Effect of resonant tunneling and Coulomb repulsion of electrons in localized states on the current-voltage characteristics of NIN, SIN, and SIS tunnel structures

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The effect of strong ($U \gg T$, eV) Coulomb repulsion of electrons in localized states in the insulator on the properties of SIS, SIN, and NIN tunnel structures is investigated within the Anderson model. The energy distribution of the localized states is assumed to be uniform and their spatial distribution is assumed to be both uniform and concentrated in a plane parallel to the boundaries of the structure. It is shown that even in NIN junctions with $U \neq 0$ the current-voltage characteristic is observed to be asymmetric and features are observed in the differential conductance for $eV \ll T$ and the current deficiency I_d or current excess I_e—depending on T and the position of the plane containing the localized states with respect to the boundaries of the structure—is observed in the current-voltage characteristic for eV$\gg T$. In SIN junctions these effects are even more pronounced. Moreover, a transition can occur in them from current deficiency ($I_d \propto \Delta(T)$ for $T \ll T_c$) to current excess ($I_e \propto T$ for $T \approx T_c$) in the current-voltage characteristic with increasing temperature; this transition is caused by the competition between the two physical mechanisms responsible for I_d and $I_e \propto T$ in SIN and NIN junctions, respectively. The results agree with the experimental data obtained in SIN tunnel junctions with high-T_c superconducting electrodes and in the study of the superconductor/semiconductor interface. It is concluded that the regions of localized states in the inteface can be determined by analyzing the features in the current-voltage characteristics of the junctions.

Analysis of the experimental data obtained with high-T_c superconducting tunnel structures, such as superconductor-insulator-superconductor (SIS) and superconductor-insulator-metal (SIN),[1–5] Josephson junctions with a semiconductor interface and superconductor/semiconductor interfaces,[6–13] as well as during surface analysis of superconducting materials using scanning tunneling microscopy (see, for example, Ref. 14) show that even though the objects studied are undoubtedly different physically, they all share certain behavioral characteristics. Thus, for example, a voltage-independent current deficit $\delta I = I - V/R_n$ (or excess voltage $\delta V = \delta I R_n$) is virtually always observed in their current-voltage characteristics at high voltages V. It is important to note that the current deficit observed in structures with two superconducting electrodes ($\delta I_{\rm SIS}$) differs by a factor of 2 from the current deficit observed in structures with a single superconducting electrode ($\delta I_{\rm SIN}$): $\delta I_{\rm SIS} \approx 2\delta I_{\rm SIN}$.[13] It can thus be concluded that the reason for the appearance of δI should be sought in the behavior accompanying the act of tunneling through a separate tunnel barrier, rather than by studying the more complicated nonequilibrium processes occurring in SINIS junctions. From our standpoint, these features are that resonant tunneling predominates over direct tunneling and that quasiparticles in localized states in the tunnel interface are subject to strong Coulomb repulsion. It will be shown below that when this repulsion is taken into account, the tunneling current becomes a nonlinear function of the population of the localized states, which determines a number of deviations in the current-voltage characteristics (IVCs) from Ohm's law, even in structures with normal electrodes (NIN).

There now exist several approaches to solving the problem of the effect of resonant tunneling on the properties of tunnel structures (see, for example, Raich and Ruzin's review in Ref. 15). In each of these approaches, at the final stage of the calculations the expressions for the current were averaged over the positions of the localized centers. When the thickness $2L$ of the insulator was large, this averaging was performed using the probability distribution of the Lifshitz percolation trajectories.[16,17] In this model it was shown that the current-voltage characteristic of SIS structures at high voltages must have an excess or deficiency, depending on whether the width Γ of the resonance zone exceeds the order parameter of the S electrodes Δ or $\Gamma \ll \Delta$, respectively.

For small L the fact that all centers are uniformly distributed in the insulator was taken into account.[18,19] In the latter case it was shown that when the Coulomb repulsion of the electrons in localized states is neglected, the current-voltage characteristic of the NIN tunnel structures has the form of Ohm's law, and if two or more localization centers are present on the resonance trajectory, the junction resistance is temperature dependent. In the case of SIN junctions, even the presence of a single center on the resonance trajectory results in significant distortion of the IVC as compared to the standard tunneling theory,[20] e.g., the appearance of a current deficit at high voltages.

It should be noted, however, that the assumption that the localized centers are distributed uniformly in the insu-

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lator is inconsistent with the real physical situation, at least in several cases of importance for practical applications:

—ultrasmall tunnel junctions (the transverse cross-sectional are $\leqslant 40\times 40$ nm); such junctions are of interest in connection with the development of single-electron electronics;

—metal (superconductor)/semiconductor interface; due to the formation of a Schottky barrier on the interface, the transport properties of the interface are close to those of SIN structures with localized centers, concentrated near the boundaries of this barrier; detailed experimental investigation of such interfaces is the first step in producing three-terminal Josephson structures; and,

—surface analysis of materials with the help of a scanning tunneling electron microscope; in such analysis the vacuum or gas interface plays the role of the insulator, and the possible localized states are concentrated either on the surface being studied (the energy levels of defects or adsorbed molecules) or in the oxide layer on the surface of the whisker.

Moreover, as will be shown below, even when localization centers are distributed uniformly, taking into account the Coulomb repulsion of the electrons in the localized states results in the appearance of features on the IVCs that result in deviation from Ohm's law. The effect of Coulomb repulsion on the IVC of different types of tunnel structures has not been previously studied systematically.

The object of the present work is to investigate the detailed structure of the current-voltage characteristics of NIN, SIN, and SIS tunnel structures with both uniform and nonuniform distribution of resonance centers in the insulator, taking into account Coulomb repulsion of the electrons localized on these centers.

