Josephson effect in high-temperature superconductors and in structures based on them

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A review is made of the current status of investigations of the Josephson effect in high-temperature superconducting materials and in structures based on them. The results are given of experimental investigations of the influence of various factors on superconducting properties of surface layers of high-temperature materials, such as the conditions during synthesis and cleaning of their surface, and also data on the ohmic contacts. This information is used to analyze the experimental results obtained for Josephson junctions between high- and low-temperature superconductors and between two high-temperature superconductors. The following junctions are considered: point contacts, tunnel junctions, SNS structures with direct conduction, junctions at internal grain boundaries in high-temperature superconducting ceramics and films, and also junctions at microcracks in high-temperature superconducting crystals. These results are compared with the predictions of theoretical models of Josephson junctions developed on the basis of the BCS theory. It is concluded that the available data are insufficient not only to determine the validity of the BCS theory in the description of high-temperature superconductors, but also to provide a reliable qualitative identification of the physical structure of the junctions. Possible topics for further experimental investigations of the Josephson effect in high-temperature superconducting junctions with direct and tunnel conduction are suggested.

1. INTRODUCTION

Many review papers have already been published on the subject of physical properties of high-temperature superconductors (see, for example, Refs. 1–6), on the methods of fabrication of these materials,[7,8] and on possible applications.[9] However, sufficient attention has not yet been given to the Josephson effect in high-temperature superconductors. The purpose of the present review is to fill this gap.

Manifestations of the Josephson effect in high-temperature superconductors and structures based on them are complex and multifaceted. For example, in the case of polycrystalline samples of high-temperature superconductors the Josephson interaction between the individual grains (crystallites) has a considerable influence on the electrodynamics, on the surface impedance,[10] and on the structure of magnetic flux quanta.[11,12] However, the most direct information on the Josephson effect in high-temperature superconductors can be obtained by investigating Josephson structures of various types prepared deliberately. They include, firstly, such well-known structures as point contacts, tunnel junctions, SNS sandwiches, and variable-thickness bridges. Secondly, much information can be obtained by investigation of the junctions in which the Josephson effect occurs at the boundaries of two or more grains which are located in the region of concentration of a superconducting current. An analysis of the processes occurring in these structures will be made paying special attention to the characteristics which distinguish high-temperature superconducting Josephson junctions from corresponding structures made of low-temperature superconductors, the properties of which have been investigated sufficiently thoroughly and have been described in familiar reviews and monographs.[13–16]

We shall begin by considering physical and chemical properties of the surfaces of high-temperature superconductors, which are essential in subsequent analysis: the influence of the phase composition of the surface of a ceramic and of its treatment on the superconductivity of surface layers; the chemical interaction between high-temperature superconductors, on the one hand, and insulators or metals, on the other. In the third and fourth sections we shall discuss the main experimental results obtained for junctions between high- and low-temperature superconductors and between two high-temperature superconductors. In the fifth section we shall give the results of theoretical calculations carried out using the framework of the BCS theory and invoking different models of Josephson junctions. We shall also compare these results with experimental data. Finally, in the sixth section, we shall outline possible further investigations of the Josephson effect in high-temperature superconductors, and consider various methods for the fabrication of Josephson high-temperature superconducting structures with high values of the characteristic voltage V_0.

2. SOME PROPERTIES OF SURFACES OF HIGH-TEMPERATURE SUPERCONDUCTING MATERIALS

The complex structure of the surfaces of high-temperature superconductors is due to the high chemical activity of metal oxide materials, giving rise to different phase compositions[1)] of the surface and inner layers. In particular, the properties of high-temperature superconductors are very sensitive to the oxygen content (see, for example, Refs. 20–38). If the concentration of oxygen in YBaCuO falls to a value $7-x \approx 6.2 \pm 0.2$, a transition takes place from metallic to semiconducting conduction characterized by a band gap $\Delta E \approx 0.7$–0.9 eV (Refs. 39–41).

The oxygen deficit in the surface layer may be due to a number of factors. We shall consider only the most important of them.

2.1. Influence of conditions during synthesis

The properties of the surfaces of high-temperature superconducting films depend strongly on the method used in

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preparation (*ex situ* or *in situ*). In the case of the most thoroughly investigated materials of the YBaCuO type this is due to the high chemical activity of barium.

If the synthesis takes place *ex situ*, then even a brief exposure of the surface of a ceramic to air during the film preparation stage destroys the superconductivity in the surface layers and this is due to the formation of BaO and $BaCO_3$ layers characterized by insulating properties.[42-47] For example, investigations of YBaCuO films carried out using a transmission electron microscope have shown[48] that the compound $YBa_2Cu_3O_7$ is formed only in the middle of a film at a distance of 350 nm from the surface. As we move toward the surface (in a layer of $\approx$50 nm thickness) it is found that large inclusions of the compound $Y_2Ba_1Cu_1O_y$ are encountered and these merge forming a homogeneous material, which no longer exhibits the superconducting properties. Figure 1 gives the results[49] of an investigation of the surface of a $YBa_2Cu_3O_y$ ceramic made using an improved version of the Rutherford backscattering method. We can see that the atomic concentration of oxygen y reaches values close to 7 only at a distance of 150 nm from the surface.

If the evaporation of the original ceramic and its annealing take place entirely in vacuum (*in situ*), the composition and properties of the surface layer depend on the presence of CO_2 vapor in the vacuum chamber[44,50] and on the rate of rise of temperature. If the rate of rise is less than 10 °C/s, then strong diffusion of Ba takes place toward the surface and this creates a phase composition different from that in the interior of a superconductor. If the rate of rise of the annealing temperature is of the order of 10 °C/s or higher, the diffusion of Ba is kinetically limited and the surface is oxidized completely forming the main phase composition.[4,51]

However, this composition is metastable and even after synthesis it decomposes continuously because of the diffusion of oxygen from the surface.[52-57] Such diffusion is significant even at very low temperatures in the range $T \geqslant 20$ K (Ref. 52) and at $T \geqslant 150$ K it influences significantly the structural properties of these materials[53] creating surface dislocations and strong mechanical stresses and thus causing the surface to crack.

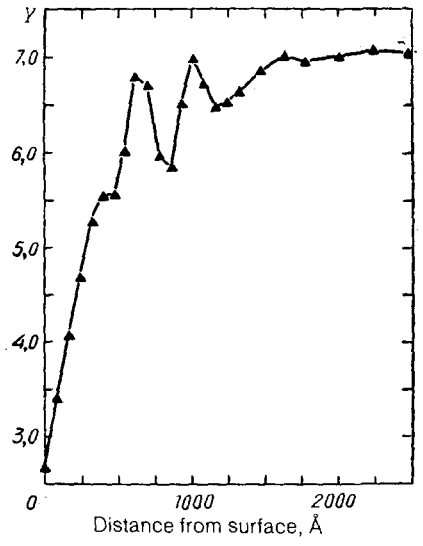

FIG. 1. Variation of the atomic concentration of oxygen y in $Y_1Ba_2Cu_3O_y$ ceramic away from the surface into the sample.[49]

2.2. Cleaning of the surfaces of high-temperature superconductors

A nonsuperconducting layer can be removed from the surface of a ceramic mechanically, by cleavage, or by scraping off the layer in vacuum or in an oxygen atmosphere. However, this method is inconvenient and it does not always give the desired result (see Secs. 3 and 4).

Ion cleaning in an inert-gas (Ar, Ne) plasma, which is traditional in microelectronics technology, reduces the thickness of the nonsuperconducting layer but does not remove it completely since it causes structural changes in this layer (Cu–O bonds are broken and oxygen diffusion takes place). For example, photoemission investigations[40,58-60] have shown that such cleaning destroys the superconductivity in a surface layer of thickness of the order of 3 nm. Cleaning in an oxygen plasma[61] results in less damage but the results depend on the cleaning procedure (its duration and angle of incidence of ions on the surface).

Another cleaning variant—cathodic sputtering of the surface (known as backsputtering)—also results in damage to the superconducting properties of the surface, but the reported results[61-66] show that this variant is preferable to ion bombardment.

It therefore follows that the surfaces of high-temperature superconducting materials are highly unstable. This means that they have to be protected by films of other materials practically immediately after synthesis. However, the number of materials suitable for this purpose is very limited.

2.3. Interaction of high-temperature superconductors with metals

A comparative analysis of the binding energy[67] of oxides of different metals shows that only nine oxides (those of Ru, Rh, Pd, Ag, Os, Ir, Pt, Au, and Hg) have a lower binding energy[2)] than CuO. All the other metals react chemically with metal oxide ceramics and this is accompanied by the loss of the superconducting properties of surface layers of high-temperature superconductors and oxidation of the materials in contact with them. This has been confirmed by experimental studies made by optical[68-72] and photoemission[40,58,59,73-89] methods for the investigation of surfaces, and it is also supported by the data on ohmic contacts.[61-66,90-111]

Optical investigations *in situ*[68] have shown that near the boundary between YBaCuO and Al or In there is an oxygen-depleted layer of $YBa_2Cu_3O_{6.33}$ of thickness of 1.5–2 and 1.2 nm, respectively, whereas at the boundaries with Au and Ag a layer of $YBa_2Cu_3O_{6.5}$ of thickness 1.5 and 1 nm is formed.

It follows from the photoemission data[77] that the process of deposition of Al on the surface of a ceramic is accompanied by oxidation and AlO_3 grows in the first $\sim$1.4 nm. In the case of thicker Al films the oxidation reaction is kinetically limited because the diffusion of oxygen across the oxide layer is hindered and, beginning from thicknesses of the order of 2.3 nm, the growth of a metallic Al film is observed. This growth is of cluster nature right up to thicknesses of the order of 10 nm. A continuous Al film is formed when the thickness of the normal (N) layer is considerable.

Similar investigations of the interfaces between the compounds LaSrCuO, YbACuO, or BiSrCaCuO with other

TABLE I. Thickness of oxide films formed as a result of deposition of various materials on the surface of $YBa_2Cu_3O_{7-y}$

Material	Fe	Al	Ti	In	Bi	Pb	Cu	Si	Ag	Au
Oxide film thickness, Å	24	14	10	8	8	4	4	2	0	0
Reference	[74]	[77, 79]	[84]	[79]	[82]	[80]	[80, 88]	[40]	[40, 80, 81, 86, 89]	

materials (Fe, Ti, In, Cu, Pt, Pb, Bi, Ge, Si, Au, Ag) have shown[40,73-91] that the kinetics of the growth of film of these materials on the surfaces of ceramics (with the exception of Ag and Au) differs from that described above for Al simply by the thickness of the oxide film (Table I). Strong oxidation of these materials is accompanied by the loss of superconductivity and the formation of a semiconducting surface layer of thickness 2–5 nm. This result has been confirmed by measurements[66,92,100,107] of the resistance R_B of the boundary between a high-temperature superconductor and a normal metal (Mg, Al, Zn, Cr, In, Ag, Au) showing that the smallest values of R_B are exhibited by interfaces between high-temperature superconductors and Ag or Au. Moreover, it is clear from the results reported in Refs. 66, 92, and 107 that the current-voltage characteristics of ohmic contacts between Mg, Al, Zn, Cr, and In, on the one hand, and metal oxide materials, on the other, are close to those expected on the basis of the diode theory of Bethe[112] applicable to an interface between a metal and a *p*-type semiconductor, whereas R_B deduced on the basis of this theory decreases on reduction in the work function of the metal[3)] forming the contact. Absolute values R_B for these contacts are high (10^{-1}–10^{-4} $\Omega\cdot cm^2$), demonstrating that it would be impossible to observe the Josephson effect in direct conduction junctions when metals other than the noble elements are used as the weak-link material.

Noble metals Ag and Au do not form oxides on the surfaces of high-temperature superconductors and have relatively little influence on the superconductivity of their surface layers.[40,80,81,86-89] The experimental data on the electrical resistivity of YBaCuO/Au and YBaCuO/Ag interfaces can be found in Table II. The majority of the data presented in this table apply to contacts formed *ex situ*, i.e., in the course of the formation of these contacts the surface of a high-temperature superconducting material is exposed to atmospheric air. The longer such an exposure[100,104] the stronger the damage to the surface and the higher the value of R_B. It should be possible to reduce R_B to 10^{-7}–10^{-9} $\Omega\cdot cm^2$ by several methods:

1) preliminary cleaning of the surface of a ceramic[61-65] in an O_2 plasma or by cathodic sputtering;[66]

2) addition of a small amount of Ag_2O to the original charge used in the synthesis of a ceramic;[104]

3) annealing of a structure in an oxygen atmosphere after the formation of a boundary.

However, none of these procedures can restore completely the superconducting properties of the surfaces of high-temperature superconductors and the structure of the boundary remains fairly complex.[101] The process of annealing of contacts is accompanied not only by the diffusion of oxygen to the contact region, but also by penetration of the normal metal into the investigated high-temperature superconducting material. The nature of the diffusion of Au and Ag into metal oxide materials is different. As a rule, gold forms large inclusions in a high-temperature superconducting matrix[113-116] and has a much lower penetrating power than silver,[4)] which can diffuse to a depth of ≈ 1 μm (Refs. 123–125). This may increase the effective contact area and it is likely that this takes place in the technologies suggested in Refs. 104 and 111.

It therefore follows that from among all the known methods for forming ohmic contacts, the most promising are those proposed in Refs. 66 and 109. In the former the deposition of a noble metal is preceded by cleaning the surface of a high-temperature superconductor so as to remove the nonsuperconducting phase by cathodic sputtering. In the latter method[109] a contact is formed *in situ* and a YBaCuO film is grown in an oxygen atmosphere (4×10^{-3} Pa) and is annealed at $T = 850$ °C reached at a high rate ($\geqslant 10$ °C/s) and gold film is deposited on the surface at $T = 20$ °C after cooling still in vacuum.

These technologies open up an opportunity (see Sec. 6) for the fabrication of high-temperature superconducting junctions exhibiting direct conduction.

