Effect of High-Frequency Electrodynamic Environment on the Single-Electron Tunneling in Ultrasmall Junctions

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Single-electron tunneling in $Al/Al_xO_y/Al$ junctions with areas below 0.01 μm^2 was studied at temperatures close to 1 K. The junctions, placed in different high-frequency environments but similar in all other aspects, exhibited different dc *I-V* curves, in accordance with the theory of correlated single-electron tunneling. Our results imply that a tunneling electron can effectively probe its electrodynamic environment at distances much larger than $c\tau_t$, where τ_t is the "traversal" time of its passage through the energy barrier.

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For many years, the Josephson junction was the sole evident example of a physical object whose dc properties were influenced considerably by its high-frequency electrodynamic environment, characterized by the impedance $Z_e(\omega)$ seen by the Josephson oscillations.

Recently, other objects, normal-metal tunnel junctions with ultrasmall areas, have been found to exhibit similar behavior. The capacitance C of such a junction is so small that its charging energy $E_c = e^2/2C$ due to tunneling of a single electron is larger than that (k_BT) of thermal fluctuations. As a result of charging effects, a considerable correlation of the tunneling events (either in time, or in space, or both) can arise in such junctions.[1,2] As for the Josephson junctions, this correlation makes the dc current through the junction dependent of values of $Z_e(\omega)$ at high frequencies [see Eq. (1) below].

Recent experiments with double tunnel junctions[3-7] and multijunction arrays[8,9] have shown a fair agreement with the "orthodox" theory of the correlated single-electron tunneling,[1,2] which uses the simplest models for $Z_e(\omega)$. The reason is that the dynamics of a multijunction structure is determined mainly by the impedance seen by its *internal* junctions, which is dominated by the well-characterized impedance of the surrounding junctions rather than that of the environment of the structure as a whole. On the contrary, experiments with single junctions[10,11] yield more ambiguous results, presumably because their dynamics are highly dependent of $Z_e(\omega)$ which is determined by a specific configuration of the junction and its current leads.

In the present work we have been able to observe clearly an influence of the environment impedance on the dc transport in ultrasmall tunnel junctions. We studied nominally identical tunnel junctions, $Al/Al_xO_y/Al$ with areas S close to 0.006 μm^2, only ~ 10 μm apart, but embedded into different electrodynamic environments (Fig. 1). One of the junctions (referred to as "solitary" in Fig. 1) was formed between two thin-film strips of initial width ~ 80 nm which were widened stepwise toward the contact pads. Another single junction was located in the middle of a 25-junction four-branch array (Fig. 1); for *I-V* measurements we used the array branches as parts of the current and voltage leads in a standard four-terminal method.

Our fabrication technique followed that by Dolan.[12] First, a desirable pattern was exposed by an e beam on a two-layer resist, spun on a Si wafer, giving an undercut mask. The structure was then formed by a thermal evaporation of two ~ 20-nm-thick aluminum layers from two different angles. Overlaps of the layers determined the tunnel junctions; tunnel barriers were formed after the first evaporation in 0.05 mbar of pure oxygen for 10 min at room temperature.

Measurements were performed at $T \approx 1.3$ K by immersing samples into pumped liquid helium. A few samples were cooled below the superconducting transition temperature, $T_c \approx 1.2$ K, in order to confirm a high quality of the junctions by observing a clear superconducting gap structure. The electronic circuit was designed in a symmetric way in order to minimize the pick up of interferences. Instrumentation amplifiers with

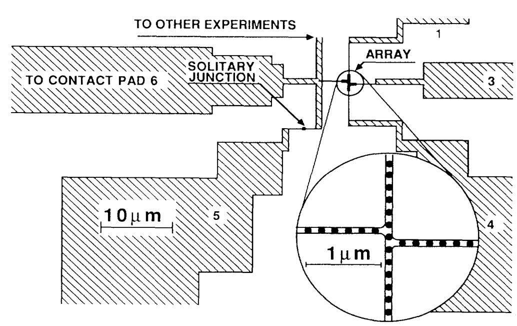

FIG. 1. Configuration of our thin-film structure. The schematically shown array region is blown up. A region which yields the largest contribution to the capacitance C_L between the solitary junction leads is marked gray.

input impedances much larger than the resistance of the arrays were employed to record both voltages and currents. Except the dc *I-V* curves, their derivatives dI/dV were measured using a standard modulation technique with two lock-in amplifiers. The modulation frequency (171 Hz) was chosen well below the *RC* cutoff frequency (~560 Hz) determined by the stray capacitances of the measuring wires and the worst-case differential resistance for the arrays.