1. MODEL OF THE CONTACT

We assume that the junction conductance determined by direct tunneling of electrons is quite low, so that when localized states are present in the interface, the direct tunneling of electrons can be neglected and the processes occurring can be described by a Hamiltonian analogous to the Anderson Hamiltonian:[20,21]

$$H=H_l+H_r+H_t+H_c, \tag{1}$$

where H_c takes into account the Coulomb repulsion of the electrons in localized states

$$H_c=\sum_{\sigma}[\varepsilon_\sigma d_\sigma^+ d_\sigma+U d_\sigma^+ d_\sigma d_{-\sigma}^+ d_{-\sigma}]. \tag{2}$$

The terms H_t and $H_{l,r}$ describe electron tunneling through a localized state:

$$H_t=\sum_{k,\sigma} T_k a_{k,\sigma}^+ d_\sigma+\sum_{p,\sigma} T_p b_{p,\sigma}^+ d_\sigma+\text{h.c.} \tag{3}$$

and the state of electrons in the electrodes

$$H_{l,r}=\sum_{k,\sigma}\varepsilon_{k,\sigma} c_{k,\sigma}^+ c_{k,\sigma}+\sum_{k}(\Delta c_{k,\sigma}^+ c_{-k,-\sigma}^+ +\text{h.c.}). \tag{4}$$

Here d_σ^+, $a_{p\sigma}^+$, and $b_{p\sigma}^+$ are creation operators for electrons with momentum p and spin projection σ in a localized state and in the left- and right-hand electrodes, respectively; T_k and T_p are constants characterizing the hybridization of the localized state with the electrodes; ε_σ and $\varepsilon_{k,\sigma}$ are the electron energy at the impurity and in the electrodes; U is the Coulomb repulsion energy of the electrons at an impurity; and Δ is the order parameter of the electrodes. The creation operators $c_{k,\sigma}^+$ in Eq. (4) are equal to $a_{k,\sigma}^+$ or $b_{k,\sigma}^+$ for the Hamiltonians of the left-hand H_l and right-hand H_r electrodes, respectively.

Below we confine our attention to the case, important in practical applications, when the width Γ of the impurity level is small:

$$\Gamma=\Gamma_l+\Gamma_r\ll T,\quad \Gamma_{l,r}=\pi N_{l,r}\langle T_{n,p}^2\rangle$$
$$=\pi N_{l,r}T_0^2\exp\{\pm 2\varkappa z\}, \tag{5}$$

where T is the temperature; T_0^2 is the squared hybridization matrix element, averaged over the Fermi surface, with symmetrically arranged localized states; $\varkappa=(2m\varepsilon/\hbar^2)^{1/2}$ is the inverse radius of a localized state; z is the coordinate measured from the center of the insulator; and $N_{l,r}$ are the densities of states of the electrodes.

When the condition (5) holds, it is easy to derive the kinetic equations for the probability that a localized state is singly or doubly occupied by performing calculations similar to those performed in Refs. 20 and 21. From these equations (in the absence of a magnetic field) we obtain for the tunneling current in the limit $U\gg\{T,eV\}$

$$I=4e(\Gamma_l\Gamma_r/\Gamma)[f(\varepsilon)-f(\varepsilon+eV)]\mathscr{F}(\langle n_\sigma\rangle),$$
$$e=-|e|. \tag{6}$$

Here $f(\varepsilon)$ is the Fermi distribution function and $\langle n_\sigma\rangle=\langle d_\sigma^+ d_\sigma\rangle$ is the average number of electrons in a localized state. The function $\mathscr{F}(\langle n_\sigma\rangle)$ has the following form:

$$\mathscr{F}(\langle n_\sigma\rangle)=\begin{cases}1-\langle n_\sigma\rangle, & \langle n_\sigma\rangle=\nu/(1+\nu), \quad (7a)\\ \langle n_\sigma\rangle, & \langle n_\sigma\rangle=1/(2-\nu), \quad (7b)\end{cases}$$

$$\nu=(\Gamma_l/\Gamma)f(\varepsilon)+(\Gamma_r/\Gamma)f(\varepsilon+eV),$$

depending on whether the energy of a single electron, ε_σ, or two electrons in a localized state, $\varepsilon_\sigma+U$, is close to the Fermi energy ε_F and is identically equal to unity in the absence of Coulomb repulsion of the electrons. It is interesting to note that in the latter case ($U=0$) the equality (6) has a simple physical interpretation. It shows that the total resistance of the junction $R\propto\Gamma^{-1}$ is the sum of two successive resistances $R_l\propto\Gamma_l^{-1}$ and $R_r\propto\Gamma_r^{-1}$, whose magnitude is determined only by the position of the localized state with respect to the boundaries of the insulator. For nonzero values of U these resistances are nonlinear functions of both the voltage and temperature.

In calculating the IVC we assume that the localized states have a uniform energy distribution with constant density g, while the spatial distribution of the localized states can be uniform over either the volume with density $W(z)=W$ or some plane, parallel to the boundaries of the electrodes, located at z_0 inside the insulator, with $W(z)=W_0\delta(z-z_0)$.

In the first case, averaging in the expressions (6) and (7) over energy and the coordinate z results in an expression of the form

$$\langle I\rangle=\frac{2\pi egSWT_0^2}{\hbar\varkappa}\times\int_{-\infty}^{\infty}\frac{\sqrt{N_rN_l}[f(\varepsilon)-f(\varepsilon+eV)]\operatorname{arctg}(\beta)}{\sqrt{P(\varepsilon)P(\varepsilon+eV)}}d\varepsilon,$$

$$\beta=\frac{2\operatorname{sh}(\varkappa L)q^{1/2}}{(1+q)},\quad q=\frac{N_lP(\varepsilon)}{N_rP(\varepsilon+eV)},$$

$$P(\varepsilon)=\begin{cases}[1+f(\varepsilon)], & \varepsilon_0\approx\varepsilon_F,\\ [2-f(\varepsilon)], & \varepsilon_0\approx\varepsilon_F-U,\end{cases}\tag{8}$$

where S is the transverse cross-sectional area of the junction and $2L$ is the thickness of the insulator.

If the barrier transparency is sufficiently low ($\varkappa L\gg1$), then in the integral (8) the integration over the energy range where the value of the arctangent in the expression (8) can differ appreciably from $\pi/2$ makes an exponentially small contribution for both normal and superconducting electrodes, and the expression (8) reduces to the following:

$$\langle I\rangle=\frac{\pi^2egSWT_0^2}{\hbar\varkappa}\int_{-\infty}^{\infty}\frac{\sqrt{N_rN_l}[f(\varepsilon)-f(\varepsilon+eV)]}{\sqrt{P(\varepsilon)P(\varepsilon+eV)}}d\varepsilon.\tag{9}$$

In the second case $[W=W_0\delta(z-z_0)]$ we have from Eqs. (6) and (7)

$$\langle I\rangle=4eW_0Sg\int_{-\infty}^{\infty}\frac{\Gamma_r(z_0)\Gamma_l(z_0)[f(\varepsilon)-f(\varepsilon+eV)]}{\Gamma_l(z_0)P(\varepsilon)+\Gamma_r(z_0)P(\varepsilon+eV)}d\varepsilon.\tag{10}$$

The expressions (9) and (10) open up the possibility of calculating exactly and numerically the IVCs of tunnel structures in a number of particular cases.