2.4. Interaction of high-temperature superconductors with insulators

According to the current state of knowledge, there are no insulators that do not react chemically with high-temperature superconducting materials. The processes occurring at an interface between such a material and an insulator depend strongly on the temperature and method used to form the interface.

For example, it is shown in Ref. 126 that the deposition by the method of rf magnetron sputtering on a YBaCuO film (500 nm) of Nb_2O_5 (600 and 155 nm) or Al_2O_3 (60 nm) layers results in considerable structural changes in the superconductor. A strong diffusion of Ba to the free surface of the insulator takes place and Nb or Al penetrates into the high-temperature superconductor to a depth of the order of 60 nm. The quality of the films deteriorates (the values of T_c and I_c decrease) and the temperature dependence $R(T)$ in the vicinity of T_c changes from metallic to superconducting.

A comparative analysis of the binding energies shows[67] that formation of Ba salts at the interface between YBaCuO and an insulator is likely for energy reasons. In fact, investigations of solid-phase chemical reactions between YBaCuO and the insulators traditionally used in microelec-

TABLE II. Resistance of the interfaces between high-temperature superconductors and Au or Ag.

Contact material	Additional treatment of contact	R_B, $\Omega \cdot cm^2$	Reference
Bulk YBaCuO/Au	Annealing for 6 h at 950 °C	$<3 \cdot 10^{-7}$	[102]
	Annealing for 1 h at:		[99]
	200 °C	$8 \cdot 10^{-5}$	
	300 °C	$7 \cdot 10^{-8}$	
	400 °C	$7 \cdot 10^{-8}$	
	Annealing:		[95]
	24 h, 900 °C		
	16 h, 700 °C	$5 \cdot 10^{-7}$	
	8 h, 400 °C		
	Contact formed after storage in air for 0.8 h	$2{,}9 \cdot 10^{-5}$	[100]
Film of YBaCuO/Au	Annealing for 1 h, 850 °C	$<10^{-6}$	[101]
	Annealing for 10 s, 750 °C	$3 \cdot 10^{-8}$	[91]
	Annealing for 20 min, 850 °C	$4 \cdot 10^{-10}$	[48]
	No annealing	$4 \cdot 10^{-10}$	[109]
	Surface cleaning in O_2 plasma	$5{,}5 \cdot 10^{-7}$	[61]
	Surface cleaning in O_2 plasma	$3 \cdot 10^{-6}$	[62]
	1 h, $P = 133$ Pa, $W = 10$ watts	$5 \cdot 10^{-7}$	
Bulk YBaCuO/Ag	Annealing for 5 h at 500 °C	$4 \cdot 10^{-8}$	[98]
	No annealing	$6 \cdot 10^{-6}$	
	Annealing for 30 min at 970 °C	$<10^{-8}$	[94]
Bulk YBaCuO/Ag/Al	Annealing for 2 h at 775 K	$7{,}5 \cdot 10^{-6}$	[96]
Bulk YBaCuO/Ag	Annealing:		[106]
	1 h, 150 °C	$15{,}4 \cdot 10^{-8}$	
	1 h, 400 °C	$4 \cdot 10^{-8}$	
	1 h, 500 °C	$3{,}3 \cdot 10^{-8}$	
	2 h, 500 °C	$6{,}1 \cdot 10^{-8}$	
	No annealing	$5 \cdot 10^{-8}$	
Bulk YBaCuO/Ag	Contact formed after storage in air for 0.8 h	$9 \cdot 10^{-6}$	[100]
	Annealing at 500 °C 2 h	$6{,}2 \cdot 10^{-5}$	
		$3 \cdot 10^{-6}$	[110]
	No annealing	$3{,}3 \cdot 10^{-8}$	[108]
Bulk YBaCuO + Ag_x/Ag	No annealing:		[104]
	$x = 0$	$1{,}5 \cdot 10^{-8}$	
	$x = 0{,}5$	$1{,}6 \cdot 10^{-5}$	
	$x = 1{,}5$	$5 \cdot 10^{-6}$	
	Annealing for 40 min at 1100 °C:		
	$x = 0{,}5$	$1 \cdot 10^{-5}$	
	$x = 4$	$2 \cdot 10^{-6}$	
	Annealing for 1 h at 1100 °C:		
	$x = 1$	$7 \cdot 10^{-7}$	
	$x = 3$	$2 \cdot 10^{-7}$	
	Storage in air for 110 days:		
	$x = 0$	$9{,}7 \cdot 10$	
	$x = 1{,}5$	$9{,}6 \cdot 10^{-6}$	
Film of YBaCuO/Ag	Annealing for 10 h at 550°C	$5 \cdot 10^{-8}$	[90]
	Annealing for 40 min at 880°C	$3 \cdot 10^{-8}$	[107]
	Annealing for 1 h at 500 °C	10^{-10}	[66]

tronics (MgO, $SrTiO_3$, ZrO_2, YSZ, Al_2O_3, TiO_2, Si, SiO_2, Cr_2O_3, CaF_2, WC) has shown[127,128] that a rapid formation of these compounds begins at certain annealing temperatures (Table III).

Studies of the chemical composition of transition layers at the interfaces between metal oxide films and various insulating substrates confirm this conclusion. Annealing at 900 °C results in intensive chemical reactions between

TABLE III. Products of chemical reactions between YBaCuO and insulators, identified using results of x-ray analysis.[127]

Insulator	Reaction products	Temperature at which compounds were detected, K
YSZ	$Ba_3Zr_2O_7$, $BaZrO_3$, BaY_2CuO_x	900
ZrO_2	$Ba_3Zr_2O_7$, $BaZrO_3$, BaY_2CuO_x	900
Al_2O_3	$BaAl_2O_4$, BaY_2CuO_x	900
TiO_2	$BaTiO_3$, BaY_2CuO_x	800
SiO_2	Ba_2SiO_4	800
Si	Ba_2SiO_4	700
CaF_2	BaF_2	700
Cr_2O_3	$BaCrO_4$, $BaCr_2O_4$	600
WC	$BaWO_4$	600

TABLE IV. Values of parameters D_0 and T_0 governing the diffusion coefficient $D = D_0 \exp(-T_0/T)$ of materials at the YBaCuO/insulator interface determined at temperatures in the range $600 \leqslant T \leqslant 1000$ °C (Ref. 138).

Diffusing element	Host material	D_0, $nm^2 \cdot s^{-1}$	T_0, K
Cu (from YBaCuO)	MgO	$7.1 \cdot 10^5$	18 200
	Quartz	$8.1 \cdot 10^4$	13 700
	Sapphire	$6.1 \cdot 10^3$	10 500
Mg (from MgO)	YBaCuO	$6.2 \cdot 10^5$	15 600
Si (from quartz)	YBaCuO	$1.2 \cdot 10^8$	18 300
Al (from sapphire)	YBaCuO	$2.0 \cdot 10^4$	12 700

YBaCuO films and substrates made of Si, SiO_2, $SrTiO_3$, ZrO_2, Al_2O_3, BaTi, and NiAlTi (Refs. 125 and 129–141). The thickness of the layer where the reaction take place increases with temperature and at $T \approx 800$–900 °C ranges from 0.15 μm (in the case of Al_2O_3 substrates[133,135] and MgO substrates[138]) to 0.4–0.6 μm (for ZrO_2 and $SrTiO_3$ substrates[125,135,140]). It follows from Table IV, which lists the mutual diffusion coefficients of some insulators and YBaCuO, and from the results reported in Refs. 129–133, that the insulator most active chemically is Si.

3. JOSEPHSON JUNCTIONS BETWEEN HIGH- AND LOW-TEMPERATURE SUPERCONDUCTORS

The methods used in the fabrication of Josephson junctions between high- and low-temperature superconductors are practically the same as those employed in the case of traditional low-temperature superconductor structures. Point contacts are formed by pressing a thin rod ("needle") made of an ordinary (low-temperature) superconductor against the surface of a high-temperature superconducting material.[142–160] Tunnel SIS junctions[90,161–166] and SNS sandwiches[62–65] are formed by depositing consecutively—on a bulk high-temperature superconducting material or on a high-temperature superconducting film—an insulator layer (SIS) or a layer of a normal metal (SNS), followed by a film made of an ordinary (low-temperature) superconductor.

Experimental investigations have shown that manifestations of the Josephson effect in structures formed from two low-temperature superconductors have much in common with the properties of structures formed from high- and low-temperature superconducting materials. Firstly, the current-voltage characteristics of these junctions exhibit a superconducting region with a nonzero critical current I_c. Secondly, exposure to a microwave signal of frequency ω may give rise to the Shapiro steps (Fig. 2) in the current-voltage characteristics and these steps occur at voltages V related to ω by the Josephson equation

$$V = \frac{\hbar\omega}{2e} n, \quad n = \pm 1, \ \pm 2, \ldots \tag{3.1}$$

The amplitude of these steps ΔI_n (and the critical current) frequently oscillate with microwave signal power, which is clear proof of the occurrence of the transient Josephson effect in the junctions and also of a single-valued (nearly sinusoidal) dependence of the superconducting current (supercurrent) on the difference between the phases of the order parameters of the two electrodes. Finally, one- or two-contact interferometers with junctions between high- and low-temperature superconductors frequently exhibit periodic dependences of the supercurrent on the external magnetic field that are analogous to the corresponding dependences in the case of interferometers with contacts between two low-temperature superconductors.

These data have been used to draw the conclusion that the singlet mechanism of electron pairing applies to high-temperature superconducting materials with the pair charge amounting to $2e$.

However, the experimental values of the main parameter of a Josephson junction, which is a characteristic voltage $V_c = I_c R_N$ (R_N is the "normal" resistance of the junction at a given temperature, which can be determined from the asymptotic slope of the current-voltage characteristic), have been found to be unexpectedly small for practically all contacts between high- and low-temperature superconductors (Table V). In fact, according to the standard theory of superconductivity in the case of, for example, a tunnel junction between high- and low-temperature superconductors, we can expect V_c to be characterized by V_{c0} greater than or of the order of 1 mV:

$$V_{c0} \approx \frac{\Delta_l}{e} \ln \frac{4\Delta_h}{\Delta_l} \approx 6 \text{ mV}, T \ll T_{cl} \ll T_{ch}; \tag{3.2}$$

here, Δ_h (≈ 20 meV) and Δ_l (≈ 1.5 meV) are the values of the moduli of the order parameters of the two superconductors forming the junction, as deduced from the BCS theory using the critical temperatures of the two materials $T_{ch} \approx 100$ K and $T_{cl} \approx 10$ K.

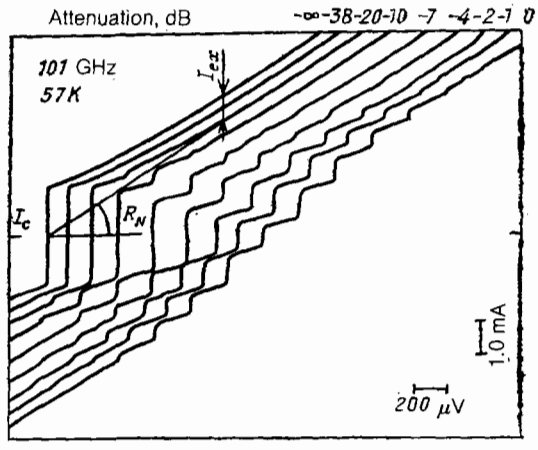

FIG. 2. Typical current-voltage characteristic of a Josephson junction with high-temperature superconducting electrodes and its evolution on increase in the microwave signal power.[223] Here, I_c is the critical current of the junction, R_N is the normal resistance of the junction, I_{ex} is the excess current. The numbers give the attenuation in decibels.

TABLE V. Principal parameters of Josephson junctions between high- and low-temperature superconductors.

Material	T_c, K	T, K	V_c, mV	R_N, Ω		Reference
Point contacts:						
YBaCuO/Nb	90	4.2	0.015	0.19	+*)	[142]
	90	1.9	0.81	73	+	[143]
	90	1.9	0.29	46	+	[144]
	92.5	4.2	0.16	2.4	+	[145]
	94	4.2	0.1	1.5	+	[146]
	89	4.2	0.1	100	+	[147]
	92	4.2	0.03	0.6	*	[148]
	93	4.2	0.12	4		[149]
	93	4.2	0.1	100	+	[150]
YBaCuO/Ag/Nb	90	3.9	0.005	0.08	+	[151]
YBaCuO/NbZr	85	4.2	0.65	150	+	[152]
YBaCuO/Pb	92	6.9	0.046	0.1	+	[153]
	94	4.2	0.8	10	*	[154]
$Ba_{0.6}Y_{0.4}CuO_3$/Pb	77	4.2	0.03	3	+	[155]
YBaCuO/Ta	94	2.85	0.75	15	+	[156]
YBaCuO/Sn	94	1.7	0.24	1	+	[156]
YBaCuO/(PbSn)	91	3.7	0.06	6	+	[157]
ErBaCuO/Nb	91	4.2	0.115	23	+	[145]
	83	4.2	0.1	0.1	+	[158]
BiSrCaCuO/Pb	74	4.2	0.5	10	*	[154]
BiSrCaCuO/Nb	76	4.2	0.015	5	*	[159]
TlCaBaCuO/Pb	125	4.2	0.3	10	*	[154]
	126	4.2	0.6	0.4	*	[160]
Tunnel junctions:						
YBaCuO/In	92	1.65	0.033	1.13	*	[161]
YBaCuO/CdS/In	92	1.8	0.005	0.18	*	[161]
YBaCuO/Au/AlO_x/Nb	90	4.2	0.04	0.8	+,*	[162, 163]
YBaCuO/AlO_x/Nb	90	4.2	0.61	7.6	+,*	[163, 164]
	90	4.2	0.037	4.1	+,*	[163, 164]
YBaCuO/SiO/Nb	90	4.2	0.1	7	*	[164]
YBaCuO/Ag/PbO_x/Pb	90	3.7	6	0.03		[90]
YBaCuO/Pb		4.2	0.36	6		[166]
SNS sandwiches:						
YBaCuO/Au/Nb:						
$d_{Au} = 30$ nm	67	4.2	0.013	0.00048	+	[62—65]
$d_{Au} = 50$ nm	64	4.2	0.007	0.0012	+	[62—65]
$d_{Au} = 100$ nm	63	4.2	0.0006	0.00016	+	[62—65]

*)Here, the symbols + and * denote papers in which the Shapiro steps were observed on exposure of junctions to a microwave signal (+) or the dependence of the supercurrent on the external magnetic field was nonmonotonic (*).