Figure 2(a) shows dc *I-V* curves for various branches of one of our arrays. One can see that the variation of the asymptotic resistances does not exceed 20%. Figure 2(b) shows I and dI/dV of the middle junction of the array as functions of dc voltage. The dc *I-V* curve is almost similar to that of the array as a whole, with a proportional decrease of the voltage scale. Both curves exhibit a considerable suppression of the tunnel current (the so-called Coulomb blockade of tunneling, in our case somewhat smeared by thermal fluctuations) at small voltages, and an offset of the linear asymptotes of the curves by $2V_{\mathrm{off}}$ at large voltages; these features are very typical for single-electron charging effects.[1-11] By switching the voltage and current leads, the current path in the array could be changed in four different ways reproducing exactly the same *I-V* curve. This indicates that the resistances in the voltage leads do not affect the measurement.

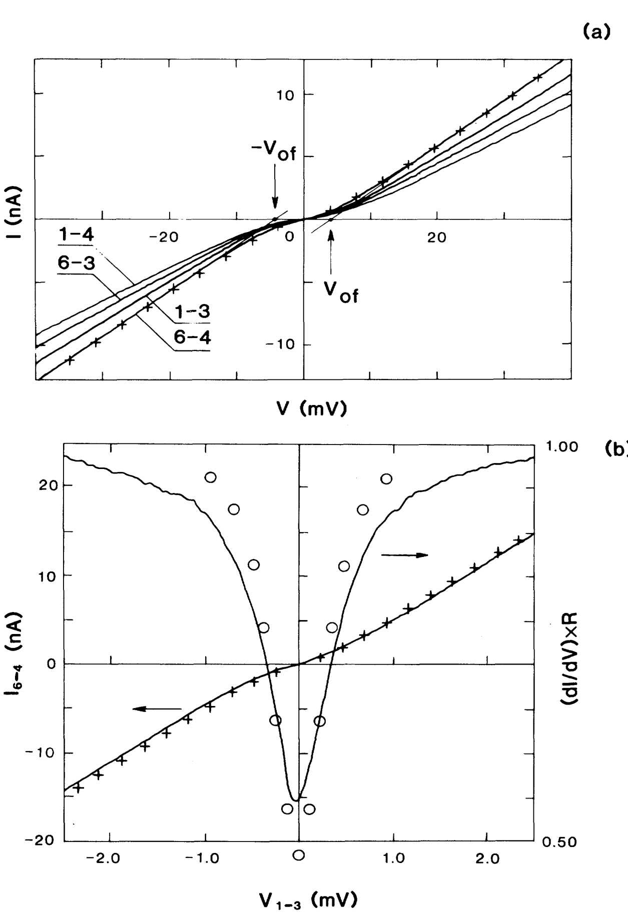

FIG. 2. *I-V* and dI/dV vs V for (a) various branches of the 2D array and (b) the middle junction of the array. Indices show numbers of the contact pads. Solid lines: experimental curves. Thin lines: asymptotes of one of the *I-V* curves, showing definition of the offset voltage. Crosses and circles: results of a numerical simulation (Ref. 13) of the dynamics of the thirteen-junction 1D array with parameters: $C_i = 2.0 \times 10^{-16}$ F, $R_i = 212$ kΩ (for $i = 7$), $C_7 = 2.8 \times 10^{-16}$ F, $R_7 = 150$ kΩ; $(C_0)_i = 0.2 \times 10^{-16}$ F (for $i \neq 6,7$), $(C_0)_6 = (C_0)_7 = 0.6 \times 10^{-16}$ F, $T = 1.31$ K.