The expressions (9) and (10) are valid for NIN, SIN, and SIS structures. In the case of junctions with at least one superconducting side there exists an energy range $\delta\varepsilon\propto\Delta[T_0^2N(0)]^2/T^2$ in a neighborhood of Δ where the inequality (5) is not satisfied because the density of states diverges. The contribution of integration over this energy range to the current (9)–(10) is, however, of the order of $(\delta\varepsilon)^{1/2}$ and can be made negligibly small by decreasing the transparency T_0.

2. METAL–INSULATOR–METAL JUNCTION (NIN)

If both electrodes of the tunnel junction are normal metals with constant density of states $N_{l,r}(0)$ in the vicinity of the Fermi energy, then in the absence of Coulomb repulsion of the electrons in the localized states we can deduce Ohm's law with conductance depending on the position of the plane with the localized states in the first layer from Eqs. (9) and (10). The value of R_n is smallest when the plane $[z_0=0,N_l(0)=N_r(0)]$ is in a symmetric position.

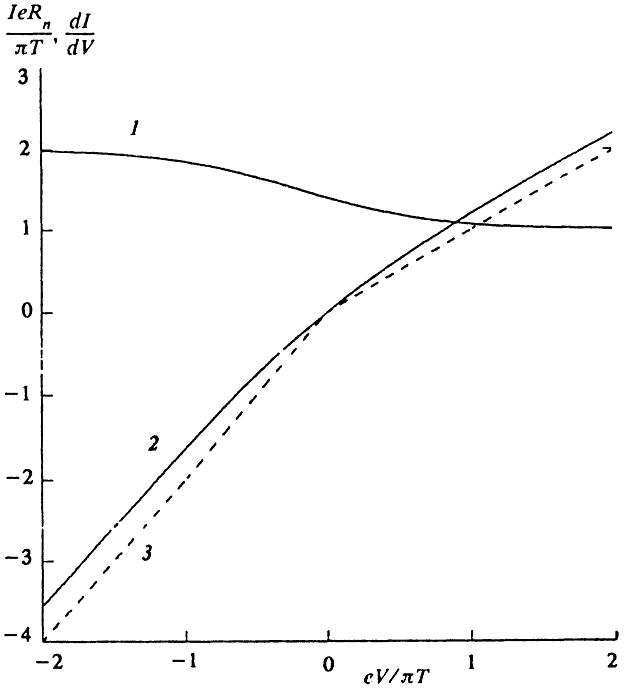

FIG. 1. IVC of NIN junction with localized states distributed in a plane at $z_0=0.9L$ with strong Coulomb interaction in the states: 1—dI/dV, 2—$I(V)$, 3—asymptote corresponding to zero temperature.

This value of $R_n(0)$ is identical to the resistance of a structure in which localized states are uniformly distributed with $W=2\varkappa W_0/\pi$. In the case of an asymmetric arrangement of the impurity plane ($z_0\neq0$), resonant tunneling predominates over direct tunneling as long as

$$|L-|z_0||\gg(2\varkappa)^{-1}\ln(N/gW_0),\tag{11}$$

where N is the density of states of the electrode closest to the plane of localized states.

Deviations from Ohm's law appear when the Coulomb repulsion of the electrons in the localized states is taken into account. In order to calculate the IVC it is sufficient to consider only the case $\varepsilon_\sigma\approx\varepsilon_F$, since for a uniform distribution of localized states over the interior of the insulator

$$\langle I\rangle_{\varepsilon_\sigma\approx\varepsilon_F}=\langle I\rangle_{\varepsilon_\sigma\approx\varepsilon_F-U}\tag{12}$$

and in the plane with the coordinate z_0

$$\langle I(V)\rangle_{\varepsilon_\sigma\approx\varepsilon_F}=-\langle I(-V)\rangle_{\varepsilon_\sigma\approx\varepsilon_F-U}.\tag{13}$$

The Coulomb interaction on the IVC is manifested most strikingly when the resonance centers are arranged asymmetrically.

Indeed, analysis of Eq. (10) shows that the IVC in this case is asymmetric, so that the junction conductance in the region of large negative voltages differs from R_n^{-1} with $eV\gg T$ (see Fig. 1):

$$\frac{\partial I/\partial V|_{V=0}}{\partial I/\partial V|_{V=-\infty}}=\ln(2)\frac{2\Gamma_{l0}+\Gamma_{r0}}{\Gamma_0},$$

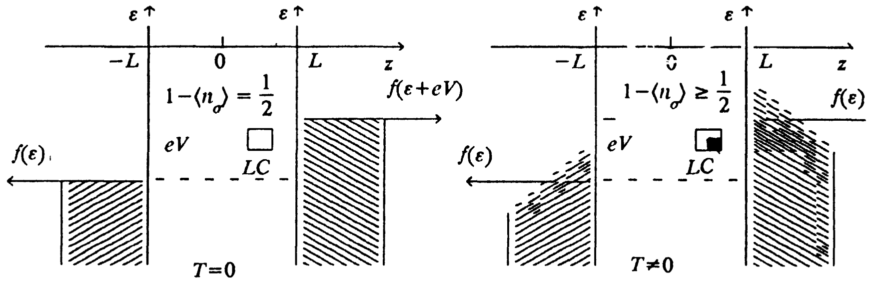

FIG. 2. Diagram of the population of localized states explaining the asymmetry of the IVC of a NIN junction and the presence of current deficiency (excess) in the IVC with asymmetrically arranged localized states in the case of strong Coulomb interaction.

$$\frac{\partial I/\partial V|_{V=0}}{\partial I/\partial V|_{V=\infty}}=\ln(2)\,\frac{2\Gamma_{r0}+\Gamma_{l0}}{\Gamma_0}, \tag{14}$$

where $\Gamma_0=\Gamma_{r0}+\Gamma_{l0}$, $\Gamma_{l0,r0}=\Gamma_{l,r}(z_0)$.

