Current flow in superconductor-semiconductor-superconductor junctions

V. N. Gubankov, S. A. Kovtonyuk, and V. P. Koshelets

Institute of Radio Engineering and Electronics, Academy of Sciences of the USSR, Moscow; Institute of Steel and Alloys, Moscow

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Charge transfer has been studied in niobium-silicon-lead thin-film superconducting junctions at thicknesses of the silicon layer from 25 to 85 Å. The behavior of such junctions, in particular the behavior of the critical current density j_c as a function of the thickness of the intermediate layer and the temperature, is quite different from the behavior of superconducting junctions in which the intermediate layer is an insulator or normal metal. The particular features of the temperature dependence $j_c(T)$ found experimentally are attributed to a mechanism of resonant tunneling of Cooper pairs in the presence of subbarrier localized states which result from the amorphous structure of the intermediate layer. Comparison of the experimental results with the theory of resonant tunneling derived by Aslamazov and Fistul' [Sov. Phys. JETP **56**, 666 (1982)] yields reasonable estimates of the parameters of the structure.

INTRODUCTION

Superconducting sandwiches with a semiconductor intermediate layer (S-Sm-S) are some of the most interesting types of weak links because they combine the Josephson effect with unusual charge-transfer mechanisms.

Three basic types of S-Sm-S junctions can be distinguished on the basis of the structure of the semiconductor: junctions with single-crystal, polycrystalline, and amorphous intermediate layers. A detailed theory for the current flow in S-Sm-S junctions has been derived in a series of papers by Aslamazov and Fistul'.[1–3] Taking a microscopic approach, they analyzed the nature of the flow of the superconducting current for various concentrations and degrees of compensation of the dopants in the semiconductor. They showed that under certain conditions the charge-transfer mechanisms may be quite different from the familiar mechanisms which operate in weak links of other types. In particular, they found that an important role is played by large-scale potential fluctuations which stem from impurity inhomogeneities in the semiconductor, and they analyzed the possibilities of resonant tunneling.

The properties of S-Sm-S junctions have been the subject of many experimental studies.[4–15] Sandwiches with an intermediate layer of an amorphous semiconductor have recently attracted particular interest.[7–13] Nevertheless, the processes involved in the current flow in these sandwiches have not been studied comprehensively. In the present paper we report an experimental study of the properties of S-Sm-S junctions carried out in an effort to determine how the critical current depends on the temperature, the thickness of the Sm intermediate layer, etc. This information will be of assistance in identifying the mechanisms for charge transfer in such structures.

In most of the previous studies, the deposition of the semiconductor film on the superconducting electrode was followed by an oxidation of the semiconductor film, carried out to "fill" possible microscopic pores in the film. The result was to introduce a substantial ambiguity in the determination of the barrier structure. There is accordingly much interest in studying junctions with an intermediate layer in "pure" form, fabricated under conditions such that the scale dimensions of the microscopic pores are small in comparison with the thickness of the semiconductor film.

EXPERIMENTAL PROCEDURE

Niobium-based sandwiches with a silicon intermediate layer were fabricated and studied. The sandwiches are fabricated on the basis of the procedure described in Ref. 16 for tunnel junctions. Figure 1 is a schematic sectional view of the Nb-Si-Pb junctions. The junctions are formed on a silicon substrate and insulated from the latter by a layer of Al_2O_3. The lower Nb layer, with a thickness $d = 2200$ Å, is insulated from the upper electrode ($d = 4000$ Å) by a SiO layer ($d = 2700$ Å) everywhere except in the area of the junction, where the upper and lower electrodes are connected through the Si intermediate layer. The areas of the junctions range from 10 to 100 μm^2. The semiconductor film is deposited by rf sputtering of undoped silicon single-crystal cathode in an atmosphere of ultrapure argon. Just before this deposition, the lower electrode is subjected to an rf cleaning. The upper Pb electrode is deposited immediately after the deposition of the semiconductor intermediate layer, without any additional oxidation. The geometry of the junctions is shaped by photolithography with a subsequent chemical etching for the lower electrode, explosive "lift-off" lithography for the

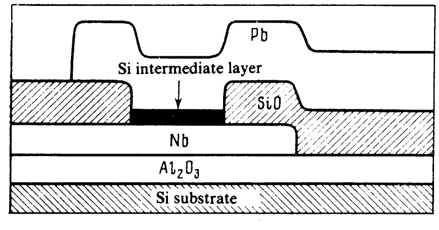

FIG. 1. Cross section of the Nb-Si-Pb junction.