We can see that experimental values of V_c, with the exception of those reported in Ref. 90, differ from V_{c0} by at least an order of magnitude. In the case of the results reported in Ref. 90 a film of YBaCuO had silver electrodes 1000 Å thick and the resultant structure was subjected to additional annealing in an atmosphere of O_2 at $T = 550$ °C for 10 h. The silver electrode was coated with a film of Pb. The authors of Ref. 90 assumed that an oxide PbO_x acting as a tunnel barrier formed automatically at the Pb/Ag interface. The current-voltage characteristic of the resultant structure, which exhibited a strong hysteresis in the range of voltages below 6 mV, and the linear temperature dependence $I_c \propto T_{c0} - T$, where $T_{c0} \approx 6.3$ K $< T_{c1} = 7.2$ K, led to the conclusion that the structure obtained was a Josephson junction of the SNIS type. Unfortunately, this junction was not exposed to a microwave signal so that no clear proof was obtained of the occurrence of the Josephson effect in the junction.

Such low values of V_c are a natural consequence of the results presented in Sec. 2. Practically all the junctions for which the parameters are listed in Table V were prepared *ex situ* and in the course of their preparation the surfaces of the high-temperature superconducting electrodes were exposed to atmospheric air so that a surface layer with a semiconducting nature of conduction was formed on these electrodes. In the absence of any preliminary purification of the high-temperature superconducting material the critical currents of the point contacts formed in this way were very small ($\leqslant 5\,\mu$A) even at low temperatures. The destruction of the resultant layer and the formation of a contact required large forces which altered significantly the radius of the point and the superconducting properties of the grains in the high-temperature superconductors in the region of the contact.[142,147,174] Consequently, a weak link[144,174] could be localized not in the region of the point contact with the surface but at the neighboring grain boundaries. The use of single crystals as the high-temperature superconducting electrodes[158] did not increase V_c since again a nonsuperconducting layer was present on the surface.

Numerous attempts designed to use such a layer as a "natural barrier" in tunnel junctions between high- and low-temperature superconductors[167–173] have failed to reveal the Josephson effect. This is fully expected. As pointed out already in Sec. 2.3, the deposition of a metal on the surface of a high-temperature superconductor is accompanied by partial oxidation of the metal and additional damage to the superconducting ceramic surface. Therefore, in the absence of

buffer layers between high- and low-temperature superconductors, a thick insulating layer is formed at the interface between them and in practice this layer prevents observation of the Josephson effect.

A preliminary treatment of the surface of a high-temperature superconducting material (mechanical polishing or ion-bombardment cleaning) has made it possible to increase the current I_c for many point contacts by an average of one order of magnitude at $T = 4.2$ K (Refs. 148, 149, 157) and to form tunnel structures with $I_c \neq 0$ (Refs. 161 and 165). Nevertheless, it has not been possible to remove completely an insulating surface layer and low values of V_c have again been obtained.

In the case of tunnel junctions the critical current has been observed mainly in the presence of deliberately formed barriers, such as films of Cd (Ref. 161), AlO_x (Refs. 162–164), and SiO (Ref. 165). The chemical activity of these insulators (see Sec. 2.4) falls steeply as a result of cooling. Therefore, cooling of the high-temperature superconducting substrate and formation of a junction should stabilize the boundaries of the structure. In fact, water cooling[162–174] increases the critical current. Moreover, in the absence of the current[162,163] the junctions formed in this way fail to manifest the Josephson properties.

It is suggested in Ref. 175 that an insulating layer should be formed by chemical interaction with the surface of a high-temperature superconducting material consecutively in two stages: in an O_2 plasma and in a CF_4 plasma. However, YBaCuO/YBaCuO:F/Nb junctions formed in this way did not exhibit a critical current. Additional investigations of the structure of the junctions showed that a short (<0.5 min) treatment in CF_4 caused niobium to react chemically with YBaCuO and a longer treatment (>2 min) induced diffusion of fluorine into a high-temperature superconductor to greater depths and destroyed the superconductivity in a layer of thickness in excess of 0.3 μm.

An alternative method for cleaning in the process of preparation of the surfaces of high-temperature superconductors was used in Refs. 143, 146, 166, and 176. Before the formation of a point[143,146] or tunnel[166] contacts a part of a high-temperature superconducting material was cleaved at a helium temperature and the resultant surface was used in the subsequent operations. However, the results obtained for junctions prepared by this method did not show an increase in V_c (as demonstrated in Table V). Most probably[177] a polycrystalline sample was split along inner grain boundaries and a material with properties different from those inside the grains again appeared on the surface. It was proposed in Ref. 166 to avoid contacts with grain boundaries by sawing a nick in the substrate and then fracturing it in helium together with an epitaxially grown film deposited on this substrate. This should produce an end surface formed not only by inner grain boundaries, but also by the superconductor itself. Evaporation of a lead film in vacuum without any exposure to air made it possible[166] to prepare tunnel junctions with $V_c \approx 0.5$ mV (at $T = 4.2$ K).

In contrast to point contacts and tunnel junctions, studies of the Josephson effect in SNS-type structures between high- and low-temperature superconductors, was carried out only by one team of researchers.[62–65] They formed YBaCuO/Au/Nb sandwiches *ex situ* and before deposition of a gold film they subjected the surface of the high-temperature superconductor to ion cleaning. This method of formation of an ohmic boundary led (see Secs. 2.2 and 2.3) to relatively high surface resistances. This was indeed confirmed experimentally: the normal resistance of the sandwiches $R_N \approx 10^{-3}$ Ω was considerably higher than an estimated resistance of the gold spacer $R_{sp} \approx 10^{-9}$ Ω and corresponded to values $R_B \approx 10^{-7}$ Ω·cm^2

Unfortunately, the majority of the experimental investigations analyzed in this section were of the demonstration type and yielded qualitative results designed simply to confirm the existence of the Josephson effect in structures formed between high- and low-temperature superconductors. Studies of point contacts (with the exception of that reported in Ref. 142) did not exhibit the dependences $V_c(T)$ and the dimensions of tunnel junctions and SNS sandwiches were considerably greater than the Josephson penetration depth λ_J. Therefore, in the subsequent discussions (see Sec. 5) we shall confine ourselves only to an analysis of the experimental data reported in Ref. 142.

4. JOSEPHSON JUNCTIONS BETWEEN TWO HIGH-TEMPERATURE SUPERCONDUCTORS

The structures formed by Josephson junctions between two high-temperature superconductors have exhibited a greater variety. In addition to the structures already obtained (point contacts,[149,152,154,160,178–186] SNS sandwiches,[123] and SN–N–NS variable-thickness bridges[91,187]), the Josephson effect was discovered also in junctions at grain boundaries of ceramics (of the break junction type[188–190] or bulk junction type[191–209]), in high-temperature superconducting films,[210–242] and also in microcracks within grains.[243,244]

As in the case of structures formed between high- and low-temperature superconductors, the current-voltage characteristics of junctions between two high-temperature superconducting materials can exhibit the Shapiro steps at voltages related to the microwave signal frequency by the Josephson expression given by Eq. (3.1). In some cases the number of these steps increased up to 30. In Ref. 209, Eq. (3.1) was used to determine accurately the ratio $2e/\hbar$, which with a relative precision of 5.6×10^{-6} was identical with the value determined for junctions between two low-temperature superconductors. Nonmonotonic dependences of the supercurrent on an external magnetic field have been observed for single junctions,[195,204,206,207] as well as for two- and one-contact interferometers used in SQUID magnetic flux sensors.[192,212–215,217,220,221,225,233,235,240,241] However, these data do not provide any information on macroscopic quantum effects in high-temperature superconductivity in addition to that presented in the preceding section.

The experimental values of the characteristic voltage V_c of practically all contacts between two high-temperature superconductors, with the exception of those reported in Refs. 243 and 244 (Table VI), have been at least an order of magnitude lower than the naive theoretical estimate of the same quantity:

$$V_{c0} \approx \frac{\Delta_h(0)}{e} \approx 20 - 30\,\text{mV}, \quad T \ll T_{ch}. \tag{4.1}$$

obtained for tunnel SIS structures with high-temperature superconducting electrodes.

TABLE VI. Principal parameters of Josephson junctions between two high-temperature superconductors.

Materials	T_c, K	T, K	V_c, mV	R_N, Ω		Reference
Point contacts:						
YBaCuO/YBaCuO	93	4.2	0.08	2—500		[149]
	94	4.2	0.12	60		[154]
	85	4.2	0.2	100	+*)	[152]
	94	4.2	0.03	6		[178, 179]
	95	4	0.2		+	[180]
	95	4	0.7	40	+	[180]
	97	4.2	0.06—0.08	0.5—5		[181]
	91	4.2	До 0.5	10—50	*	[182]
	93	4.2	0.04	0.25	*	[183]
	88	77	0.04	2	+	[184]
		77	0.01	2		[185]
YBaCuO/BSCCO		4.2	0.75	1500		[154]
YBaCuO/TCBCO		4.2	0.2	20		[154]
CdBaCuO/CdBaCuO	94	2	0.05	50	+	[186]
BiSrCaCuO/BSCCO	74	4.2	2	100		[154]
TlCaBaCuO/TCBCO	125	4.2	0.7	70		[154]
Grain-boundary contacts:	122	10	0.14	14	*	[160]
YBaCuO	90	4.2	1	0.05	+	[188]
(break junctions)	90	4.2	2	0.2	+	[189, 190]
YBaCuO	80	4.2	0.4	0.1	+	[191]
(bulk junctions)	93	10	3	2	*, +	[192]
	88	50	0.22	0.002	+	[193]
	90	77	0.16	0.38	+	[199]
		77	0.5	0.1	*, +	[195]
	87.8	77	0.2	0.02	+	[196]
	87.8	77	0.05	0.08	+	[196]
	93	77	0.2	2	*,+	[192]
		77	0.03	0.03	+	[197]
	90	77	0.03	0.006	+	[198]
	92	77	0.45	6	+	[199]
	93	77	0.07	0.07	*, +	[200]
	91	77	1.6	0.008		[201]
	90	77	0.03	0.005	*, +	[202]
	80	77	<1	0.1—10		[243]
		77	0.05	0.5	+	[203]
BiSrCaCuO	54	4.2	0.21	1.2	*, +	[204]
TlBaCaCuO	118	77	0.18	0.08	+	[205]
YBaCuO	90	4.2	0.06	0.5	+	[229]
(film)	85	4.2	0.01	0.001		[237]
	78	4.2	0.5	0.01	*	[213]
	91	4.2	0.5	0.25	*, +	[214, 215]
	81	4.2	0.23	1.4	+	[239]
	89	4.2	1.5	0.03	+	[238]
	88	5	1	1.13	+	[226—228]
	74.5	5.5	2	1	*	[212]
	88	24	0.2	8		[216]
		41	<3	3	*	[219]
	70	43	0.1	0.36	*, +	[225]
	86	57	0.48	0.3	+	[223]
	70	60	0.006	0.14	*, +	[225]
	78	70	0.02	1.25	*, +	[221]
	91	77	0.1	0.4	*, +	[214, 215]
	90.7	77	0.18	0.3	*, +	[221]
		77	0.14	14		[236]
	85	77	0.04	0.16	*, +	[235]
	90.7	77	0.18	0.3	+, *	[222]
BiSrCaCuO	70	4.2	3	100	*	[240]
TlBaCaCuO	114	77	1.4	2	*	[220]
TlBaCaCuO	105	77	0.26	0.07	*	[233]
	105	77	0.08	0.13	*	[233]
	105	77	0.34	0.2	*	[233]
Microcrack junctions in grains:						
YBaCuO	90	4.2	5.5		+	[243]
BiSrCaCuO	87	4.2	19		+	[243, 244]
TlBaCaCuO	108	4.2	20		+	[243]
Tunnel junctions:						
YBaCuO/YBaCuO	50	4.2	0			[246, 247]
Weak links:						
sandwich						
YBaCuO/Ag/YBaCuO	80	4.2	1.5	0.1	+	[123]
variable-thickness bridge						
YBaCuO/Ag/YBaCuO	90	4.2	0.0035	0.33	+	[91]

*) Here, the symbols + and * denote papers in which the Shapiro steps were observed on exposure of junctions to a microwave signal (+) or the dependence of the supercurrent on the external magnetic field was nonmonotonic (*).

4.1. Point contacts

Formation of point contacts between two high-temperature superconductors meets with the same difficulties, associated with the destruction of a nonsuperconducting surface layer in high-temperature superconducting materials, as in the case of analogous junctions between high- and low-temperature superconductors. The values of the characteristic voltage in the case of contacts between two high-temperature superconductors[149,152,154,178–186] at $T = 4.2$ K lie within a range 0.1–1 mV and the critical optical currents are low ($< 5\ \mu$A). On increase in temperature ($T > 40$ K) these currents are usually suppressed by thermal fluctuations. Therefore, we shall not consider in detail the results obtained for these structures.

4.2. Junctions at microcracks (break junctions)

A Josephson junction of the break type is formed as a result of deformation of a bulk polycrystalline sample at helium or nitrogen temperatures[181–183] when such a sample is supported, for example, by a spring. Such deformation is interrupted immediately after fracture (manifested by a steep rise of the resistance).