Moreover, as the voltage increases, a transition occurs from current deficiency (excess) $\delta I=R_n^{-1}[V-I(V)]$ for $eV\ll -T$ to current excess (deficiency) for $eV\gg T$, depending on whether the spatial coordinate of the plane with the localized states is positive or negative. The absolute value of δI depends on the physical temperature of the transition and the position of the localized states in the insulator:

$$\frac{eR_n\delta I}{T}=\begin{cases}\ln|(2\Gamma_{r0}+\Gamma_{l0})^2/2\Gamma_0^2|, & V>0,\\ \dfrac{2\Gamma_{r0}+\Gamma_{l0}}{\Gamma_{r0}+2\Gamma_{l0}}\ln|(\Gamma_{r0}+2\Gamma_{l0})^2/2\Gamma_0^2|, & V<0.\end{cases} \tag{15}$$

The reasons for this form of the IVC can be easily deduced from the expressions (6) and (7). They are connected with the way the current flowing through the junction depends on the population of the localized states ($I\propto 1-\langle n_\sigma\rangle$). Let $\Gamma_{r0}\gg\Gamma_{l0}$, so that the plane with the localized states lies near the right-hand electrode (see Figs. 1 and 2). Then for $T=0$ and $V>0$ in the electrode closest to the localized states all states are occupied, as a result of which a localized state always contains one electron: $1-\langle n_\sigma\rangle\approx 1/2$ (in the model under consideration the energy level of the second electron in a localized state satisfies $\varepsilon_F+U\gg\{T,eV\}$, i.e., this state is always free). When the voltage has the opposite sign (which is equivalent to symmetric reflection of the plane of localized states about the plane passing through the center of the junction) all states in the near electrode are empty. For this reason, electrons easily leave the localized states, so that $\langle n_\sigma\rangle\approx 0$, $1-\langle n_\sigma\rangle\approx 1$, and in accordance with the expression (6) R^{-1} is larger by a factor of 2. Due to the thermal smearing of the Fermi step the occupation of the electronic states in the N metal changes at $\varepsilon\approx\varepsilon_\sigma$ and the channels for resonant tunneling are partially blocked ($1-\langle n_\sigma\rangle<1$, $V<0$) or additional channels are opened ($1-\langle n_\sigma\rangle>1/2$, $V>0$) and a current deficiency or excess, respectively, forms in the IVC.

It is interesting to note that when the plane of localized states is symmetrically positioned and the densities of states in the electrodes are equal ($\Gamma_{l0}=\Gamma_{r0}$), the competition between the above mechanisms for suppression and stimulation of current transport through the localized states results in a small current excess:

$$eR_n\delta I=T\ln(1.125)\approx -0.1\ \mathrm{T},\quad V>0, \tag{16}$$

while when the bulk distribution of localized states is uniform a small current deficit is obtained after averaging (see Fig. 3):

$$eR_n\delta I=-T2\ln(4\sqrt{2}/(1+\sqrt{2})^2)\approx 0.06\ \mathrm{T},\quad V>0, \tag{17}$$

and the differential conductance of the NIN junction with a symmetric arrangement of the plane of localized states with $V=0$ is $(3/2)\ln(2)\approx 1.04$ times its value in the case $eV\gg T$, and the differential conductance of the NIN junction with localized states distributed uniformly over the insulating layer is $(\sqrt{2})\ln(2)\approx 0.98$ times its value in the case $eV\gg T$ (Fig. 3).

Thus when the Coulomb repulsion of the electrons in the localized states is taken into account, temperature-dependent features appear in the IVCs of NIN structures,

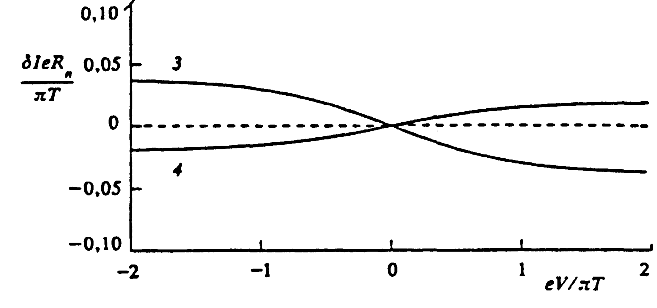

FIG. 3. Singularities in the IVC of a NIN junction with strong Coulomb interaction in the localized states. *1*—conductance dI/dV with symmetric arrangement of the plane with localized states; *2*—conductance dI/dV with uniform distribution of localized states over the volume of the insulator; *3*—current excess on the IVC of a NIN junction with symmetric arrangement of the plane with localized states; *4*—current deficiency in the IVC of a NIN junction with a uniform distribution of localized states over the volume of the insulator.

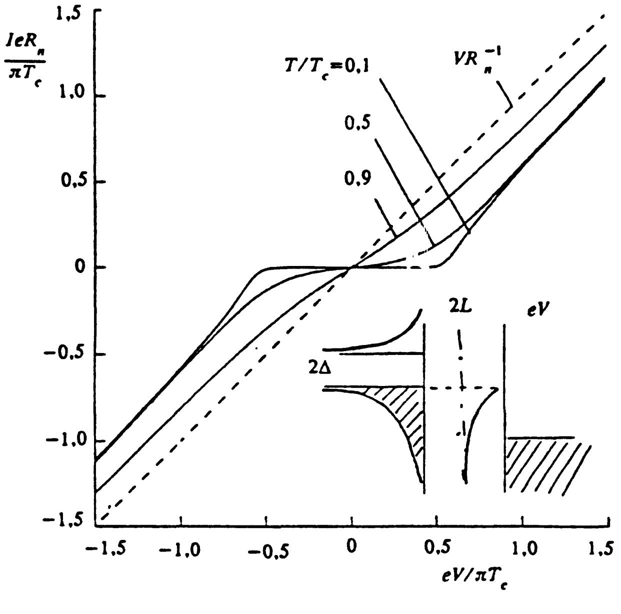

FIG. 4. IVC of a SIN junction with localized states distributed uniformly over throughout the insulator and in the absence of Coulomb interaction in them.

and these features must be taken into account when analyzing the properties of junctions with superconducting electrodes.[1)]

3. SUPERCONDUCTOR–INSULATOR–METAL JUNCTION (SIN)

For definiteness, let the left-hand electrode of the tunnel structure be a superconductor. Then the parameter Γ_l in Eqs. (6)–(10) depends on the energy and is proportional to the density of states of the superconductor:

$$\Gamma_l \propto |\varepsilon|/(\varepsilon^2-\Delta^2)^{1/2}\theta(|\varepsilon|-\Delta),$$

where $\theta(z)$ is the Heaviside step function.

