Observation of one-electron Coulomb effects in end-type tunnel junctions

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A shift of asymptotes and periodic oscillations characteristic of the correlated one-electron tunneling through an intermediate electrode have been observed on the current-voltage characteristics of end-type tunnel junctions of submicron area ($S = 0.01$–$3\ \mu m^2$). Some possible mechanisms for this behavior are discussed briefly.

A new theory for the processes that occur in tunnel junctions of small dimensions (Refs. 1 and 10, for example) predicts many new one-electron effects: a Coulomb blocking of tunneling at low voltages, coherent one-electron oscillations, a sensitivity of a tunneling current to subelectron changes in electric charge, etc. So far, the theoretical predictions have been reliably confirmed only for double tunnel junctions,[2-4] although changes of the Coulomb-blocking type have been observed on the current-voltage characteristics of single junctions.[5,6] Our purpose in the present study was to determine whether it is possible to observe one-electron Coulomb effects in single tunnel junctions of very small area.

For this purpose we fabricated some end-type tunnel junctions of both "small" area ($S = 0.014$–$0.06\ \mu m^2$) and "large" area ($S = 0.7$–$3\ \mu m^2$). These areas were determined by the product of the thickness of the lower Al or NbN electrode ($h = 7$–30 nm) and the width of the upper PbSb electrode ($W = 2$–$3\ \mu m$ or $100\ \mu m$). The lower electrode was formed either by dry etching in an rf discharge (in the case of Al) or by explosive lithography with oxidation in an rf discharge (for the NbN). Comparing the conditions under which the tunnel junction was formed and also its resistance with published data,[6] we find the estimate $d \approx 20$ Å for the barrier thickness.

At liquid-helium temperatures, the current-voltage characteristics of both the small junctions (Fig. 1a) and the large junctions (Fig. 1b) have a typical asymptote shift $2V_t$ which ranges in magnitude from a few millivolts to tens of millivolts. In addition, on the current-voltage characteristics of the small junctions we frequently saw pronounced sinusoidal oscillations with a voltage step ΔV on the order of 5–20 mV (Figs. 1a and 2a). On the large junctions, the voltage oscillations of this type were not always seen, and they usually decayed rapidly with increasing V (Fig. 1b).

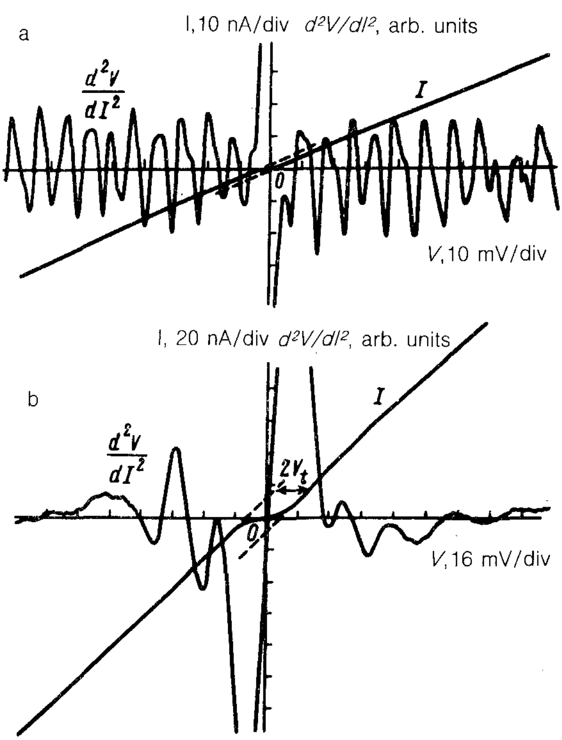

FIG. 1. Current-voltage characteristics of end-type Al–Al_2O_3–PbSb tunnel junctions with areas of (a) $S = 0.06\ \mu m^2$ and (b) $S = 2\ \mu m^2$; their second derivatives at $T = 4.2$ K.