The contacts prepared by this method from samples with transverse dimensions exceeding greatly the average size of grains have values of V_c not exceeding several millivolts at helium temperatures and the corresponding values of R_N are in the range 0.1–10 Ω. An internal crack in such a sample follows grain boundaries and a Josephson junction appears at one or several such boundaries in the region of a fracture. Junctions of this type are extremely unstable and their parameters vary as a result of cycling of external conditions. We shall therefore ignore the results obtained for these junctions.

4.3. Junctions at internal grain boundaries

In junctions of this type a weak link is established between grains in metal oxide ceramics. In the case of bulk samples (bulk junctions),[140,181–200] such junctions are formed mechanically by reducing the thickness of the sample in one or two dimensions. In the case of thin films[210–242] a similar result can be obtained by an abrupt change in the width of a part of a film (formation of a Dayem bridge) produced by photolithography[192,212–223] or by laser beam ablation.[224–228] Similar results follow irradiation of an additional part of a film with ions[229–233] or injection of quasiparticles;[218] Local thermal diffusion of gold along grain boundaries in high-temperature superconducting ceramics can also be used.[242]

Investigations of junctions at grain boundaries can be divided into two groups. The first (and more numerous) includes studies of structures containing a statistically large number of grain boundaries in the region where the supercurrent is concentrated. This makes it quite difficult to interpret the results obtained and may result in suppression of the amplitude of the Shapiro steps in the current-voltage characteristics[11] or it may induce subharmonic singularities in these characteristics.[193,198,245] The temperature dependences of the critical current $I_c(T) \propto (T_c - T)^n$ at $T \approx T_c$ established experimentally for these junctions can also vary greatly. The power exponent n in such dependences is reported to be close to 2 in Refs. 197, 210, 221, 222, and 225, whereas according to Refs. 191, 212, 213, and 237 it is 3/2 and the value $n = 1$ is given in Refs. 197, 199, 217, and 228. Moreover, as in any other granulated system, an increase in the supercurrent first results in destruction of the separate weaker parts of the junction. This leads to typical "humped" (at low voltages) current-voltage characteristics with a critical current which is difficult to determine. Clear information on the properties of the individual grain boundaries is very difficult to obtain from an analysis of such current-voltage characteristics. We shall therefore not consider the properties of these junctions.

It is much more interesting to discuss the results of investigations of junctions with few boundaries in the region where the supercurrent is concentrated.[221–228,233,238] Such junctions are of the Dayem bridge type and they can be formed if the size of a grain in the original high-temperature superconducting film is comparable with the geometric dimensions of the constriction where the supercurrent is concentrated. In the case of ceramics based on Bi (Refs. 243 and 244) and Tl (Ref. 233) the formation of large grains presents no serious difficulties. In the case of YBaCuO films it is possible to form large (5–100 μm) grains by annealing at high ($\geqslant 900$ °C) temperatures.[221–225,238]

In spite of the use of different high-temperature superconducting materials, the grain-boundary junctions have a number of properties in common. Firstly, their specific normal resistance R_N lies in the range 10^{-7}–10^{-8} Ω·cm^2. It is important to note that an increase in temperature may reduce R_N considerably (Refs. 225 and 238). Secondly, the current-voltage characteristics of these junctions[221–228,238] are typical of structures with direct conduction (an excess current is observed at high voltages and there is no hysteresis). Thirdly, the absolute values of the characterstic voltage of such contacts are considerably less than the limit described by Eq. (4.1), and the rate of rise of V_c falls strongly as a result of cooling, so that at temperatures in the range $T/T_c \lesssim 0.3$ the dependence $V_c(T)$ becomes practically a plateau.[224,225,238]

The results of an investigation of the dependences of the properties of grain boundaries on the mutual orientation of crystallographic axes forming a grain boundary are of special interest.[226–228]

4.4. Influence of grain misorientation on properties of grain-boundary junctions

A series of investigations[226–228] of a bicrystal $SrTiO_3$ film made it possible to grow epitaxially structures in the form of a YBaCuO crystal characterized by $T_{ch} \approx 86$–88 K with the temperature width of the superconducting transition $\Delta T \approx 3$–6 K. The geometry of the substrate crystals was selected so that the vectors [0, 0, 1] for the grown crystals were perpendicular to the substrate and the vectors [1, 0, 0] of the components of the bicrystal met at an angle of θ. A laser beam was used to cut superconducting strips 10 μm wide in each of them and such a strip contained a grain boundary (Fig. 3). Investigations of this boundary in a transmission electron microscope as well as the results of ion spectroscopy demonstrated that the boundary was abrupt on the atomic scale and its composition was close to that of the grains (small differences in the concentrations of Sr and Ti occurred only in the immediate vicinity of the substrate).

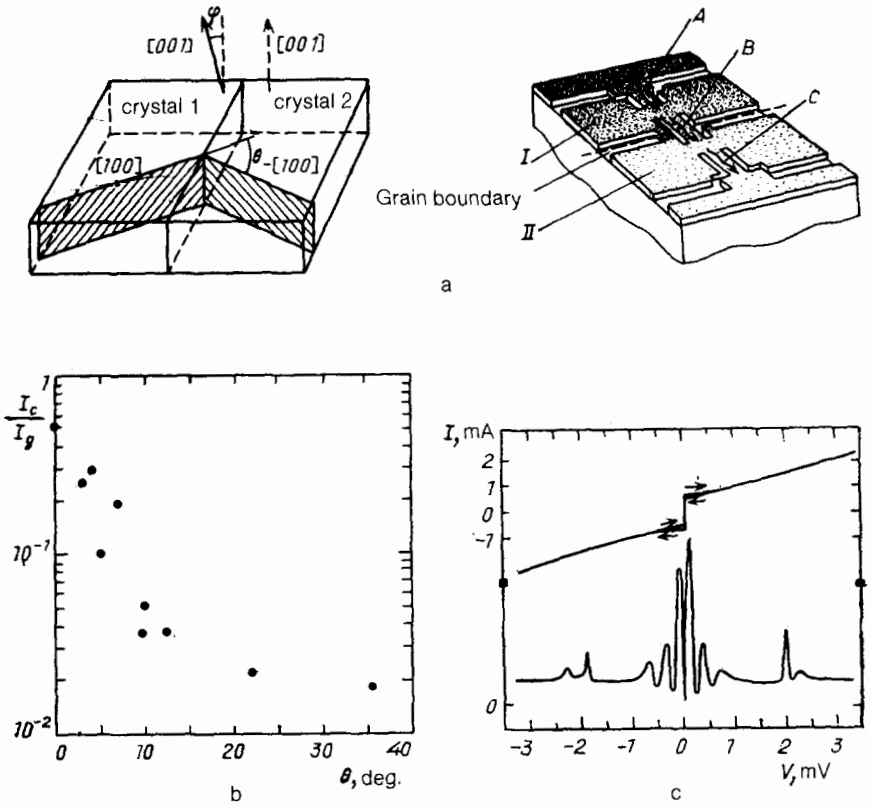

FIG. 3. Main results of an investigation of the influence of grain misorientation on the properties of grain-boundary high-temperature superconducting junctions.[226-229] a) Schematic representation of a grain boundary and an associated junction. b) Dependence of the ratio of the critical current of the grain boundary to the critical current of the grain on the misorientation angle θ (at $T = 5$ K). c) Current-voltage characteristic of the junction and its first derivative (in relative units) at $T = 5$ K for $\theta \approx 37°$.

The average distance b between dislocations localized at the boundary decreased ($b \propto \theta^{-1}$) on increase in θ and in the range $\theta \gtrsim 10°$ the dislocation regions overlapped.

The presence of dislocations gave rise to a strong dependence of the critical current of the boundary I_c on the angle θ (Fig. 3): it fell approximately by a factor of 50 when the angle θ was increased from 0° to 20° and reached a practically constant value in the range $\theta \gtrsim 20°$. The results obtained in Ref. 227 for films with very different densities of the current in the grains all fitted the same curve and were in mutual agreement.

The dependence of the critical current in a boundary I_c on a magnetic field B perpendicular to the film was very different from the dependence of the critical current in a grain I_g on the same field B. The value of I_g fell approximately twofold on increase in B from zero to 1 T, whereas an increase in the field from zero to 0.002 T suppressed I_c by about an order of magnitude in the angular range $\theta \gtrsim 5°$. Such a sensitivity to small changes in the magnetic field was typical of weak links.

The temperature dependences of the critical currents I_c and I_g were found to be practically the same for grains oriented in the same way ($\theta \lesssim 2.5°$). However, in the range $\theta \gtrsim 5°$ there were qualitative differences between these dependences.

A characteristic voltage of the structures described in Refs. 226–228 was in the range 0.15–3 mV at $T = 4.2$ K, which was considerably lower than the estimate obtained from Eq. (4.1). Unfortunately, the absence of any data on the reaction of the junctions to microwave radiation and the normal resistance made it impossible to analyze the reported results in detail. One could simply say that the differences between the orientations of the crystallographic axes of the grains in contacts amounting to a few degrees ($\gtrsim 5°$) were sufficient to form a grain-boundary Josephson junction.

The above analysis of the experimental results obtained for grain boundaries thus indicates that the most reliable information on the Josephson properties of these boundaries is given in Refs. 221–225, 233, and 238. A more detailed analysis of these results will be made in Sec. 5.

4.5. Junctions at microcracks in crystals

A bulk polycrystalline sample with grains of 100–200 μm size was used in the studies reported in Refs. 243 and 244:. it was bonded to a substrate (in such a way that the c axis was perpendicular to the substrate) and ground down to a thickness of 0.1 mm, comparable with the grain size. Then, a constriction 0.1–0.2 mm wide was formed mechanically in the central part of the sample; the usual method (described in Sec. 4.2) was then employed to form a microcrack at helium or nitrogen temperature. In the case of junctions with high values of V_c the crack usually passed along twinning boundaries within a single grain located in the constriction region. Therefore, a Josephson junction was formed at an interface between crystal blocks with the [0, 0, 1] crystallographic axes oriented almost parallel in the two blocks.

When junctions characterized by $V_c > 5$ mV were subjected to high voltages, the current-voltage characteristics recorded during cooling exhibited a transition from an excess current to a deficit (Fig. 4). At low voltages the junctions formed in BiCaSrCuO exhibited a clear hysteresis and frequently a nonmonotonic temperature dependence of the

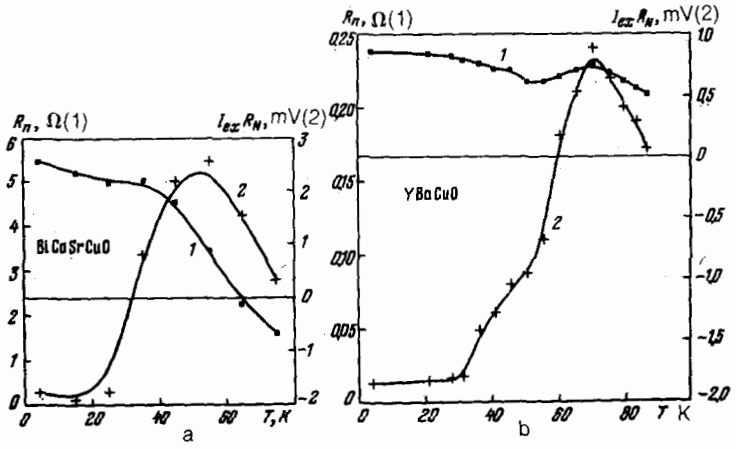

FIG. 4. Temperature dependences of the normal resistance R_N and of the excess current I_{ex} of junctions formed at microcracks in grains. a) Junctions made of BiCaSrCuO ($V_c \approx 7.8$ mV). b) Junctions made of YBaCuO ($V_c \approx 5$ mV).

critical current (with a maximum at $T \approx 0.7T_c$). However, these effects were absent in the case of samples made of YBaCuO and TlCaBaCuO. It is interesting to note that the junction resistance in the normal state R_N increased as a rule on reduction in temperature (Fig. 4), which most likely indicated the existence (see Sec. 5) of a channel of indirect tunneling of electrons via localized states in a weak-link material.

The results obtained in Refs. 243 and 244 were of fundamental importance. They provided the first experimental demonstration of the feasibility of formation of Josephson high-temperature superconductor junctions with high [close to the theoretical estimate given by Eq. (4.1)] values of the characteristic voltage.

4.6. Tunnel junctions between two high-temperature superconductors

We are aware of just two reports[246,247] of an attempt to form a YBaCuO/YBaCuO tunnel junction. Textured films (with the c axis perpendicular to the substrate) used as electrodes in the study reported in Ref. 246 were about 1 μm wide and had a thickness of the same order of magnitude, and they exhibited a transition to the superconducting state at $T \approx 50$ K.

The most important feature of the formation of a junction was the absence of a high-temperature annealing stage in the case of separate films and of the structure as a whole. An insulating barrier was formed on the surface of one of the electrodes as a result of a 20-min treatment in a CF_4 plasma at a pressure of 0.5 Torr when the power supplied to the discharge was 100 W. After the formation of this barrier a second electrode was deposited on the first film under the same conditions. The method used to form junctions in the second study[247] was practically the same.

The structures made in this way exhibited a current-voltage characteristic at $T = 4.2$ K which was typical of NIS junctions with a clear singularity at a voltage $V = \Delta_h/e$, where $\Delta_h \approx 18$ mV was the order parameter of the superconductor; the leakage current was low and the critical current was zero.

These results were in full agreement with the data obtained for tunnel junctions between high- and low-temperature superconductors with a "natural" barrier and for YBaCuO/YBaCuO:F/Nb junctions, indicating perhaps that little advantage would be gained from the use of a surface high-temperature superconducting layer as an insulating spacer in tunnel junctions.

4.7. Structures of the SNS type

The Josephson effect in SNS structures with high-temperature superconducting electrodes was observed for junctions formed both *ex situ* (Refs. 91 and 123) and *in situ* (Ref. 187).