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layer of the SiO insulator, and rf etching for the upper electrode.

The deposited silicon films are generally amorphous. Measurements of the conductivity of thick silicon films ($d = 0.5$–$1\,\mu$m) produced by this method confirm that they have an amorphous structure. The Fermi level of undoped amorphous silicon is pinned in the band gap by localized states which arise because of various types of defects: ruptured bonds, divacancies, microscopic pores, etc. The density of localized states depend strongly on the silicon deposition conditions: the deposition rate, the substrate temperature, the composition of the atmosphere in the deposition chamber, etc. The state density increases with increasing deposition rate[17] and decreases upon annealing or when an oxygen or hydrogen dopant is added to the silicon.[17]

The silicon deposition technique used in the present study is quite different from the techniques described in Refs. 7–10. In the first place, our deposition rate is about an order of magnitude higher; second, as mentioned earlier, the silicon which is deposited is immediately covered by the upper electrode, without an additional oxidation; this technique prevents diffusion of oxygen into the silicon intermediate layer and eliminates the high-temperature hold required in the step of thermal oxidation.

These circumstances suggest the following band structure of the Nb-Si-Pb junctions: The two superconductors are separated by a potential barrier $V-\mu$, where V is the bottom of the conduction band, and μ is the chemical potential. Since the semiconductor is amorphous, there is a certain density of subbarrier localized states near the level of the chemical potential. Schottky barriers may form near the interfaces of the semiconductor with the superconductors.

Junctions synthesized by this technique, with silicon intermediate layers d from 25 to 85 Å thick, were studied over the wide temperature range from 2 to 15 K. All of the experimental results and also some special experiments which were carried out (e.g., to determine how the critical current of the junctions depends on the magnetic field) provide evidence that there are no bridges of the material of the superconducting electrodes through the semiconductor intermediate layer which have an important effect on the current flow in these structures. The junctions are highly stable and endure temperature cycling. The electrical properties of the junctions did not change significantly after storage for a year under ordinary conditions.

EXPERIMENTAL RESULTS AND DISCUSSION

1. Electrical characteristics

Curves 1–3 in Fig. 2 show the electrical properties of the Nb-Si-Pb junctions versus the thickness of the Si intermediate layer. The properties of the junctions are determined from the voltage-current chaacteristics. The normal resistance R_N is measured at voltages above the gap voltage, $V > (\Delta_{\rm Nb} + \Delta_{\rm Pb})/e$. The curves of the critical current density j_c and of the parameter $V_c = I_c R_N$ (I_c is the critical current of the junctions) versus the thickness of the Si intermediate layer are shown for a temperature $T = 4.2$ K (curves 2 and 3).

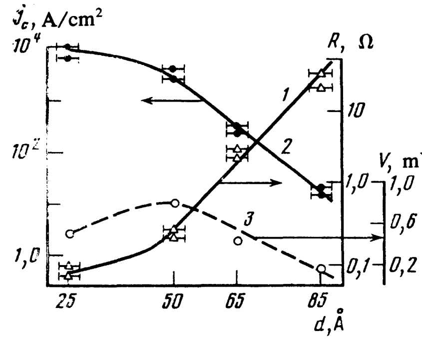

FIG. 2. Electrical properties of Nb-Si-Pb junctions versus the thickness of the silicon intermediate layer. 1—$R_N(d)$; 2—$j_c(d)$ at $T = 4.2$ K; 3—$V_c(d)$ at $T = 4.2$ K.

Figure 3 shows a typical voltage-current characteristics of the Nb-Si-Pb junctions. The shape of the characteristics remains the same as d is increased from 25 to 85 Å. On the characteristics of all the junctions we observe an excess current I_{ex} and also gap and subharmonic structural features at the voltages

$$V = \frac{1}{e}(\Delta_{\rm Nb}+\Delta_{\rm Pb}),\quad \frac{1}{e}(\Delta_{\rm Nb}-\Delta_{\rm Pb}),\quad \frac{\Delta_{\rm Nb}}{ne},\ \frac{\Delta_{\rm Pb}}{ne}.$$

