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ON THE WORK OF SINGLE-ELECTRON TRANSISTORS

The effect of the Coulomb blockade in a single-electron transistor, a device where Fermi-liquid leads are mediated by a quantum dot, plays an essential role in condensed matter physics, mesoscopics, and open quantum systems. The Coulomb spectroscopy and transport through a quantum dot are sensitive to the precise nature of the nonequilibrium steady state, the mechanisms of relaxation, electronic interactions, and topological order [1]. The “orthodox” theory of the Coulomb blockade is based on rate equations formulated in the basis of different charged states in the island [2]. Such states are well defined for almost isolated quantum dots which have weak tunnel coupling to the leads, i.e., with a small dimensionless conductance. In this theory, the distribution function in the island is not affected by the coupling to contacts; i.e., the internal relaxation in the island is assumed to prevail on the characteristic tunneling time scale.

The elementary tunnel design schematically represents a kind of sandwich: a massive gold film (emitter) with a deposited dielectric; islands of monatomic height (disc-shaped clusters) [3] or spherical-like gold clusters [4] are formed on the dielectric film; a tunneling microscope tip (STM), also coated with gold, was used as the third electrode (collector). Measured $I-V$ characteristics have a plateau of the zero current (a current gap).

In the limit of weak tunnelling, the probability P_n of detecting “on average” n excess electrons on the island determined by the master equation in the stationary limit. The current flowing through the quantum island (with a limitation on the Coulomb instability [2]) was defined as

$$I = -e \sum_{n_{\min}}^{n_{\max}} P_n (\overrightarrow{\omega}_n - \overleftarrow{\omega}_n) \quad (1)$$

where $\overrightarrow{\omega}_n$ are the electron flows to the island from left to right and from right to left.

In this work, in comparison with [1], the dependence of the tunnel rate

$$\Gamma(d_c) = \Gamma_0 \exp\left(-\frac{2d_c \sqrt{2mW}}{\hbar}\right) \quad (2)$$

on the island-collector distance (d_c) is taken into account for calculating the reduced current $\tilde{I} \equiv I / (eP_0\Gamma_0)$; W is the work function of electrons from gold. In this manner we have restored the correct dependence $I(V, d_c)$ missed in our previous article [2].

The width of the current gap ΔV_{is} is determined by the threshold voltages V_{0+} / V_{0-} from the condition of equality of zero collector current on the forward/reverse branches of the I - V characteristic. In the low-temperature limit ($k_B T_{eff} \ll \Delta \varepsilon_F$) for the current gap of almost isolated island (weak coupling) an analytical expression is obtained,

$$\Delta V_{is} = V_{0+} - |V_{0-}|, |V_{0\pm}| = \frac{1}{2 - \eta^\pm(d_c)} \left(\frac{1}{2e} \tilde{E}_c + \frac{1}{e} \Delta \varepsilon \right) \quad (3)$$

where $\eta^\pm(d_c)$ are the fractions of the voltage, $\tilde{E}_c$ is the Coulomb charging energy of island, and $\Delta \varepsilon \equiv \varepsilon^{\text{HO}} - \mu_{is} \geq 0$. Here ε^{HO} and μ_{is} are highest occupied electron level and the chemical potential of electrons in the island, respectively.

For the case of “strong quantization” the size of the current gap for non-magic clusters is equal to zero explicitly, because the emitter Fermi level is in line with the closed levels in the cluster. In this regime, the expression (2) describes the experimental values well.

In the experiment [4] for the structure based on the magic disk with a radius of $R \cong 22 a_0$ a feature was discovered: the current gap varies as $0.8 \rightarrow 0.4 \rightarrow 0.7$ V for cyclic variation of $d_c \cong 2 \rightarrow 4 \rightarrow 2 a_0$, respectively. Such small values of d_c , smaller than the radius of a gold atom, indicate that this situation is associated with a strong tunneling coupling regime between the island and the collector. This leads to the fact that the values of $\tilde{E}_c$ and $\eta^\pm(d_c)$ become indefinite from the point of view of electrostatics. In this regard, formula (3) becomes inapplicable to this case.

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