In the absence of Coulomb repulsion in the localized states the junction IVC is asymmetric for any impurity distribution in the insulator. In particular, when the impurities are uniformly distributed[20] the IVC has a current deficit (see Fig. 4), whose temperature dependence is determined by the function $\Delta(T)$:

$$eR_n\delta I \approx 0.6\Delta(T). \tag{18}$$

The reason for the appearance of current deficit on the IVC is quite simple: the channels for tunneling of electrons whose energy lies within Δ of the gap are different in NIN and SIN junctions. Indeed, in NIN structures $[N_l(0)=N_r(0)]$ the optimal localized states lie at the center of the insulator ($z=0$). The presence of singularities in the density of states of the superconductor causes the position of the optimum resonance center to be displaced by $\delta z(\varepsilon) \propto \varkappa^{-1}\ln[N_l(\varepsilon)]$ in the direction of the N metal (see inset in Fig. 4). The probability of tunneling through such asymmetrically arranged localized states is smaller by a factor of $\exp\{\varkappa\delta z(\varepsilon)\}$ than through localized states with $z=0$, and this is why a current deficit appears.

In the case when the localized states are localized in the plane with coordinate z_0 the form of the junction IVC will depend on both the temperature and z_0. In particular, with $T=0$ we have

$$eR_n\langle I\rangle = \frac{\Delta}{2}\left[\mathscr{U}(v)-1-\frac{\Gamma_0}{\Gamma_-}\left[\left(1-\frac{1}{\mathscr{U}(v)}\right)\right]\right.$$
$$\left.+\frac{4\Gamma_{l0}\Gamma_{r0}}{\Gamma_0\Gamma_-}F(v)\right],$$

$$F(v)=\int_1^{U(v)}\frac{dt}{(t^2+\Gamma_-/\Gamma_0)}$$
$$=\eta\begin{cases}\mathrm{arctg}[\eta\mathscr{U}(v)]-\mathrm{arctg}(\eta), & \Gamma_->0,\\ \mathrm{arccth}[\eta\mathscr{U}(v)]-\mathrm{arcth}(\eta), & \Gamma_-<0,\end{cases}$$

$$\mathscr{U}(v)=v+(v^2-1)^{1/2},\quad v=eV/\Delta,$$

$$\Gamma_-=\Gamma_{l0}-\Gamma_{r0},\quad \eta=\left(\frac{\Gamma_{l0}}{\Gamma_{r0}}\right)^{1/2} \tag{19}$$

The IVCs for arbitrary temperatures were calculated numerically. They are displayed in Fig. 5 for three values of z_0. It is evident that the largest difference from the IVC of a standard SIN junction is observed when the plane with the localized states lies near the superconducting electrode (Fig. 5a). In this case the IVC is virtually identical to that of ultrasmall tunnel junctions, which is determined by charge effects (Coulomb blockade):[22] A current deficit exists and the derivative dI/dV at $V=\Delta/e$ is small. Away from the plane with the localized states in the direction of the N metal the current deficit δI decreases (Figs. 5b and c):

$$\frac{eR_n\delta I}{\Delta(T)}=\begin{cases}\dfrac{1}{1+x}\dfrac{2x}{1-x}(q^{-1}\,\mathrm{arctg}(q)-1), & \Gamma_{l0}>\Gamma_{r0},\\ \dfrac{1}{x-1}\left[\dfrac{2x}{(x+1)q}\,\mathrm{arccth}\left(\dfrac{1}{q}\right)-1\right], & \Gamma_{l0}<\Gamma_r,\end{cases}$$

$$x=\Gamma_{l0}/\Gamma_{r0},\quad q=[|1-x|/(1+x)]^{1/2}, \tag{20}$$

the derivative at the point Δ/e increases and the IVC is transformed increasingly into that of a standard SIN junction.

It follows from Eq. (20) that the temperature dependence of δI is identical to that of the order parameter $\Delta(T)$, and the current deficit (Fig. 6) decreases continuously from 1 at $z_0=-L$ to 0 at $z_0=L$.

When the Coulomb repulsion of the electrons in the localized states is taken into account, the junction IVC changes significantly. Just as in the case of NIN junctions, it is sufficient to consider only one of the two possible values of the energy of a localized state, for example, $\varepsilon_\sigma \approx \varepsilon_F$, since in this case Eq. (13) is satisfied for any distribution of localized states over the insulator.

In this case the IVC becomes symmetric with respect to voltage (see Figs. 7 and 8), and at high voltages it approaches asymptotes parallel to the IVCs of NIN structures. As a result, the temperature dependence of the cur-