We have found that the *I-V* curves shown in Fig. 2 can be well described by the theory[13] of correlated tunneling in a *one-dimensional* thirteen-junction array. Such an effective 1D array corresponds to the current-carrying part of the real array, small 2D effects produced by the voltage-lead branches can be well described by small additional capacitances of the middle junction electrodes. Note that the theoretical curves shown in Fig. 2 have been calculated without free fitting parameters: We only used experimental values of the asymptotic resistances of the array as a whole (2.7 MΩ) and of the middle junction (0.15 MΩ), of the offset voltage (4.0 mV) of the array as a whole (but not that of the middle junction), the calculated value (2×10^{-17} F) of the stray capacitance of the junction electrodes, and an assumption of the constant specific conductance $g = 1/RS$ of the tunnel barriers. (The last assumption is based on a virtual constancy of the ratio $V_{\mathrm{off}}/R \propto g^1 S^0$ for the various branches of the array; see Fig. 2.)

One can see that even without any fitting parameters the agreement between theory and experiment is quite satisfactory (the junction capacitance $C = 2.0 \times 10^{-16}$ F implied by the calculations is also close to the value following from the independently estimated area S). Moreover, the *I-V* curve of the single junction [Fig. 2(b)] is close to that given by the orthodox theory[2,3] with the simplest assumption of a fixed bias current, because the resistances of the array branches are much larger than that of the junction.

The properties of the solitary junction are rather different. Figure 3 shows the dc *I-V* curve of such a junction fabricated together with those presented in Fig. 2. One can see that the curve is virtually linear, with only a minor (6%) dip of the conductance near the origin, so that the offset of the asymptotes is very small: $V_{\mathrm{off}} = 27 \pm 3$ μV.

The recent results obtained by Nazarov[14] enable one, in principle, to calculate corrections to the linear *I-V* curve due to an arbitrary electrodynamic environment with $|Z_e(\omega)| \ll R$ (this condition is well fulfilled for the solitary junction). As a first approximation to estimate $Z_e(\omega)$, one can use a suggestion by Büttiker and Landauer[15] that the tunneling electron can probe the envi-

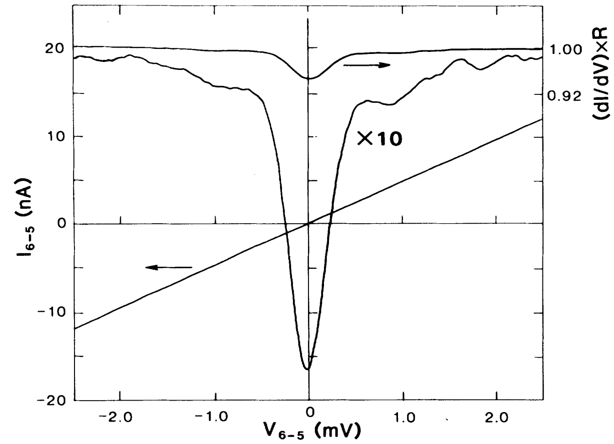

FIG. 3. dc current and differential conductance vs dc voltage for the solitary junction of the same sample and at the same temperature as in Fig. 2. The magnified curve for the conductance is offset vertically to approach the same horizontal asymptote at large voltages as the original curve.

ronment at distances $r < r_t = c\tau_t$, where τ_t is the "traversal" time of the electron passage through the energy barrier. For our native aluminum-oxide barriers, τ_t can be estimated to be less than at least 10^{-14} s, so that one obtains the relation $r_t < 1$ μm, taking the dielectric constant of the substrate into account. Using experimental parameters and standard formulas, it is straightforward to show that at small distances and high frequencies, the solitary junction leads can be considered as semi-infinite *LRC* transmission lines with the specific inductance close to 6×10^{-13} H/μm, specific series resistance below 10 Ω/μm (for $T \approx 1$ K), and specific capacitance of order 10^{-16} F/μm. In this case, $Z_e(\omega)$ should be almost exactly real and close to 150 Ω. With these parameters and our values of temperature and junction capacitance, we calculate[16] a voltage offset as large as that for the junction inside the array (≈ 400 μV), and a very wide $\sim$10-mV conductance dip, in clear contradiction with the data (Fig. 3).