At $T = 2.3$ K the ratio $I_{\rm ex}/I_c$ changes from 1.1 to 1.9 as d is increased from 25 to 85 Å. There is no hysteresis on the voltage-current characteristics for any of the junctions at temperatures down to $T = 2.3$ K. Only in the case of the junctions with $d = 50$ Å do we observe a slight hysteresis as the temperatures is lowered further, to 2.2 K. The capacitance C calculated from the time at which the hysteresis appears with the help of the McCumber parameter β is 0.013 pF/μm^2. The dielectric constant $\epsilon = 7.5$ found in this manner is a satisfactory estimate for amorphous silicon. The value of the parameter $R_N C = 2.5\cdot10^{-13}$ s for the junction with $d = 50$ Å is comparable to the estimate $1.5\cdot10^{-13}$ s found in Ref. 18 for junctions on a silicon membrane. When the junctions are exposed to microwave power, their voltage-current characteristics develop Josephson steps (see the inset in Fig.

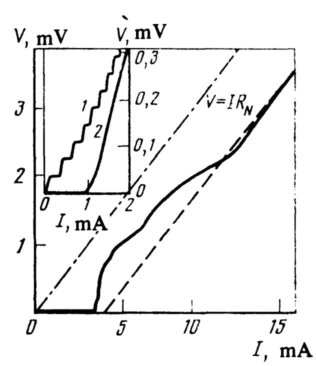

FIG. 3. Voltage-current characteristic of a Nb-Si-Pb junction with $d = 50$ Å at $T = 2.3$ K. The inset shows the voltage-current characteristic of the same junction during the application of microwave power (1) and without it (2) at $T = 5$ K.

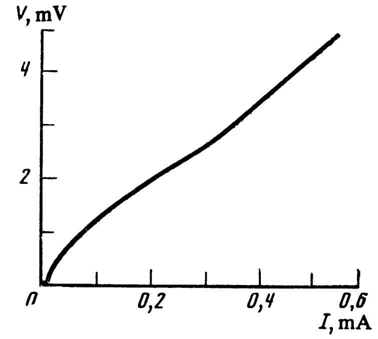

FIG. 4. Voltage-current characteristic of a Nb-Si-Pb junction with $d = 70$ Å fabricated by a special technique.

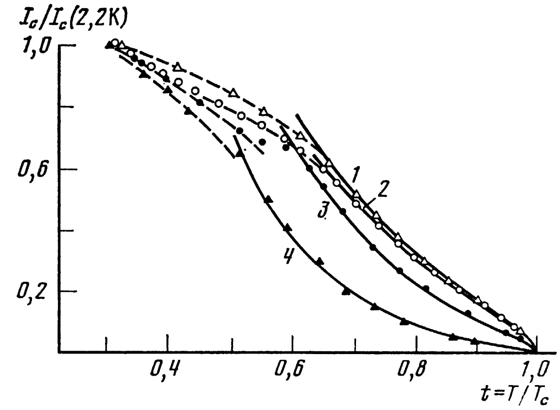

FIG. 5. Temperature dependence of the critical current of the junctions. Curves 1–4 correspond to silicon thicknesses $d = 50$, 25, 65, and 85 Å. Solid lines—Theoretical function (3), drawn to coincide with the experimental results; dashed lines—quadratic function $j_c \propto 1 - (T/T^*)^2$.

3), whose height—and also the critical current—oscillate with increasing power.

It can be seen from Fig. 2 that the functional dependence $R_N(d)$ is very nonlinear, nearly exponential. The differential resistance $R_d = dV/dI$ of the junctions at $T = 10$ K decreases significantly with increasing applied voltage. These results agree with the suggested band structure (see the discussion above) of Nb-Si-Pb junctions, according to which the semiconducting intermediate layer is an effective potential barrier. On the other hand, the presence of an excess current on the voltage-current characteristics (Fig. 3) is evidence that superconducting current does not flow by tunneling.