The process used in the fabrication of SNS sandwiches[123] consisted, as the first stage, of evaporation and annealing in an oxygen atmosphere of two YBaCuO films on different substrates. Then, the surfaces of these films were coated by a thin (5–20 nm) silver film and the samples were subjected to a fast heat treatment (heating to 400 °C in 30 s, holding at this temperature for 60 s, cooling to room temperature in 30 s). In the absence of such a fast heat treatment it was not possible to form contacts characterized by the Josephson properties. These substrates were deposited crosswise and were pressed mechanically until a contact was established. The parameters of such a junction with a silver film 5 nm thick were as follows at $T = 4.2$ K: $V_c \approx 2$ mV, $R_N \approx 0.13\ \Omega$. The value of R_N was considerably higher than the resistance of the silver film ($\approx 10^{-5}\ \Omega$) indicating that the transparency of the SN boundaries in the investigated structure was low.[123]

A method of fabrication of SN–N–NS variable-thickness bridges described in Ref. 91 consisted of three stages. In the first two stages the methods of direct photolithography and electron lithography were used to form two YBaCuO films separated by a gap of 1 μm. Annealing in an oxygen atmosphere was followed by the formation, using explosive photolithography, of a gold film 0.24 μm thick and 10×10 μm dimensions (when viewed from above); this film joined the electrodes. The junction was then annealed additionally in an oxygen atmosphere (10 s, $T = 750$ °C). The results reported in Sec. 2.3 indicated that the SN interface formed in this way should have a low transparency. This was manifested experimentally by the junction resistance $R_N \approx 0.33\ \Omega$, which was an order of magnitude higher than the resistance of the bridging film (0.015 Ω). The value of the parameter V_c was very low ($\approx 3.6\ \mu$V at $T = 4.2$ K) because the length of the bridging film was large compared with the coherence

length of gold and because of the low transparency of the SN interface.

One of the possible ways of forming SN–N–NS variable-thickness bridges *in situ* was described in Ref. 187. The main idea was to use the ability (mentioned in Sec. 1) of ceramics to react with insulating substrates. A substrate made of a chemically less active insulator (MgO) carried a narrow (1 μm) strip consisting of a more active material (Si). This was followed by deposition of a YBaCuO film which was 200 nm thick. In the process of deposition the substrate temperature was maintained at 650 °C. At this temperature it was found that barium and copper silicides formed actively at the interface with silicon. Consequently, the superconducting phase appeared only on MgO and a nonsuperconducting compound with a large specific resistance formed on Si. The bridge structure was produced by deposition of a silver film connecting the superconducting electrodes. The parameters of the junction describing Ref. 245 were as follows at $T = 4.2$ K: $V_c \approx 70\,\mu$V, $R_N \approx 0.54\,\Omega$. Unfortunately, the reaction of the junction to a microwave signal was not investigated in the former case.[187]

The current-voltage characteristics of all three junctions were typical of the Josephson structures with direct conduction. In Sec. 5 we shall return to a discussion of the results of these investigations.

4.8. Twinning boundary as a possible Josephson contact

Investigations of the dependences of the critical current in one-and two-contact interferometers on an external magnetic field have frequently revealed (see, for example, Ref. 225) oscillations corresponding to contours of quantization of a magnetic flux much smaller than the average grain size in high-temperature superconducting films. One of the hypotheses explaining this fact was the assumption that these intragrain contours included twinning boundaries exhibiting the Josephson effect. However, to the best of our knowledge, a direct proof of this hypothesis is still lacking.

5. DISCUSSION OF THE EXPERIMENTAL DATA. COMPARISON WITH THE THEORY

There many theoretical approaches to the problem of high-temperature superconductivity (a brief review can be provided, for example, in Ref. 6), but none of them can account for all the observed properties of high-temperature superconductors. Therefore, an analysis of the experimental data on high-temperature superconducting contacts will be made using models developed on the basis of the BSC theory.

5.1. Models of short weak link

The properties of junctions with an extremely short length L can be described either by the Ambegaokar–Baratoff (AB) theory [248] (which applies in the case of the tunnel conduction process) or by the Kulik–Omel'yanchuk theories (KO-1, KO-2)[249] (in the direct conduction case). At $T \approx T_c$ all three theoretical models predict that V_c should obey a universal temperature dependence

$$V_c(T) = A(T_c - T), \quad A = \frac{\pi}{4e}\left|\frac{d\Delta^2}{dT}\right|_{T=T_c} \approx 635\ \mu\text{V/K}. \quad (5.1)$$

When the temperature T of the junction is lowered, the KO theories predict an increase in the parameter V_c at a somewhat faster rate than that deduced from the AB theory, but the maximum difference between the absolute values of V_c obtained in these two cases does not exceed 50%. At high voltages ($\geqslant \Delta_h/e$) the current-voltage characteristics predicted by these models differ mainly by the presence (in the nontunnel conduction case[250–255]) or the absence (in the tunnel case[257–259]) of an excess current.

Comparison of these results with the experimental data (given in Secs. 3 and 4) shows that, contrary to the frequent assertions [based on an analysis of the dependences $I_c(T)/I_c(0)$], the predictions of the AB and KO theories are relatively close to the experimental dependences $V_c(T)$ obtained for junctions at microcracks in grains[243,244] (Fig. 5). However, even in the case of these structures the two theories fail to account for all the experimental observations, such as an increase in the normal resistance and a change from an excess to a deficit of the current exhibited by the current-voltage characteristics when a junction is cooled. The theoretical predictions can be made to match the experimental results better only by using more complex KO and AB models.

5.2. More complex models of direct-conduction junctions

The first factor in the more complex KO model, which is the finite length of a weak link, is allowed for in a simple model of SNS junctions described in Refs. 260–262. This model ignores suppression of the superconductivity of the S electrode because of the proximity of the N metal, whose critical temperature is assumed to be zero.[5)]

Calculations carried out using this model in the "dirty" ($l \ll \xi_N^*$)[250,251] and "clean" ($l \gg \xi_N^*$)[252,254] limits predict an excess current in the current-voltage characteristics and the values of R_N governed either by the N layer resistance (in the case when $l \ll \xi_N^*$) or by the resistance due to the nonequilibrium nature of the distribution function of electrons

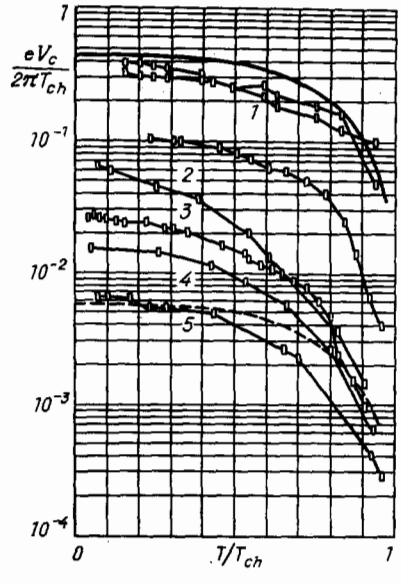

FIG. 5. Experimental temperature dependences of the characteristic voltage V_c recorded for microcrack junctions in grains observed in TlCaBaCuO, BiCaSrCuO, and YBaCuO (curves labeled 1, data taken from Refs. 243 and 244), and for grain-boundary junctions (curves 2–5, data taken from Refs. 221–223, 238, 224, and 225). The continuous curve is the dependence $V_c(T)$ plotted using the AB theory. The dashed curve is the same dependence but with a lower value of $V_c(0)$ (see Sec. 5.3).

in the S electrodes (in the case when $l \gg \xi_N^*$). The parameter V_c (see graphs in Refs. 260 and 261) decreases on increase in the thickness of the N layer in accordance with a power law [$V_c \propto (\Delta(0)/e)(\xi_N^*/L)^2$] at temperatures $T \leqslant T_0 \approx T_c(\xi_N^*/L)^2$ and exponentially $\{V_c \sim (\Delta/e)\exp[-(L/\xi_N^*)(T/T_c)^{1/2}\}$ at $T \geqslant T_0$. In the vicinity of T_0 there is change in the sign of the curvature of the dependence $V_c(T)$ from positive ($T > T_0$) to negative ($T < T_0$).

In spite of the possibility of describing, on the basis of this model, the experimentally observed suppression of the characteristic voltage of a junction, the actual application of the model gives rise to a number of discrepancies with the experimental data for practically all the high-temperature superconducting junctions.:

1) The values $V_c \leqslant 1$ mV observed for these junctions can be explained if we assume that $L \geqslant 10\xi_N^*$. However, for these values of L the characteristic temperature $(T_0)_{theor} \approx 0.01T_c$ is considerably less than the temperature $(T_0)_{exp} \approx 0.3T_c$ at which there is an experimentally observed change in the sign of the curvature of the dependence $V_c(T)$. An allowance for a strong spatial inhomogeneity of the junction over its area does not eliminate this contradiction.

2) A simple SNS model cannot account for the change from an excess to a deficit of the current exhibited by the current-voltage characteristics of junctions formed at microcracks in grains characterized by $V_c \geqslant 10$ mV.

3) This model also does not account for the high experimental values of the normal resistance of the junctions $(R_N)_{exp} \approx 10^{-7}$–$10^{-8}$ $\Omega \cdot cm^2$. In fact, if $L \approx 10\xi_N^*$, then in the case of structures formed from noble metals ($\rho_N \approx 10^{-6}$ $\Omega \cdot cm^2$, $\xi_N^* \approx 20$ nm) the maximum theoretical values $(R_N)_{theor} \approx \rho_N L$ do not exceed[6] 10^{-10} $\Omega \cdot cm^2$. Since the absolute values of the resistance of high-temperature superconducting films in the case of the normal and semiconducting temperature dependences of $R(T)$ in the vicinity of T_c differ on the average by no more than one order of magnitude, it is reasonable to estimate R_N for junctions at grain boundaries by assuming that $\rho_N \approx \rho_S \approx 10^{-4}$ $\Omega \cdot cm^2$ and $\xi_N^* \approx \xi_S^* \approx 1$ nm, which again gives $(R_N)_{theor} \approx 10^{-10}$ $\Omega \cdot cm^2$.

Another possible reason for the suppression of V_c is the mutual nature of the proximity effect in the vicinity of an SN interface. If the metals forming an SNS junction satisfy the "dirty" limit conditions [if the mean free path of electrons obeys $l \ll \xi_N^* = (D_N/(2\pi T_{ch})^{1/2})$], then V_c depends (for $L \gg \xi_N^*$) on two suppression parameters[7] describing this effect:[265–267]

$$\gamma = \frac{\rho_S \xi_S^*}{\rho_N \xi_N^*}, \quad \gamma_B = \frac{R_B}{\rho_N \xi_N^*}. \tag{5.2}$$

The parameters γ and γ_B have a simple physical meaning. The former is in fact governed (in the case of the simple gas model) by the ratio of the electron densities $n_{s,n}$ in the two metals in contact. If $n_n > n_s$, i.e., if $\gamma \gg 1$, then in the vicinity of the interface there are many quasiparticles which diffuse (if $\gamma_B = 0$) into the superconductor and suppress the order parameter at distances amounting to about ξ_S^*. In the opposite case ($\gamma \ll 1$) the proximity to a normal metal has little effect on the properties of a superconductor: its order parameter is practically constant right up to the interface and the Cooper pairs penetrate the normal metal to a depth of ξ_N^*.

The second parameter (γ_B) differs from zero if an insulating barrier is present at the SN interface or if this interface is abrupt on the atomic scale and separates metals with very different transport properties.[8] A reduction in the interface transparency (i.e., an increase in γ_B) limits the diffusion of quasiparticles from the N metal to the superconductor, and the value of Δ_h at the SN interface increases. However, since this gives rise to a discontinuity of the anomalous Green functions at the interface, the values of these functions for the N metal are lower than in the case when $\gamma_B = 0$. Therefore, an increase in either of the parameters γ or γ_B weakens the superconducting properties of the N metal and suppresses V_c.

In estimating the values of γ and γ_B for the interface between a high-temperature superconductor and Ag or Au we shall use parameters typical of metal oxide ceramics and films of noble metals: $\xi_S^* \approx 0.5$ nm, $\rho_S \approx 2 \times 10^{-3}$ $\Omega \cdot cm^2$ (Refs. 1–3), $\xi_N^* \approx 10^2$ nm, $\rho_N \approx 2 \times 10^{-6}$ $\Omega \cdot cm^2$ (Refs. 62–65 and 91), and the values $R_B \approx 10^{-8}$–10^{-10} $\Omega \cdot cm^2$ taken from Table II. Substituting these parameters into Eq. (5.2), we obtain

$$\gamma_B \approx 25 - 2500, \quad \gamma \gg 1. \tag{5.3}$$

For this ratio of γ and γ_B the superconducting electrodes should exhibit a practically homogeneous (in space) superconducting state and the anomalous Green functions Φ_N induced by the proximity effect in the case of the N metal should be small compared with πT. A calculation[267,268] of the parameters of SNS sandwiches with a spacer made of a "dirty" normal metal of thickness L, carried out for the case of practical interest defined by

$$\gamma_B \gg \left(\frac{T_{ch}}{T}\right)^{1/2}, \quad \gamma_B^{-1} \ll \frac{L}{\xi_N^*} \ll \gamma_B$$

leads to the following expressions:

$$\frac{eV_c}{2\pi T_{ch}} = \frac{2}{\gamma_B}\left(\frac{T}{T_{ch}}\right)^{1/2} \sum_{\omega > 0} \frac{\Delta_h^2}{\omega^2 + \Delta_h^2}\left(\frac{\pi T}{\omega}\right)^{1/2} \mathrm{sh}^{-1}\left[\frac{L}{\xi_N^*}\left(\frac{\omega}{\pi T_{ch}}\right)^{1/2}\right]; \tag{5.4}$$

$$R_N = 2\rho_N \xi_N^* \gamma_B S^{-1}; \tag{5.5}$$

here, S is the area of a transverse section through the junction and $\omega = \pi T(2n + 1)$ are the Matsubara frequencies. The dependences $V_c(L,T)$ calculated from Eq. (5.4) for different values of L and T are plotted in Fig. 6. They allow us to estimate quite simply the values of γ_B using the experimental data.

