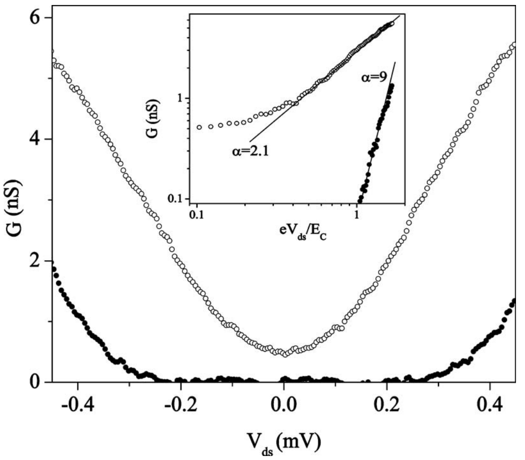

FIG. 3. Differential conductance of the SET dI/dV_{ds} vs V_{ds} in peaks (open circles) and valleys (black dots) of CB oscillations measured at $T=45$ mK. Inset: log-log plot of conductance vs normalized source-drain voltage eV_{ds}/E_C. As a guide for the eye two lines are shown, corresponding to the slopes of the *I-V* characteristic in the peak: $\alpha=2.1$ and in the valley $\alpha=9$.

the structure of the CrO_x using transmission electron microscopy (TEM), the CrO_x is also deposited on a carbon film on a TEM grid, under the same conditions as the actual devices. The electron diffraction pattern contains rings which match the *d* spacings of elemental Cr, plus one strong innermost ring which we attribute to Cr oxide. High-resolution lattice images show that the Cr is nanocrystalline, with grains in the 2–10 nm size range [Fig. 1(b)]. Dark-field images from the Cr diffraction rings and the innermost oxide ring both show particles of similar size. The oxide could therefore be present as either a grain boundary film between metallic Cr grains, as discrete oxide particles mixed with the Cr grains, or both. Thus the TEM analysis confirms the granular structure of the film and the incorporation of oxygen.

The differential conductance of the devices measured immediately after the evaporation is $G\approx 0.6-0.8\ \mu\text{S}$. Our measurements of bare CrO_x strips show that oxidation of the film continues after deposition but it saturates after a few days with a total conductance drop of about 10%–15% from its initial value. However, in the devices reported here the conductance drops by an order of magnitude after 2 days of storage and did not noticeably change after that (for a period over 60 days). We therefore believe that the change in total *G* is caused primarily by continuing oxidation at the junction interface and is not related to the changes in the film forming the island. Measurements of the devices are performed in a range of temperatures down to 30 mK using a dilution refrigerator. Differential conductance is measured using a lock-in technique with excitation voltages $\sim 20\ \mu\text{V}$ at 1.3 Hz. To suppress the superconductivity of Al a magnetic field of 1 T is applied.

All six tested devices show Coulomb blockade oscillations [Fig. 2(a)] at low temperatures ($T<1.5$ K) with a characteristic period and charging energy typical to that of Al/AlO_x SETs with similar geometry of electrodes. However, in our devices the conductance in the peaks of the Coulomb blockade is a strong function of temperature [Fig. 2(b)] and applied source-drain bias V_{ds} (Fig. 3). These characteristics are similar to that of the devices studied in Refs. 5–7. Unlike Al/AlO_x SETs, where the conductance is defined by the junctions and is almost temperature independent, due to the granulated metal film in our device the conductance changes by several orders of magnitude for *T* in the range of 77–0.05 K. The observed temperature dependence of the film below 10 K as previously reported[7] can be fitted using a variable-range hopping law:[9] $\ln G\sim -(T_0/T)^{1/2}$ commonly observed in granulated metal films.

Strong temperature dependence in our device correlates with a strong nonlinearity in the peaks of CBOs, where the Coulomb blockade is lifted. The plot of differential conductance as a function of applied source-drain bias measured in the peaks and valleys of CBOs at 60 mK is shown in Fig. 3. In the peaks the *I-V* characteristic follows a power law $I\sim V^{\alpha}$, where $\alpha\approx 2$, while in the blockade region the slope of the *I-V* curve close to the threshold of Coulomb blockade ($eV_{\text{ds}}\sim E_C$) reveals $\alpha\approx 9$, indicating a significant suppression of the cotunneling. We need to note that the value of dI/dV_{ds} below threshold is so small that the signal to noise ratio quickly becomes less than unity. This narrows the region of source-drain biases where the power law dependence could be analyzed.

The scanning tunneling microscopy studies of the SET island film indicate that it is composed of small metallic Cr granules with typical size <10 nm mixed with the oxide. Therefore we suggest that this film can be represented by a network of metallic dots interconnected by an oxide. Due to the unavoidable presence of random offset charges in the oxide, the thresholds of Coulomb blockade are randomly shifted from granule to granule.[10] Since the size of the granules varies, it broadens the distribution of charging energies in the array which in turn further reduces the Coulomb gap in the density of states.[9] Thus a film forming the island can be viewed as a frustrated array of metal dots[10] with a significantly reduced Coulomb charging energy. The value of the "dynamic" activation energy extracted from the temperature dependence of conductance in the peaks of CBOs ($0.5<T<0.1$ K), is indeed small, $\Delta E_A\approx 15\ \mu\text{eV}$. This suggests that despite the high resistance of the film an electron is not strongly localized, since $\Delta E_A/kT\leqslant 1$ in this range of temperatures and the motion of an electron within the island could be treated as quasicontinuous.[10] The value of the charging energy of the SET, $E_C^{\mathrm{SET}} \approx 0.27$ meV, exceeds the activation energy within the film, ΔE_A, by more than one order of magnitude. Therefore with respect to the external gate the granulated film island acts as a good metal and CBOs are completely defined by the larger scale parameter, $E_C^{\mathrm{SET}} \gg \Delta E_A$. The charging in the frustrated array is expected to be insensitive to the external gate.[10] This agrees well with the fact that CBOs observed in all studied SETs show a single frequency periodic pattern and do not reveal any beating patterns typical of multiple-dot systems, ruling out the formation of internal "dots" within the island as a cause for observed CBOs.

The detailed theory of cotunneling reduction in our device requires further investigation. Nevertheless, the underlying physics is likely to be similar to the lithographically defined magnetic tunnel junctions (MTJs): the presence of media which can be treated as a network of tunnel junctions hampers the cotunneling. The details of the transport mechanism through a SET with a granulated metal island may perhaps better be explained by a recently proposed mechanism of "multiple cotunneling"[11] which can be responsible for electron transport in granulated films at low temperatures. We must note that the theory[3] cannot be directly applied to our case because it was developed for Ohmic resistors where the electron transport mechanism is diffusive.

Thus we demonstrate that a single-electron transistor equipped with a highly resistive granulated film island shows significant suppression of cotunneling. By using the granulated film instead of lithographically fabricated MTJs one can eliminate the need to compensate the background charges for each island of the MTJ.[2]

The increase of the film conductance with an applied electric field observed in the peaks is potentially very useful in applications because it would allow fast electron transit time through the resistive island (when high bias is applied) and at the same time prevent electron escape for smaller biases (e.g., this behavior is very desirable for clocked QCA employing single-electron latches[12]). In contrast with the previously studied devices,[5–7] in our device the SET island itself acts as a cotunneling suppressor while the parameters of the Coulomb blockade which govern transport through the device are set by the well-defined Al/AlO$_x$ junctions. Other possible applications include single-electron pumps and memories.

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