A direct passage of superconducting electrons through a potential barrier is possible in the case of resonant tunneling.[3] A necessary condition for this charge-transport mechanism is the presence of subbarrier localized states (impurity levels) near the chemical potential. There are localized states in Nb-Si-Pb junctions because of the amorphous structure of the intermediate layer. To determine the effect of these states on the characteristics of the junctions we fabricated special Nb-Si-Pb junctions with $d = 70$ Å, by a technique differing from that described above in that the residual gas pressure during the deposition of the silicon (the pressure in the chamber just before the admission of the Ar) was twice the standard value. The increase in the residual pressure leads to an increase in the partial pressure of various gases (including O_2 and H_2) in the deposition chamber during the deposition of the silicon. According to Ref. 19, this circumstance leads to a substantial decrease in the density of localized states in the energy gap of the amorphous silicon. It can be seen from Fig. 4 that the voltage-current characteristics of these junctions are of a tunneling type without an excess current. This result suggests that transport observed experimentally for superconducting electrons at junctions fabricated by the standard technique is determined by the effect of subbarrier states. This suggestion is supported by temperature measurements.

2. Temperature dependences of the critical current

Curves 1–4 in Fig. 5 show the temperature dependences of the critical current density $j_c(T)$ of Nb-Si-Pb junctions at various thicknesses of the Si intermediate layer. On these curves we can see a characteristic temperature T_0, which decreases from 4.5 to 3.8 K as d is increased from 25 to 85 Å. At $T > T_0$, the $j_c(T)$ curve is concave; this shape is not described by the expressions which have been offered for junctions with a purely metallic or degenerate semiconducting intermediate layer. At $T < T_0$, the critical current increases quadratically, $j_c \propto 1 - (T/T^*)^2$, where $T^* = \text{const}$ (for a junction with $d = 25$ Å, the quadratic law gives way to a weak logarithmic increase upon cooling below 3 K). As d is increased, the parameter T^* decreases, and the degree of concavity increases at $T > T_0$. These results are quite different from those predicted theoretically for both tunnel junctions[20] and junctions with a purely metallic conductivity.

It was shown in Ref. 3 that in S-Sm-S junctions with a nondegenerate single-crystal intermediate layer, when there are impurity levels near the chemical potential, there may be a resonant tunneling of coherence electrons through the semiconductor barrier. The resonant transmission outweighs ordinary tunneling under the condition

$$T_1 = (V - \mu)(na_B^3)^{1/2} > T_c, \quad (1)$$

where T_c is the lowest of the critical temperatures of the superconductors, n is the impurity concentration, and a_B is the Bohr radius of the impurity.

The results of this study can also be used to describe the processes which occur at S-Sm-S junctions with an amorphous intermediate layer. The difference between the amorphous structure of the barrier and the single-crystal model discussed in Ref. 3 is no important obstacle since, as mentioned above, the decisive factor is the presence of a potential barrier between the two superconductors and the presence of localized subbarrier states near the level of the chemical potential. That the band structure of the Nb-Si-Pb junctions corresponds to these conditions follows from the set of curves of $R_N(d)$ and $R_d(V)$ and also from the results of the special experiment described above (Fig. 4).

For the case of an intermediate layer of an amorphous semiconductor, condition (1) takes the form

$$T_1=(V-\mu)(\alpha^{-3}N_E V_0)^{1/2}>T_c, \tag{2}$$

where we have made corresponding changes in the parameters: $\alpha_B \to \alpha^{-1}$ (the radius of the localized states); $n \to 1/\alpha_E^3 = N_E V_0$, where α_E is the distance between the localized states at the E level, N_E is the density of localized states, and V_0 is a disorder parameter. Typical values for amorphous silicon are $\alpha^{-1} = 3$ Å, $N_E = 10^{19}$ eV^{-1}·cm^{-3}, and $V_0 = 1$ eV (Refs. 17–21). Also assuming $V-\mu = 0.5$ eV for the Nb-Si-Pb structure, we substitute these values into (2). As a result we find $T_1 = 25$ K, which is significantly higher than $T_c = 7.2$ K for a lead electrode.

The critical current density under conditions of resonant tunneling is given by the following expression according to Ref. 3:

$$j_c \propto \frac{\ln^{7/2}(1/\beta)\Delta_1\Delta_2 T^2}{(\pi^2T^2+\Delta_1^2)^{1/2}(\pi^2T^2+\Delta_2^2)^{1/2}L^{5/2}\ln^5(1/c)} \exp\left(-L\frac{\ln c}{\ln \beta}\right), \tag{3}$$

where $\beta = \pi T/2(V-\mu)$, $c = n/\alpha^3$, $L = d\alpha$, and Δ_1 and Δ_2 are the ordering parameters of the superconducting electrodes.