For example, it is reported in Ref. 123 that in the case of junctions of the SNS sandwich type characterized by $T/T_c \approx 0.05$ and $L/\xi_N^* \approx 0.5$ it is found that $eV_c/2\pi T_{ch} \approx 0.035$. Using Fig. 6 we find that these data are in agreement with theoretical calculations if we assume a reasonable value $\gamma_B \approx 100$. Unfortunately, much information needed in a further comparison is not given in Ref. 123: we would like to know the temperature dependences of I_c, I_{ex}, and R_N, as well as the dependences of I_c on an external magnetic field H, which could be used to estimate the effective contact area S. It should be pointed out that in the case of YBaCuO/Au/Nb junctions in which the interface with gold has approximately the same specific resistance,[62–65] the difference between the total and effective [determined from the dependence I_c

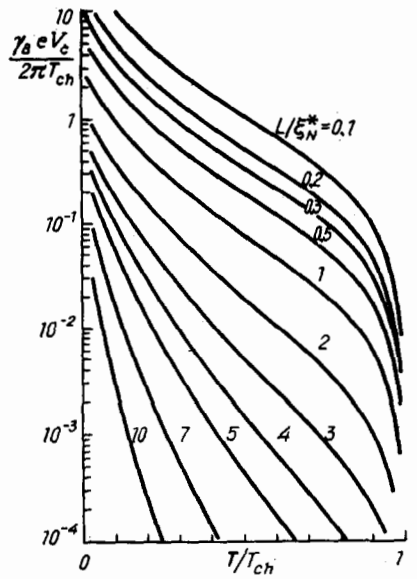

FIG. 6. Temperature dependences of the characteristic voltage V_c for SNS sandwiches with low-transparency SN interfaces and different thicknesses of the N layer.

(H)] junction areas is two orders of magnitude, which may be due to a strong inhomogeneity of the interface between a high-temperature superconductor and Ag or Au (see Sec. 2). Substitution of $\gamma_B \approx 100$ into Eq. (5.4) gives $S \approx 10^{-8}$ cm^2, which is again much smaller than the total area of the investigated contact.[123]

Application of the same theory (characterized by $\gamma_B \gg \gamma$) to SNS junctions with a complex geometry, such as variable-thickness bridges of the SN–N–NS type, gives rise to large depths of penetration of the normal and superconducting currents into the N film of the composite SN electrode.[269] For this reason, the resistance of the SN interface makes a finite contribution to the total junction resistance in the normal state:

$$R_N = \rho_N (L + 2\xi_{SN}^* \gamma_{BM}^{1/2}) S_t^{-1}, \; d_N \ll \xi_{SN}^* \gamma_{BM}^{1/2}, \; \gamma_{BM} = \frac{\gamma d_N}{\xi_{SN}^*}, \tag{5.6}$$

where S_t is the area of the transverse section of the N film and d_N is its thickness. The temperature dependence of the parameter V_c in the case defined by

$$1 + \gamma_{BM} \gg \max\left\{\gamma_M\left(1 - \frac{T}{T_c}\right)^{-1/2}, \left(\frac{T_c}{T}\right)^{1/2}\right\}, \; L \ll \xi_{SN}^* \gamma_B^{1/2} \tag{5.7}$$

is given by the expression

$$V_c = \frac{2\pi T}{e} \sum_{\omega > 0} \frac{\Delta_h^2}{\omega^2 + \Delta_h^2} \left(\frac{\pi T_{ch}}{\omega \gamma_{BM}}\right)^{3/2} \exp\left[-\frac{L}{\xi_{SN}^*}\left(\frac{\omega}{\pi T_{ch}}\right)^{1/2}\right], \tag{5.8}$$

i.e., it falls on reduction in the transparency of the SN interface faster than in the case of SNS sandwiches.

The relationship (5.8) makes it possible to estimate γ_{BM} using the experimental data. For example, according to Ref. 91, in the case of an SN–N–NS bridge at $T/T_c \approx 0.047$, when $L \leqslant 1\,\mu$m and $\rho_N \approx (1\text{–}2) \times 10^{-6}\,\Omega\cdot$cm, it is found that $eV_c/2\pi T_{ch} \approx 7.4 \cdot 10^{-5}$. Using the familiar data for gold $V_F \approx 1.4 \times 10^6$ m/s and $(\rho l)^{-1} \approx 8.4 \times 10^{10}\,\Omega^{-1}\cdot$cm^{-2} (Refs. 272 and 273), we find that $\xi_N^* \approx 20\text{–}30$ nm, i.e., $L/\xi_N^* \approx 30\text{–}50 \gg 1$. For these values of the parameters only the first term is important in the sum over ω. Using this fact, we find that the experimental data are in agreement with the theoretical calculations if $\gamma_{BM} \approx 1\text{–}10$. This quantity is much less than the estimate[9)] obtained from the expression for R_N. It should be pointed out that the substitution of the experimental values of the parameters L/ξ_N^* and T in the expressions obtained using the simple SNS model gives a value of V_c much higher than the experimental one. Therefore, indeterminacy in the experimental values of L and ξ_N^* [because of the exponential dependence $V_c(L)$ when $L \gg \xi_N^*$] and the absence of the experimental dependences $V_c(T)$, $R_N(T)$, and $I_c(H)$ do not allow us to make a definite judgement on whether the proposed model of a junction describes the experimental situation satisfactorily.

For example, the available experimental data on SNS junctions are insufficient to decide reliably whether the BCS theory can be applied to the properties of high-temperature superconducting junctions with a deliberately introduced spacer.

Application of the same model to the properties of junctions at grain boundaries gives rise to a contradiction similar to that discussed above in dealing with the simple SNS model: the experimental and low-temperature absolute values of V_c can be matched to those deduced from Eq. (5.4) if we assume that $\gamma_B > 10$; however, for these values of γ_B a strong fall of V_c on increase in T begins at a temperature $T \approx T_c \gamma_B^{-2}$, i.e., it occurs much earlier than in the experiments.

The model in question can be made to describe the observed properties of junctions at microcracks in grains with $V_c > $ mV (Refs. 243 and 244) if we assume that these junctions have regions of the SNS type and of thickness $L \ll \xi_N^*$, separated from the high-temperature superconducting matrix by an atomically abrupt boundary with a resistance which dominates R_N. It follows from calculations[255] that in the case of these SNS sandwiches with low-transparency SN interfaces ($\gamma_B \gg 1$) there may be a change from an excess to a deficit of the current in the current-voltage characteristics (Fig. 7) if $\gamma_{BM} = \gamma_B(L/\xi_N^*) > 1$. The temperature dependences of the parameter V_c are then described by

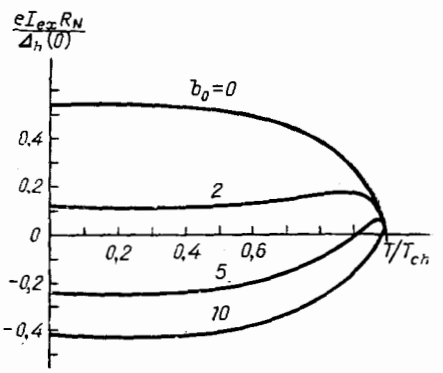

FIG. 7. Temperature dependences of the excess current exhibited by the current-voltage characteristics of SNS sandwiches with low-transparency SN interfaces and with the N-layer thickness obeying $L \ll \xi_N^*$, plotted for different values of the parameter $b_0 = \gamma_{BM}/\gamma^*$, where $\gamma^* \approx 1.78$ is the Euler constant.[255]

$$\frac{eV_c}{2\pi T_{ch}} = \frac{T}{T_{ch}} \max_{\varphi} \sum_{\omega>0} \frac{\Delta_h^2 G_S \sin\varphi}{\omega\left[\omega^2\left(1+0{,}5\gamma_{BM}\omega G_S/\pi T_{ch}\right)^2+\Delta_h^2\cos^2(\varphi/2)\right]^{1/2}}, \tag{5.9}$$

where $G_S = \omega(\omega^2+\Delta_h^2)^{1/2}$, and they are close to the experimental values (see Figs. 5 and 8). However, this model cannot explain the experimental temperature dependences $R_N(T)$ of these junctions and even the hypothesis of the presence of an N layer with sharp boundaries is in conflict with the proposed structure of the junction where the space between the boundaries of a crack is in all probability filled with randomly distributed impurity atoms.

The third possible reason for the almost homogeneous (on the temperature scale) suppression of V_c in the case of grain-boundary junctions is the existence of some temperature-independent mechanism resulting in an additional destruction of the superconducting properties. This may be, for example, the scattering of electrons by localized uncompensated spin magnetic moments of copper Cu^{2+} present in oxygen-depleted regions in high-temperature superconducting materials. Similar effects may be produced by strong electron–phonon[274] and electron–electron[275] interactions.

The interaction of the Cooper pairs with local magnetic moments (both ordered and distributed at random) can be described by introducing, in semiclassical equations of superconductivity, a term proportional to the characteristic time τ_S for electron scattering accompanied by spin reversal. The solution of these equations for an N material of a weak link with "stringent" boundary conditions at the interfaces with superconducting electrodes yields the following expression for V_c:

$$\frac{eV_c}{2\pi T_{ch}} = 32\frac{T}{T_{ch}}\sum_{\omega>0}\frac{q^2\exp\left[-(L/\xi_N^*)(\omega p/\pi T_{ch})^{1/2}\right]}{\left[1+(1+q^2p)^{1/2}\right]^2}, \quad L \gg \xi_N^*\left(\frac{Tp}{\pi T_{ch}}\right)^{1/2}, \tag{5.10}$$

where

$$p = 1+\frac{1}{\omega\tau_S}, \quad q = \frac{\Delta_h}{\omega+(\omega^2+\Delta_h^2)^{1/2}}.$$

The dependences $V_c(T)$ calculated from Eq. (5.10) for various values of L/ξ_N^* and $\tau_S = 1/2\pi T_{ch}$ are plotted in Fig. 9. We can see that they are in satisfactory qualitative agreement with the experimental curves (Fig. 5) obtained for junctions at grain boundaries. However, a quantitative agreement with the experimental values of the specific resistance $R_N \approx 10^{-8}\ \Omega\cdot cm^2$ of such junctions can be obtained only if we assume that the spacer material is characterized by an exceptionally high resistivity. In fact, if $L \approx \xi_N^* \approx 5$ nm, it is found that the resistivity of the N layer is $\rho_N \approx 2\times 10^{-2}\ \Omega\cdot cm$, which is of the order of the hopping conductivity and not the metallic one. Information on the nature of the conduction process in a weak-link material can be obtained from the experimental dependences $R_N(T)$. However, measurements of this kind (with the exception of those reported in Refs. 243 and 244) have not yet, unfortunately, been published.

5.3. More complex models of tunnel junctions

A complication of the tunnel model of a Josephson junction is possible if we allow for additional processes which occur in a superconducting electrode or in a weak-link material.

In the former case the suppression of V_c is possible because of partial suppression of the superconductivity of the electrodes near the junction, associated with the formation of normal-conduction layers. In this case the value of V_c depends on the thickness of these layers and on the parameters γ and γ_B (Refs. 258 and 259). It follows from numerical calculations that the use of one of these parameters or any combination of them fails to account simultaneously for two experimental observations: low absolute values of V_c and a smooth reduction in the characteristic voltage on increase in T in the range $T \leqslant 0.3T_c$.

In the second case the most probable reason for the sup-

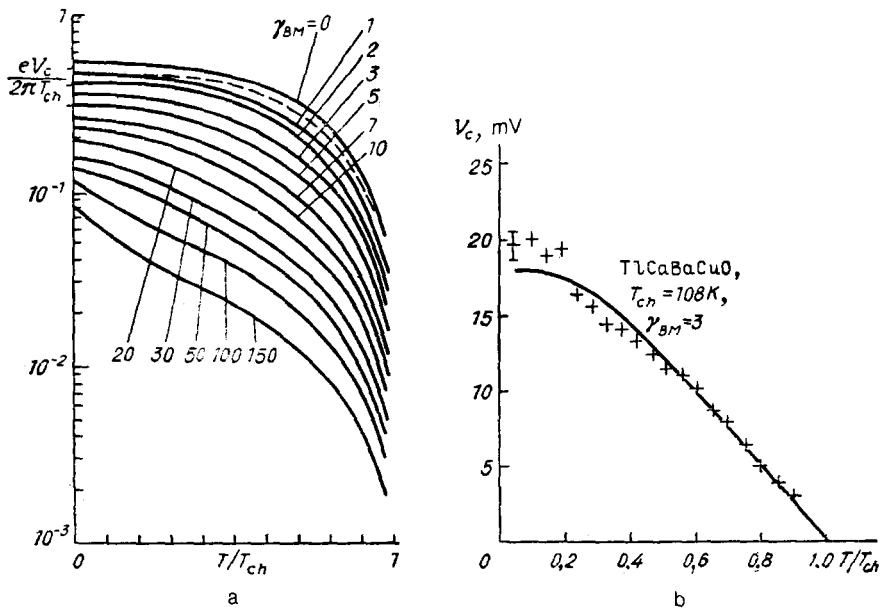

FIG. 8. Temperature dependences of the characteristic voltage V_c of SNS sandwiches with low-transparency SN interfaces and with the N-layer thickness obeying $L \ll \xi_N^*$: a) plotted for different values of the parameter γ_{BM} [the dependence $V_c(T)$ deduced from the AB theory is represented by the dashed curve]; b) plotted for $\gamma_{BM} = 3$ (the "+" symbols represent the experimental values obtained for microcrack junctions in grains found in TlCaBaCuO).[243,244]