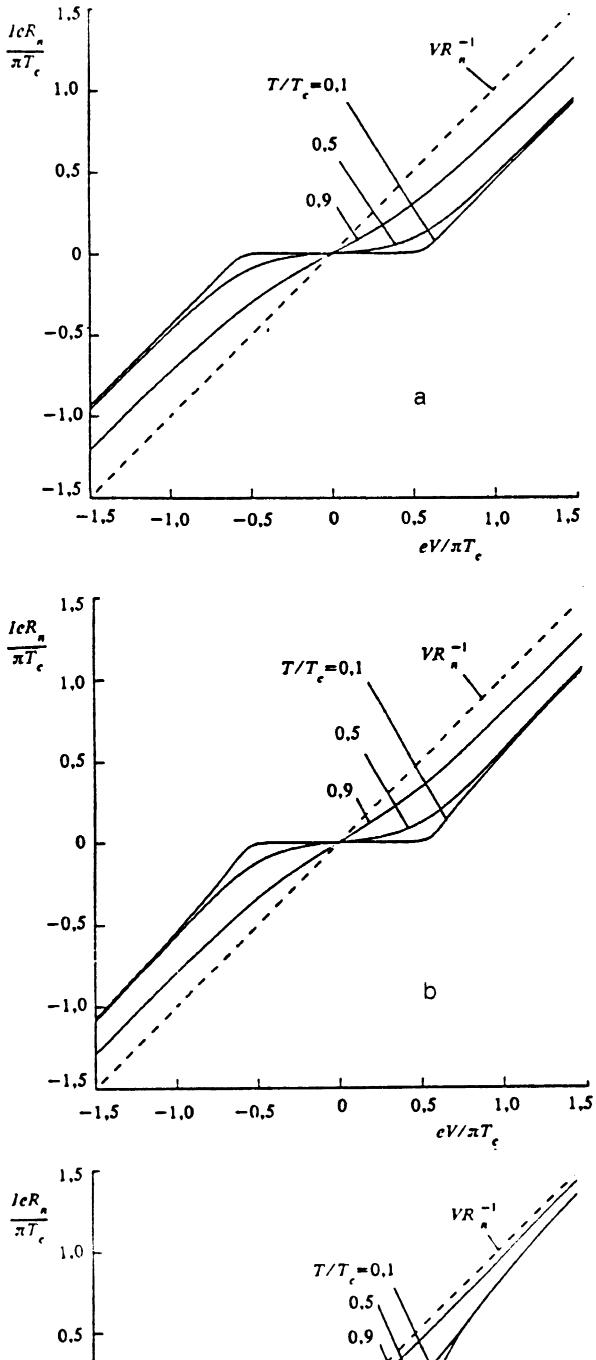

FIG. 5. IVC of a SIN junction with localized states distributed in the plane with the coordinate z_0 in the absence of Coulomb interaction in the states. a) The case when the plane of localized states lies near the superconducting side ($z_0=-0.9L$); b) the plane with localized states lies at the center of the insulator ($z_0=0$); c) the plane with localized states lies near the normal-metal electrode ($z_0=0.9L$).

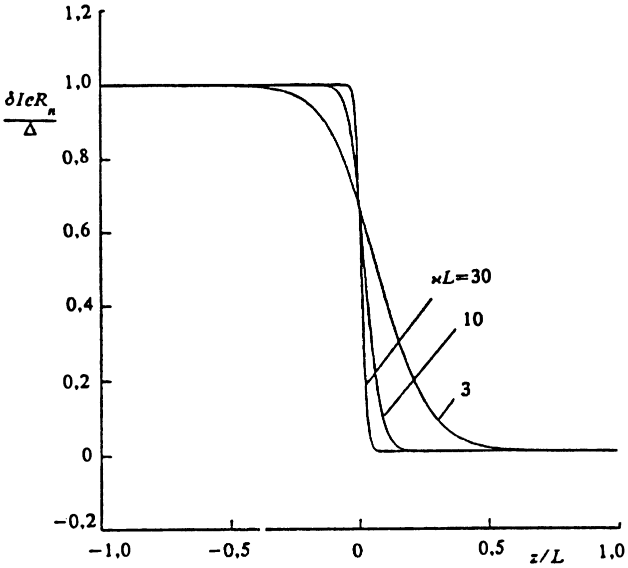

FIG. 6. Current deficit of a SIN junction as a function of the location of the plane of localized states in the absence of Coulomb interaction in them and for different values of the transparency for $\varkappa L$.

rent deficit $\delta I=R_n^{-1}[V-I(V)]$ contains contributions proportional to both $\Delta(T)$ and the physical temperature of the contact (as in NIN structures).

In the case of a uniform distribution of localized states in the insulator the IVC always contains a current deficit. However, its temperature dependence $\delta I(T)$ differs from $\Delta(T)$ and is different for positive and negative voltages (see Fig. 9). This fact is physically obvious, and it is actually a consequence of the asymmetry of the current-voltage characteristics of NIN structures discussed above. In particular, this same circumstance leads to nonzero values of δI at temperatures $T>T_c$, as determined by the Eq. (17).

The situation changes even more radically when the localized states are distributed in a plane parallel to the junction plane. In this case the current deficit can be intensified and a transition can occur from current excess to current deficiency[2)] (see Figs. 7 and 10) by the competition between the mechanisms resulting in current excess in NIN junctions and current deficit in SIN junctions. We note that the current deficit in the case of SIN junctions with strong Coulomb interaction in the localized states was naturally calculated not with respect to the IVCs of the corresponding NIN junctions with $T>T_c$ but rather with respect to the dashed asymptotes in Fig. 7.

The dots in Figs. 10a and b represent the experimental data of Ref. 13, which were obtained in a study of a Schottky barrier on the Nb$-n^+$In$_{0.53}$Ga$_{0.47}$As interface ($n\approx 2.5\cdot 10^{19}$ cm^{-3} at $T=0.5$ K). It is interesting to note that satisfactory agreement with experiment is observed for the case of localized states distributed in a plane parallel to the boundaries of the structure and passing through the center of the insulator.