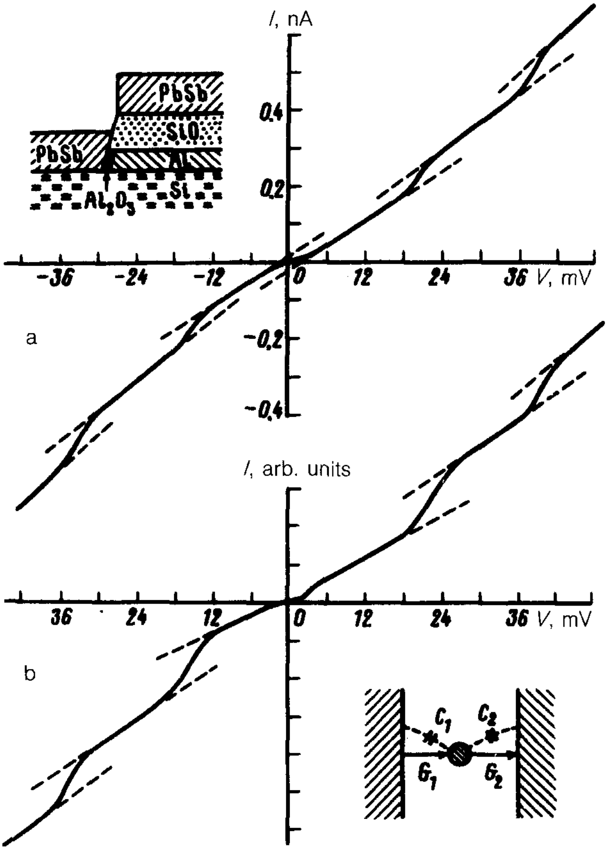

FIG. 2. a—Current-voltage characteristics of an Al–Al_2O_3–PbSb end-type tunnel junction with an area $S = 0.06$ μm^2; b—theoretical current-voltage characteristic for the model of a correlated one-electron tunneling through a double junction with parameter values $C_1 = C_2 = 2\times 10^{-17}$ F, $R_2 = 0.05$ R_1, $T = 4.2$ K, and $Q_0 = 0.35e$.

After the application of a voltage pulse to the junction, or after the junction was temporarily heated to room temperature, the entire periodic structure sometimes shifted along the voltage scale in one direction, by an amount equal to a small fraction of a period.

Several explanations for these effects could be advanced: 1) First, there is the possibility of a Coulomb blocking of tunneling due to the capacitance of the tunnel junction itself.[1] This hypothesis,[5] however, leads to values of $2V_t$ which are considerably smaller (by at least an order of magnitude) than that seen experimentally. Furthermore, this hypothesis fails to explain the oscillations observed on the current-voltage curves. 2) Another possibility is a one-electron correlated tunneling through an individual metallic inclusion at the tunnel barrier. The theoretical current-voltage characteristics which follow from this model[1] (Fig. 2b) agree quite well with the experimental characteristics. The shifts of the periodic structure which are observed can also be explained in the theory of small ($|\Delta Q| \ll e$) changes in the charge induced at an inclusion by charged impurities in the tunnel barrier, as a result of their diffusion. The experimental curves differ from the theoretical curves in that the oscillation period which spans the origin of coordinates is slightly longer than the others. Furthermore, after each jump there is some increase in the differential conductivity of the junction (Fig. 2a). The latter difference might be explained on the basis of a suppression of the tunnel barrier for direct tunneling of electrons in regions adjacent to a metallic inclusion when there is a change in its charge. Admittedly, the estimate of the dimensions of the inclusion ($D \geqslant 10$ nm), which follows from an estimate of the capacitance C_1 from the oscillation period and the tabulated value $\varepsilon \approx 10$, does not agree well with the estimate of the oxide thickness given above.

Despite this contradiction, other explanations of effects of this sort[7,8] clearly do not apply to our junctions. Analyzing the results as a whole, we conclude that the observed effects stem from some version of the one-electron Coulomb effects. A similar shift of the $2V_t$ asymptotes has been observed by several other investigators.[5,6] It may also be due to a tunneling through inclusions at the barrier. Furthermore, periodic structural features on the current-voltage characteristic similar to those described here have been observed by the present authors[9] and also by other authors (see the bibliography in Ref. 6) at point contacts of the tunneling type with high-temperature superconductors. In several cases, these structural features have been interpreted as a consequence of a complex gap structure of these materials. In light of the results presented here, this interpretation does not seem adequate.

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