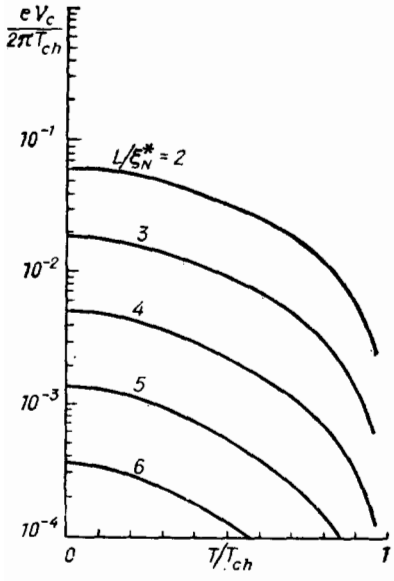

FIG. 9. Temperature dependences of the characteristic voltage V_c of SNS sandwiches with transparent interfaces ($\gamma \ll 1$, $\gamma_B \ll 1$), plotted for different thicknesses of the N layer on the assumption that $(\pi T_{ch}\tau_S) = 0.5$.

pression of V_c is the presence, in a dielectric spacer, of impurities with localized electron states. If the spacer thickness obeys $L > \alpha \ln(\alpha/\lambda)$, where $\alpha = [2m(U - E_F)]^{1/2}$, is the radius of a localized state (U is the potential at the bottom of the conduction band and E_F is the Fermi energy) and λ is the de Broglie wavelength, then in addition to the usual tunneling we can expect also two other charge transport channels: hopping conduction and resonance tunneling via localized states. The first of these channels cannot ensure the transport of a supercurrent, because each electron jump from one state to another is accompanied by a change in its energy and, consequently, by dephasing of its wave function. However, the values of R_N can be explained by just this mechanism. If

$$T \geqslant T_2 \approx \frac{1}{4}(g\alpha^2 L)^{-1}\left(\frac{\rho S^5}{\Lambda E_F}\, g\alpha^2 L\right)^{1/4} \exp\left(-\frac{L}{4\alpha}\right), \qquad (5.11)$$

this mechanism leads to a temperature-dependent component of the conductivity σ_h of a junction:[276]

$$\sigma_h = \sum_n \sigma_n, \quad \sigma_n \propto T^{n-[2/(n+1)]} \exp\left[-\frac{2L}{(n+1)\alpha}\right] \qquad (5.12)$$

where σ_n is the conductivity of a chain of n impurity atoms; S is the velocity of sound; ρ is the density of the spacer material; Λ is the deformation potential; g is the density of the localized states. On increase in temperature the process of charge transport extends to chains with an increasing number of impurities and at temperatures

$$T > T_n^* = (gL^2\alpha)^{-1} \exp\left(-\frac{L}{8\alpha}\right)$$

the conductivity σ_h is governed primarily by chains characterized by $n \gg 1$ and amounts to[276,277]

$$\sigma_h \propto \exp\left\{-2\left[2\,\frac{L}{\alpha}\,\ln(gTL^2\alpha)^{-1}\right]^{1/2}\right\}, \quad T_n^* < T < T^*. \qquad (5.13)$$

Finally, if $T \geqslant T^* = (g\alpha^3)^{-1}(\alpha/L)^{-5/2}$ the discrete nature of the energy levels of the localized states becomes unimportant and the conductivity of a junction obeys the Mott law $\sigma_n \propto \exp\{-(T_0/T)^{1/4}\}$.

The second channel for the passage of electrons across an insulating spacer is resonance tunneling along the Lifshitz percolation paths (see Refs. 278–281) passing through n centers separated by a distance $2y$ from one another and characterized by a localized electron state energy E_D. This gives rise to resonant energy bands of width

$$B = \frac{\alpha}{y}(U - E_F)\exp\left(-\frac{2y}{\alpha}\right) \approx c\alpha^3 (U - E_F)\exp\left(-\frac{1}{c\alpha^3}\right) \qquad (5.14)$$

that increases on increase in the concentration c of the localized centers (on reduction in y). The multiplicity of such paths shunts the insulating barrier, so that its properties become close to those of SNS junctions, but with an N-type layer strongly inhomogeneous in respect of its properties. The conductivity of such a resonant junction is governed by the motion of electrons along all the resonant paths and is given by[281]

$$\sigma_r \propto \exp\left[-2\left\{\frac{L}{\alpha}\ln(cL\alpha^2)^{-1}\right\}^{1/2}\right], \quad L \geqslant \alpha\,\frac{\ln^2 \min\{D_1, D_2\}}{\ln(1/c\alpha^3)},$$

$$\propto \exp\left\{-\frac{L}{\alpha}\,\frac{\ln[1/c\alpha^2 L]}{\ln(1/\min\{D_1, D_2\})}\right\}, \quad L \leqslant \alpha\,\frac{\ln^2 \min\{D_1, D_2\}}{\ln(1/c\alpha^3)}; \qquad (5.15)$$

here, $D_{1,2}$ is the transparency of the SI interfaces. The critical current of the junction depends on the relationship between L and the electron coherence length ξ_N^* described by

$$\xi_N^* \approx \frac{2yB}{T} \approx 2y \ln\left(\frac{U - E_F}{T}\right)\ln^{-1}\frac{1}{c\alpha^3}, \qquad (5.16)$$

which differs from one channel to another. If $L > (\xi_N^*)_{max}$, the value of I_c is governed by the critical channel characterized by the highest value of ξ_N^* (Ref. 279). In this case the change in the sign of the curvature of the dependence $V_c(T)$ occurs in the vicinity of a temperature $T_0 \approx (U - E_F)(c\alpha^3)^n$, where n is the number of centers on a path.

The nature of the current-voltage characteristics of such junctions[281] depend strongly on the ratio of the order parameter Δ to the band width B. If $B > \Delta$, i.e., in the case when

$$L < \alpha \ln^2\left[\frac{\Delta}{U - E_F}\right]\ln^{-1}\frac{1}{c\alpha^3}, \quad D_{1,2} > \frac{\Delta}{U - E_F}, \qquad (5.17)$$

the junctions in question do not differ qualitatively in their properties from SNS structures. Their current-voltage characteristic exhibits an excess current associated with the existence of a channel representing the Andreev reflection of electrons which on reaching the SN interface may be reflected in the form of a hole forming a Cooper pair in the superconductor.[282] A reduction in B suppresses this effect. If $B \ll \Delta$, the Andreev reflection is unimportant and the current-voltage characteristics of the junctions exhibit not an excess but a deficit of the current. This is due to the fact that, because of the smallness of B, not all the quasiparticles can participate in the charge transport process. It is important to point out that if $B \approx \Delta$, then cooling should result in a change

from an excess current [$T \approx T_c$, $B \gg \Delta(T \approx T_c)$] to a deficit [$T \ll T_c$, $B \leqslant \Delta(0)$] and this should be manifested by the current-voltage characteristics. If we substitute in Eq. (5.13) the values $U - E_F \approx 1$ eV and $B \approx \Delta(0) \approx 10^{-2}$ eV, we find[10] that this effect should occur when $\alpha^3 c \approx 0.1$.

This model describes qualitatively the main properties of high-temperature superconducting junctions at grain boundaries and microcracks in grains and of point contacts. For example, if at high voltages the current-voltage characteristics become ohmic, it is natural to assume that the flow of a supercurrent through a junction is accompanied by the usual tunneling. The dependence $I_c(T)$ should then be close to that predicted by the AB theory. However, the main contribution to R_N may be related not to the usual tunneling but to hopping conduction. This automatically results in suppression of the parameter V_c and in a modification of its temperature dependence particularly at high temperatures. If the current-voltage characteristics for the junctions exhibit an excess current throughout the investigated temperature range or a change from an excess to a deficit of the current as a result of cooling, it is natural to identify the transport of the supercurrent with resonance tunneling of electrons. The dependence $I_c(T)$ should then be close to that deduced from the simple SNS model. Suppression of V_c may also be related to a reduction in R_N caused by hopping conduction.

The existence of the hopping conduction mechanism is supported by the semiconducting temperature dependence $R_N(T)$ of the investigated junctions [see Eqs. (5.12) and (5.13)]. However, the suppression of V_c is possible also even if R_N is practically independent of temperature and the main mechanism of the flow of the normal current is inelastic tunneling through one center.

Finally, a reduction in V_c of the tunnel junctions can also in principle be due to the processes of tunneling accompanied by spin reversal, which is possible if magnetic impurities are present in the insulating spacer. Calculations carried out for this case[283,284] lead to a dependence $V_c(T)$ similar to that deduced from the AB theory, but with a smaller value of $V_c(0)$:

$$\frac{eV_c}{2\pi T_{ch}} = \frac{t^2 - S(S+1)v^2}{t^2 + S(S+1)v^2} \frac{\Delta_h}{4T_{ch}} \operatorname{th} \frac{\Delta_h}{2T}, \qquad (5.18)$$

$$R_N^{-1} = 4\pi^2 e^2 N(0) [t^2 + S(S+1)v^2],$$

where $N(0)$ is the density of the electron states on the Fermi surface, and t and v are the average values of the matrix elements of the tunneling via nonmagnetic and magnetic localized states, respectively, and S is the total magnetic moment in this state. It is shown in Ref. 285 that the suppression of I_c associated with the Coulomb repulsion of electrons at impurities in a barrier at energies KT_c exceeding the width of an impurity level also give rise to a temperature dependence of the critical current of the type described by Eq. (5.10).

This model makes it possible to describe satisfactorily only those junctions which have current-voltage characteristics without an excess current at high voltages, i.e., it applies to junctions at grain boundaries characterized by $R_N < 10^{-7}\ \Omega \cdot \text{cm}^2$. The experimentally observed absence of an excess current in the current-voltage characteristics was reported only for a junction at a grain boundary in yttrium ceramic by the authors of Ref. 225. The temperature dependence $V_c(T)$ reported there (curve 5 in Fig. 5) was qualitatively similar to that predicted by the AB theory, with the exception of a somewhat less steep fall of V_c on increase in T in the range $T \geqslant 0.5T_c$. A better agreement could be obtained by comparing the results of Ref. 225 with calculations based on the SNINS model of a junction with magnetic impurities in the N region. The question where the magnetic moments are localized (in the insulator or in a medium with the metallic conduction near the grain boundary) requires further experimental studies.

5.4. Brief summary

We shall now summarize our discussion of the Josephson junctions of various types.

1. Among all the experimentally realized Josephson junctions made of high-temperature superconductors, very distinct properties are exhibited by the junctions at microcracks in crystals [243,244] with dependences $V_c(T)$ close to that following from the AB and KO models. These and other properties of these junctions [semiconducting nature of the dependence $R_N(T)$ and the change from a deficit to an excess of the current in the current-voltage characteristic] are best described by a model of junctions with resonance percolation tunneling of electrons between energy bands of width $B \leqslant \Delta(T)$. However, the irreproducibility of the experimental results on the one hand and the absence of a theory of such structures for the range $L \leqslant \xi_N^*$—which includes the resonance and elastic tunneling—on the other, means that a qualitative comparison cannot be made and no rigorous conclusions can be drawn.

2. Point junctions between high- and low-temperature superconductors[142] and point contacts between two high-temperature superconductors, and similar (in respect of their properties) grain-boundary junctions are irregular and irreproducible structures. Those among them which have a clearly demonstrated excess current can be described approximately within the framework of either the SNS model with localized magnetic centers in the N layer or a tunnel resonance percolation model with such a relationship between the parameters described by Eq. (5.17) which ensures in practice a matching of these models. In the opposite case (in the absence of an excess current) the grain-boundary junctions are clearly structures either with resonance tunneling of electrons or with ordinary tunneling, but they are characterized by the presence of localized magnetic moments in an insulating spacer or in the adjoining normal region (SNS junctions). The irreproducibility of the experimental results and the absence of a theory allowing for the simultaneous processes of resonance and inelastic scattering, also prevent drawing of any definite conclusions at this stage.

3. Planar SNS structures with a deliberately introduced spacer and also variable-thickness bridges of the SN–N–NS type can probably be described by the SNS model with low-transparency SN interfaces ($\gamma_B \gg 1$). However, such an approach leads to underestimates of the effective junction area (compared with its total area). The absence of experimental dependences $I_c(H)$ and $V_c(T)$ prevents us from answering the question whether this model provides a satisfactory description of real junctions. Nevertheless, the properties of such junctions can be, in contrast to grain-boundary junc-

tions, fully reproducible and a future detailed comparison of their properties with the theory of these junctions[255,267,269,271] may allow us to answer the question whether the BCS theory applies to the processes occurring in high-temperature superconducting junctions.

6. CONCLUSIONS. POSSIBLE TRENDS IN FURTHER RESEARCH ON THE JOSEPHSON EFFECT IN HIGH-TEMPERATURE SUPERCONDUCTOR JUNCTIONS

As pointed out in Sec. 5, the irreproducibility of the existing Josephson high-temperature superconductor junctions and the absence of reliable experimental data on their properties makes it impossible not only to answer at present the question whether the BCS theory is applicable to high-temperature superconductors, but even to provide reliable qualitative identification of the physical structure of the junctions. In our opinion, the only way forward is the construction of regular high-quality structures with direct and tunnel conduction mechanisms.

6.1. Structures with direct conduction

The first step in the development of reproducible high-temperature superconductor junctions with direct conduction would be the fabrication *in situ* and a detailed study of interfaces between high-temperature superconductors and noble metals (Ag, Au) or other materials exhibiting metallic conduction and not interacting chemically with high-temperature superconductors. The only interfaces of practical interest are those with a specific resistance in the range $R_B \leqslant 10^{-10}\ \Omega\cdot\text{cm}^2$ formed by single-crystal high-temperature superconducting films (with the c axis perpendicular to the substrate) and characterized by a surface smooth on the atomic scale, because this should minimize possible errors in the determination of the junction area (see Sec. 1) associated with the diffusion of the normal metal along grain boundaries.