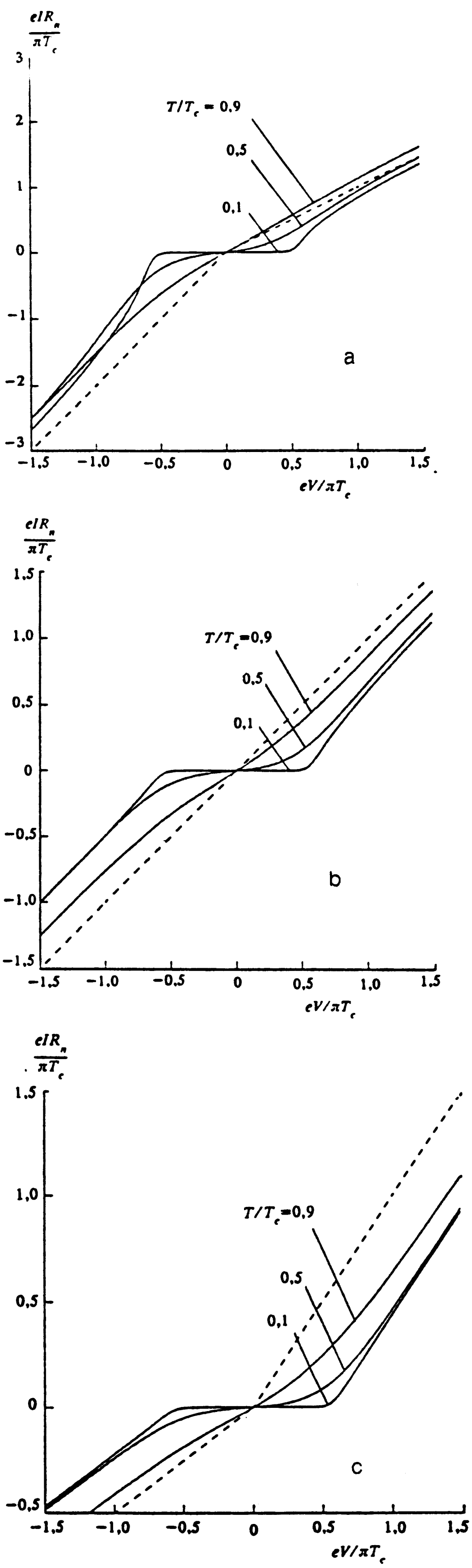

FIG. 7. IVC of a SIN junction with localized states lying in the plane at z_0 with strong Coulomb interaction in the localized states. The dashed lines correspond to the IVC of a NIN junction at $T=0$. a) The plane with localized states lies near the superconducting side ($z_0=-0.9L$); b) the plane with localized states lies at the center of the insulator ($z_0=0$); c) the plane with localized states lies near the normal-metal electrode ($z_0=0.9L$).

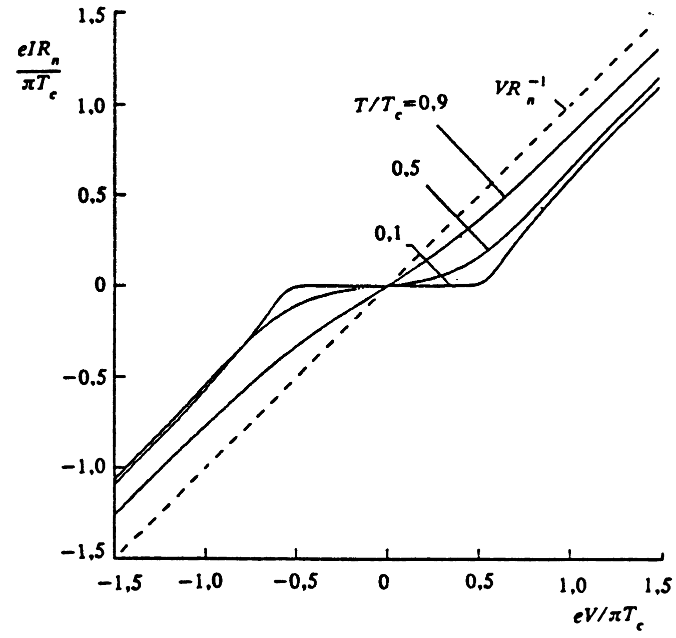

FIG. 8. IVC of a SIN junction with localized states distributed uniformly over the interior of the insulator in the presence of strong Coulomb interaction in the localized states.

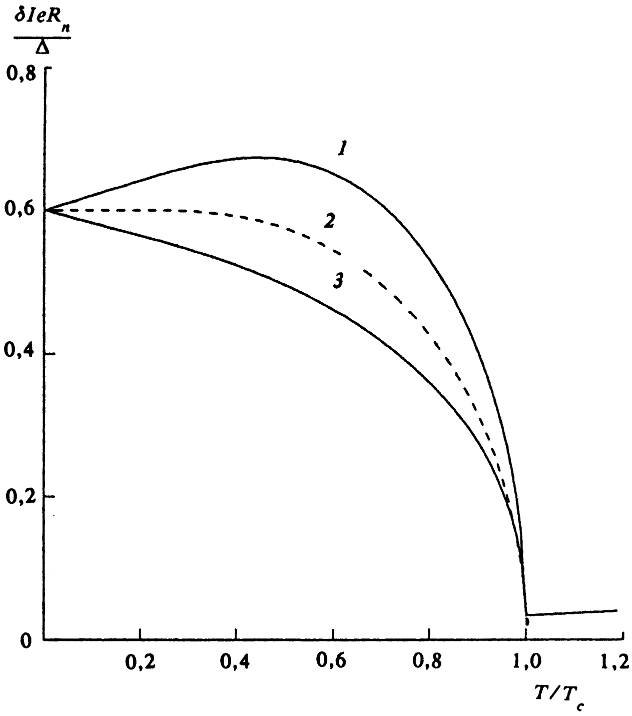

FIG. 9. Current deficit of a SIN junction with localized states distributed uniformly over the volume of the insulator with strong Coulomb interaction in the localized states. *1*—current deficit with $V<0$; *2*—temperature dependence of current deficit, proportional to $\Delta(T)$, of a SIN junction in the absence of Coulomb interaction in the localized states; *3*—current deficit for $V>0$.