The solid lines in Fig. 5 (curves 1–4) show the theoretical function (3), drawn to match the experimental results at the point $T_2 = 6$ K, with

$$P=\alpha|\ln c|/\ln^2[2(V-\mu)/\pi T_2]$$

used as an adjustable parameter. We see from this figure that there is a good agreement between experiment and theory over a broad temperature range $t>0.5$, where $t = T/T_c$. The size of the adjustable parameter is the same for junctions with $d \geqslant 50$ Å, indicating that the parameter values $V-\mu$, α^{-1}, and N_E for these junctions are identical. On the other hand, the value of P for the junctions with $d = 25$ Å is considerably larger than that for other values of d.

According to Ref. 3, the superconducting current is transported along Lifshitz resonant trajectories.[22] These trajectories form because some of the total number of randomly positioned impurity centers are, with a low probability, aligned periodically spaced $2y$ apart. In this case, because of the overlap of the wave functions of the electrons of adjacent centers, a band of width $B = \exp(-2\alpha y)$ forms. A superconducting current can propagate along this band with a damping due to a coherence loss $\exp(-d/\xi)$ (ξ is the coherence length). The set of these trajectories shunts the semiconducting barrier and allows a direct flow of superconducting current.

The discrepancy between experiment and theory at low temperatures $t<0.5$ (Fig. 5), where $j_c(T)$ varies more slowly (quadratically), is probably due to the circumstance that the coherence length is comparable to the thickness of the intermediate layer. According to Ref. 3, expression (3) is no longer valid.

The correspondence between the experimental results on the critical current as a function of the temperature, on the one hand, and the theoretical prediction, (3), on the other, suggests that the transport of superconducting electrons is due to a resonant tunneling. This suggestion is supported by estimates of the characteristic parameters describing the structure of the real barrier ($V-\mu$, α^{-1}, N_E) based on the conclusions of Ref. 3 and a comparison of these estimates with the corresponding barriers for amorphous silicon which have been found by other investigators.

3. Estimates of parameters

We estimate the parameters $V-\mu$, α^{-1}, and N_E by comparing expression (3) with the experimental curves of $j_c(T)$ and $j_c d^{5/2}(d)$. In addition to (3), we also use the condition that resonant tunneling is predominant [see (2)] and the expression found in Ref. 3 for the temperature (T_0) of the inflection point on $j_c(T)$. These estimates lead to the following regions of possible values of the parameters of the semiconducting barrier[1)]: The height $V-\mu$ of the potential barrier is restricted to the interval 200–700 mV; the lower estimate corresponds to the values $\alpha^{-1} = 6$–7.5 Å and $N_E = (1$–$3)10^{19}$ eV^{-1}·cm^{-3}, while the upper estimate corresponds to $\alpha^{-1} = 2.5$–3.5 Å and $N_E = (2.5)10^{20}$ eV^{-1}·cm^{-3}.

These values agree quite well with the existing data for amorphous silicon. A density of localized states in the interval 10^{19}–10^{21} eV^{-1}·cm^{-3} for amorphous silicon has been found in several studies.[17,19,23] A value of $\alpha^{-1} = 3$ Å was found for the radius of localized states in the interior of the energy gap of amorphous silicon in Ref. 23. The height of the potential barrier is also quite plausible—on the order of the half-width of the energy gap of amorphous silicon.[23]

These values of the parameters $V-\mu$, α^{-1}, and N_E can be used to estimate the distance between localized states on a resonant trajectory ($2y = 10$–25 Å) and the width of the band which arises in an ordered arrangement of these states [$B = (2$–$4)\pi T$]. According to Ref. 3, expression (3) holds under the conditions

$$B \gg \pi T, \quad N\pi T/B \gg 1,$$

where $N = (d/2y)(1+\theta^2/2)$, and θ is the trajectory curvature angle.

It is not difficult to show that these conditions hold in our case. This result is further evidence in favor of the use of the model of resonant tunneling in a discussion of the experimental results reported above.

We wish to thank L. G. Aslamazov and M. V. Fistul' for useful discussions of these results.

[1)] These estimates are valid for junctions with $d = 25$ Å, so that the values of V_c, j_c, and R_N for these junctions "drop out" of the overall picture (Fig. 2). This circumstance is evidence of certain structural features in the barrier due to the small thickness of the Si.

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