This conclusion cannot be changed by a slight modification of the theory. The whole body of the data accumulated in the field[1,2] gives a firm support to the basic relation $V_{\text{off}} = e/2(C+C_L)$, where C_L is the effective capacitance between the junction leads. In order to describe the observed behavior of the single junction, we would need a value $C_L \sim 3\times10^{-15}$ F which is far beyond that available on the scale of r_t.

This result is not quite surprising. A general expression for the tunnel current[14] implies that the most important contribution to its dc component comes from $Z_e(\omega)$ at much lower frequencies than corresponding to τ_t,

$$h\omega \sim \Delta E \approx \max(eV, k_B T) . \qquad (1)$$

This expression is a manifestation of the quantum nature of the tunneling process. In fact, according to the uncertainty relation, an electron crossing the tunnel barrier in order to eventually gain an energy difference ΔE, should spend a time period Δt not less than $h/\Delta E$, "probing" whether the difference really does exist. The electromagnetic field created by virtual tunneling events during this period spreads to distances up to $ch/\Delta E$. If the field has a considerable back action on the tunneling electron, the tunneling probability will depend on the electrodynamic environment at distances up to $ch/\Delta E$.

For experiments such as ours, the latter distance is much larger than $r_t = c\tau_t$; note, however, that it is the case only if $\Delta E \tau_t \ll h$. In the opposite limit, the relativistic radius is determined by the largest time period which now is essentially the traversal time τ_t. Thus, our result does not contradict that obtained for the macroscopic quantum tunneling in systems with delayed friction.[17,18] There, ΔE is much larger than the barrier height and the environment is probed at distances of order $c\tau_B$, where τ_B is the "bounce" time which coincides with τ_t (in the limit of low friction).

Returning to Fig. 3, for our voltage and temperature scales, Eq. (1) yields $\omega \sim 10^{12}$ s^{-1}, so that the corresponding relativistic radius is of order 300 μm. On this scale, $Z_e(\omega)$ can be crudely approximated as $(G_e + i\omega \times C_L)^{-1}$, where the capacitance $C_L = 3\times10^{-15}$ F is determined mainly by the region marked gray in Fig. 1 and the active conductance, $G_e \approx (100\,\Omega)^{-1}$, by the radiation leakage along the extrapolated current leads. With these figures, the theory[16] yields V_{off} close to the experimental value, and the width ΔV of the conductance dip only a factor of 2 larger than the experimental one. In spite of this reasonable agreement, we believe that the observed suppression of the conductance of the solitary junction and a quasiperiodic structure distinguishable on the wings of the dI/dV vs V curve at large magnification (Fig. 3) are mainly due to single-electron charging of small conducting embedments inside its tunnel barrier rather than of the junction electrodes themselves.[6,11] Three different solitary junctions could be measured. All showed a very small V_{off} and a small conductance dip. The smallest values were those of Fig. 3; the other two gave approximately 2 times larger V_{off}. The quasiperiodic wing structure was more pronounced for a larger V_{off}. The quasiperiodic structure shifted between different cooldowns of the same sample, presumably due to varying charge distributions on the "traps." All these observations support our hypothesis of tunneling via inclusions adding to the total tunnel current although other contributions, such as scattering against magnetic impurities, cannot be completely ruled out. This ambiguity, however, does not concern the main observation of this work, the smallness of the offset voltage V_{off} of the solitary junction, because the "internal" charging (or other) effects could only increase V_{off}.

In conclusion, we have observed a strong effect of the high-frequency electrodynamic environment on the dc I-V curves of ultrasmall tunnel junctions. Junctions placed into a highly resistive environment can be quantitatively described by using the orthodox theory of correlated tunneling.[1,2] Observed properties of the solitary junctions, seeing much lower impedance of their current leads, give a strong evidence against a suggestion[15] that the space region sensed by a tunneling electron is limited by the traversal time of its passage through the energy barrier.

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