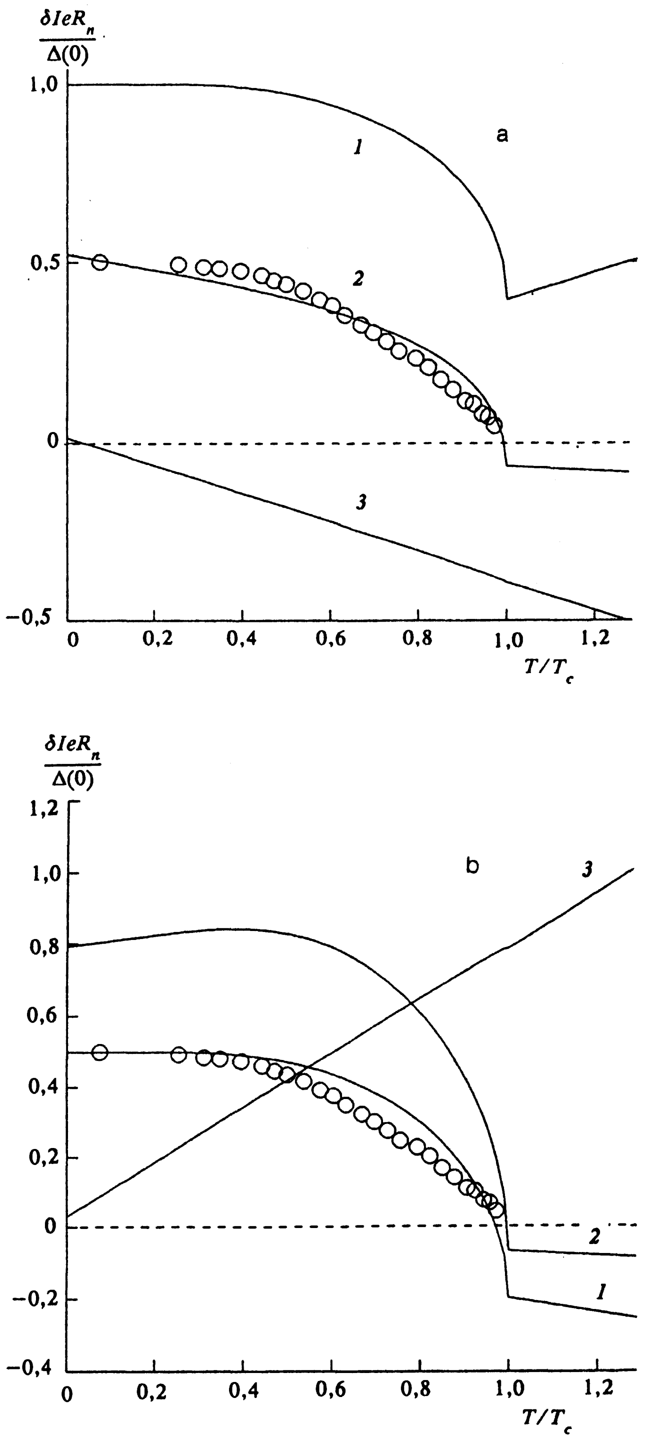

FIG. 10. Current deficit, determined in regions of positive (a) and negative (b) voltages, of a SIN junction with strong Coulomb repulsion of electrons in the localized states. The numbers 1, 2, and 3 correspond to the case when the plane with the localized states lies near the superconducting ($z_0=-0.9L$) electrode, at the center of the insulating layer ($z_0=0$), and near the N electrode ($z_0=0.9L$), respectively.

4. SUPERCONDUCTOR-INSULATOR=SUPERCONDUCTOR JUNCTION (SIS)

In studying the IVC of SIS junctions we confine our attention to the case of uniform distribution of localized states in the insulator. It follows from expression (6) with

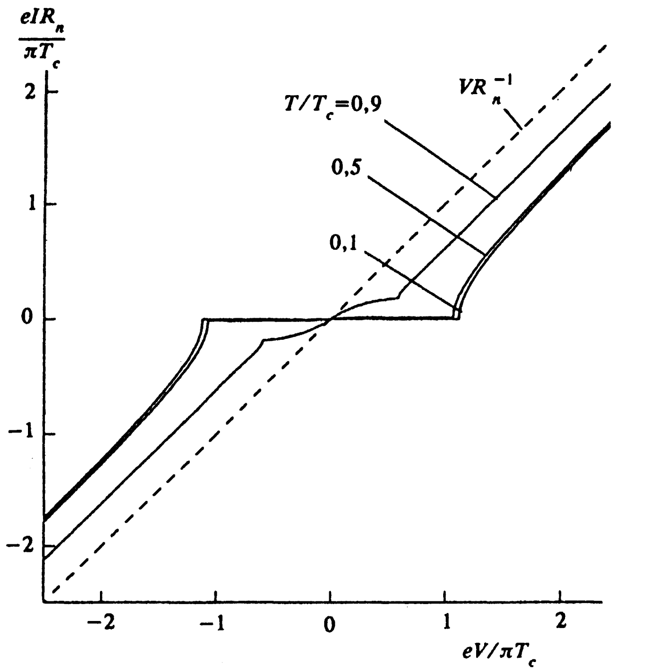

FIG. 11. IVC of a SIS junction with localized states distributed uniformly in the insulator.

$N_{l,r}=N_{l,r}(0)\ |\varepsilon|/(\varepsilon^2-\Delta^2)^{1/2}\ \theta(|\varepsilon|-\Delta)$ that the IVCs of such structures are close to those of two SIN junctions connected in series, in which a localized state plays the role of the N electrode.

Thus in the absence of Coulomb interaction of the electrons in a localized state the IVC does not contain a jump at $V=2\Delta/e$ (see Fig. 11), and the current deficit at high voltages is equal to exactly twice the value for SIN contacts:

$$eR_n\delta I\approx 1.2\Delta(T). \tag{21}$$

In this case Coulomb repulsion leads only to a virtually unnoticeable change in the form of the IVC of the SIS junction in the region $eV\approx 2\Delta$.

5. CONCLUSIONS

The calculations performed in this work show that even a simple model of a tunnel junction with localized states in the insulator can explain an entire series of experimentally observed effects in superconductor/semiconductor structures and in a series of high-T_c superconducting Josephson contacts.[1-14] They include anomalous behavior of the conductance at low voltages, even in the absence of superconducting electrodes (this behavior was previously explained only within a time-dependent theory of the proximity effect, which assumed the existence of at least one superconducting electrode); the existence of a current deficit on the junction IVC; and transition from current excess to current deficiency in the IVC with decreasing temperature. It is important to note that these effects depend on the position of the localized states in the layer with tunneling conductance. This opens up additional possibilities for determining where localized states are located by studying the features of junction IVCs. The latter problem is very important both in surface studies using the method of scanning tunneling microscopy and for developing technology for fabricating hybrid devices containing superconducting and semiconductor components.

[1)]The asymmetry of the current flowing through a separate localized state that can in principle appear with strong Coulomb interaction in the state when the sign of the voltage changes was first pointed out in Ref. 21.

[2)]An analogous change in sign of δI was predicted previously in other models of Josephson structures: SNS sandwiches with finite transparency of the interfaces[24] and *SSmS* structures in which the electrons move in the semiconductor (*Sm*) along Lifshitz percolation trajectories containing a large number of localized states.[17]

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