Investigations of such interfaces, together with the monitoring of the elemental composition and structure of the interface should include determination of the resistivities ρ_S and ρ_N of the materials forming the interface, an estimate of the mean free path of electrons in the N layer, and determination of the temperature dependence of the resistance R_B of an interface. In the course of these measurements it is necessary to overcome the difficulties associated with separation of the interface resistance R_B from the total measured value R_Σ, which includes not only R_B but also the resistance of the N film R_n and the resistance R_s due to the nonequilibrium nature of the electron distribution function near the interface (the value of R_s depends on the mutual nature of the effect of the proximity of the N and S materials, and it depends also on the parameters γ and γ_B). The value of R_n can be estimated by recording, for example, the dependence of R_Σ on the N-layer thickness, but a correct estimate of R_s requires additional theoretical calculations. The measurements should then be used to estimate the values of the parameters γ_B (or γ_{BM}) and ξ_N^*.

The next stage should be a study of tunnel junctions of the SNIN type made from SN sandwiches investigated in the first stage and characterized by a tunnel layer resistance much higher than both R_B and R_n. A study of the current-voltage characteristics of such junctions (or, more exactly, of the dependence of the differential conductance dV/dI on V) should give, at temperatures $T \ll T_{ch}$, information on the density of states $N(\varepsilon)$ on the outer surface of a normal spacer. In the most interesting (from the practical point of view) case of a "dirty" N metal of small thickness $L \ll \xi_N^*$ a calculation reported in Ref. 259 shows that if $\gamma_{BM} > \max[I, \gamma_M]$ the density of states $N(\epsilon)$ should exhibit two singularities (Fig. 10) at $\varepsilon = \Delta_h$ and $\varepsilon = z_0\Delta_h$. The position of the first singularity on the energy axis is independent of γ_{BM}, whereas the second one shifts on increase in γ_{BM} toward lower energies so that $z_0 \to \pi T_{ch}/\gamma_{BM}\Delta_h$ when $\gamma_{BM} \gg 1$. If we allow for nonzero values of γ_M, we find that this singularity at $\varepsilon = z_0\Delta_h$ is smoothed out and the peak at $\varepsilon = \Delta_h$ is practically suppressed, but a singularity of the derivative $dN(\varepsilon)/d\varepsilon$ at $\varepsilon = \Delta_h$ is retained. These measurements have made it possible to estimate the values of the parameter γ_{BM} in a situation which practically excludes nonequilibrium effects at the SN interface and can possibly be used (in a simultaneous analysis with the data obtained in the first stage) to obtain more definite information on the contribution of these effects to the resistance of the interface.

The third possible stage is the fabrication and investigation of small (with planar dimensions smaller than the Josephson penetration depth λ_J) Josephson tunnel junctions of the SNIS' type, where S' is a low-temperature superconductor. At this stage it is necessary to record and analyze the experimental dependences of the parameter V_c on the external magnetic field H, on the thickness L of the N layer, and on the ambient temperature T. The first of these dependences can be used, on the basis of the oscillation period ΔH, to monitor the correspondence between the effective ($S \sim \Phi_0/\Delta H$) and total areas of the junction. The dependence $V_c(L)$ allows us to determine the value of ξ_N^* for the normal metal [$V_c \propto \exp(-L/\xi_N^*)$ if $L \gg \xi_N^*$]. A comparison of this quantity with an estimate obtained in the first stage can be used to check once again that the predictions of the theories based on the singlet mechanism of electron pairing apply to an N metal or it may be found that these predictions are invalid. Finally, the dependence $V_c(T)$ can give information on the parameters γ_B and γ_{BM}. The calculations

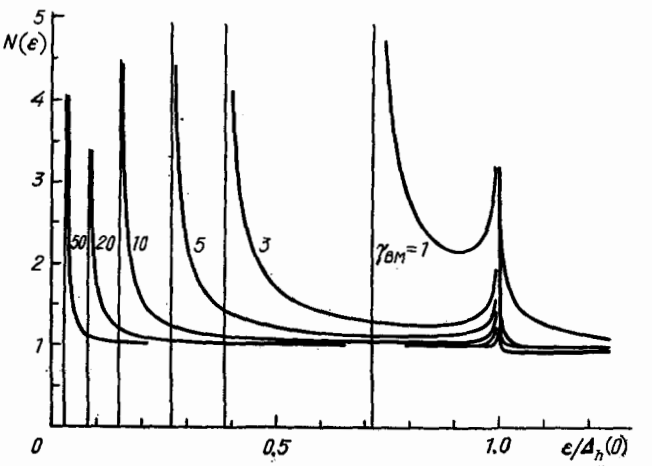

FIG. 10. Density of states $N(\varepsilon)$ at an SN interface in a sandwich obtained for low thicknesses of the N layer in the range $L \ll \xi_N^*$ in the case when $\gamma_M \ll 1$ and the parameter γ_{BM} has different values.[259]

reported in Ref. 259 indicate that if the conditions for the "dirty" limit ($L < \xi_N^*$ and $\gamma_{BM} > \gamma_M$) are satisfied by an N metal, the dependence $V_c(T, \gamma_B)$ for an SNIS′ junction is given by the expression

$$V_c = \frac{2\pi T}{e} \sum_{\omega>0} \frac{\Delta_1 \Delta_h}{\{(\omega^2+\Delta_1^2)\,(\omega^2+\Delta_h^2)\,[1+\gamma_{BM}^2(\omega/\pi T_{ch})^2+(2\omega\gamma_{BM}G_S/\pi T_{ch})]\}^{1/2}}, \tag{6.1}$$

where Δ_1 is the modulus of the order parameter of the S′ electrode. In the case of practical importance when $\Delta_h \gg \Delta_1$ and $\gamma_{BM} \gg T_{ch}/T_{c1}$, we find that Eq. (6.1) simplifies and reduces to the familiar expression for asymmetric tunnel junctions:

$$V_c = \frac{2\pi T}{e} \sum_{\omega>0} \frac{(\pi T_{ch}/\gamma_{BM})\,\Delta_1}{\{(\omega^2+\Delta_1^2)\,[\omega^2+(\pi T_{ch}/\gamma_{BM})^2]\}^{1/2}}. \tag{6.2}$$

It is clear from Eq. (6.2) that the role of the order parameter of a composite SN electrode is played by a quantity $\pi T_{ch}/\gamma_{BM}$ which in the range $\gamma_{BM} \geqslant \gamma_M \approx 10$ and for $T_{ch} \approx 100$ K does not exceed the order parameter of ordinary (low-temperature) superconductors, such as niobium.

The conclusions reached at this stage of the proposed research program may be confirmed (or rejected) by a study of the properties of Josephson junctions of the SNS′ sandwich type. The necessary condition is then an additional monitoring of the processes at the NS′ interface associated with the mutual diffusion of the materials, as well as an independent determination of the characteristic suppression parameter $\gamma_1 = (\rho_{S1}\xi_{S1}/\rho_N\xi_N)$ (which can be obtained, for example, by a comparison of the properties of S′ NS′ sandwiches with the theory). If the "dirty" limit condition is satisfied by the N and S materials and if

$$\gamma_1 \geqslant \left(1-\frac{T}{T_{c1}}\right)^{1/2} \min\left(1, \frac{L}{\xi_N^*}\right), \quad \xi_{S_1} = \left(\frac{D_S}{2\pi T}\right)^{1/2},$$

$$\gamma_B \geqslant \left(\frac{T_{c1}}{T}\right)^{1/2} \max\left\{1, \left(1-\frac{T}{T_{c1}}\right)^{-1/2} \mathrm{sh}^{-1}\frac{L}{\xi_N}\right\}, \tag{6.3}$$

$$\xi_N = \left(\frac{D_N}{2\pi T}\right)^{1/2},$$

then the parameters of such an SNS junction are given by the expressions[271]

$$\frac{eV_c}{2\pi T_{c1}} = \frac{1}{\gamma_1}\left(\frac{T_{c1}}{T}\right)^{1/2} \frac{B(T)}{\pi T_{c1}} \sum_{\omega>0} \left(\frac{\pi T}{\omega}\right)^{3/2} \mathrm{sh}^{-1}\left[\frac{L}{\xi_N}\left(\frac{\omega}{\pi T}\right)^{1/2}\right], \tag{6.4}$$

$$R_N = \rho_N \xi_N^* \gamma_{BM} S^{-1}, \; B(T) = \frac{2T_{c1}}{(7\zeta(3))^{1/2}}\left(1-\frac{T^2}{T_{c1}^2}\right), \tag{6.5}$$

where ρ_{S1} and ξ_{S1} represent the electrical resistivity and the coherence length of the S′ electrode, whereas $\zeta(3)$ is the Riemann zeta function. It follows from Eq. (6.4) that the parameter γ_B does not occur directly in the expression for V_c. Nevertheless, a comparison of the experimental values of V_c, R_N, and I_c with Eqs. (6.4) and (6.5) allows us to estimate [on the basis of $V_c(T)$] the supression parameter γ_1 and then to determine the value of γ_B if we know the effective [deduced from the dependence $I_c(H)$] junction area.

The next stage of this program should finally confirm (or reject) the possibility of existence of not only the usual singlet pairing, but also of other superconductivity mechanisms in high-temperature superconductors. This can be done by investigating the properties of high-temperature superconductor junctions of the SNS type.

The first (nonintegrated) method for fabrication of these structures may consist, for example, of mechanical pressing of two SN sandwiches [high-temperature superconductor/Ag(Au)] together[123] to form a single SNS junction of the sandwich type. Unfortunately, it is not yet clear how to fabricate similar structures by modern integrated technology methods.

The second method relies on the use of the progress made in modern photolithography and electron lithography in the fabrication of SN–N–NS junctions representing a variable-thickness bridge. The following technological variants of tackling this problem can be envisaged.

The first variant described in Ref. 91 involves evaporation of a resist on the original SN sandwich and then an electron beam is used to form a strip of width 1 μm. Then, the exposed part of the metals under it are removed forming a gap of size of the order of 0.1 μm in the original SN sandwich. After removal of the resist the electrodes formed in this way are connected by a normal metal strip about 1 μm wide.

In the second variant a sandwich is coated by a thick film of a normal metal in which a gap of size of the order of 0.1 μm is formed exactly as described above. The structure is then exposed to an ion beam which destroys the superconductivity in the part of the sandwich which can be reached by ions. If necessary, after removal of the metal mask, the resultant electrodes can be joined by an additional strip made of a noble metal.

In the third variant the gap in the original sandwich is formed exactly as in variant 1, but not over the whole width of the film, but so as to retain a variable-thickness bridge. A highly directional ion beam is then used to destroy the superconductivity in that part of the high-temperature superconducting film which is located under the normal film of the bridge.

In the fourth variant a vertical step is formed on the substrate and then a high-temperature superconducting film as well as a film of a noble metal are deposited *in situ*. This produces two SN sandwiches shifted relative to one another and in the final stage these sandwiches are connected by a strip of normal metal formed by oblique evaporation.

In the fifth and final variant, described in Ref. 187, a substrate is first coated by a film of triangular cross section made of a chemically active insulator (for example, Si) and this is followed by the formation of an SN sandwich in which—exactly as in variant 2—a cut centered on the Si film is made. The superconductivity under the normal bridge film is destroyed not by ions (as in variant 3), but by a chemical reaction with silicon.

In addition to the dependences $I_c(H)$ and $V_c(T)$ for

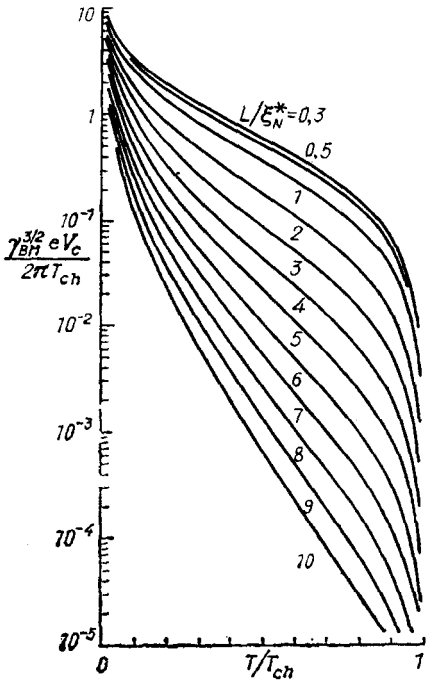

FIG. 11. Temperature dependences of the characteristic voltage V_c of Josephson junctions of the SN–N–NS variable-thickness bridge type with low-transparency SN interfaces, plotted for different distances L between the S electrodes.

the SNS sandwiches and SN–N–NS variable-thickness bridges with high-temperature superconducting electrodes, it is important to analyze the nature of the temperature dependences of the excess current I_{ex} in the current-voltage characteristic. If there is only singlet pairing of electrons in high-temperature superconducting electrodes, characterized by just one order parameter, the dependences of the characteristic parameters R_N, V_c, and I_{ex} on the ambient temperature, thickness of the N layer, and suppression parameters are given by Eqs. (5.4)–(5.9) and are illustrated in Figs. 5–7 and 11. In the case of SNS sandwiches these theoretical results provide a unique opportunity for independent determination of γ_{BM} from the steady-state and transient characteristics of the junctions.

If $T \approx 0.5T_{ch}$ and $L \leqslant \xi_N^* \approx 20$ nm, it follows from Eqs. (5.4) and (5.8) that V_c for sandwich ("sand") and bridge ("brid") junctions can be described by the following simple expressions

$$(V_c)_{sand} \approx 80 \frac{\xi_N^*}{L\gamma_B} \text{ mV}, \quad (V_c)_{brid} \approx 60\gamma_{BM}^{-3/2} \text{ mV}, \qquad (6.6)$$

which demonstrate that in the case of the Josephson junctions investigated at liquid nitrogen temperatures the values of V_c can be in the range $0.1 \leqslant V_c \leqslant 1$ mV when $\gamma_B \approx 20$. It is thus clear that the last stage of the proposed research program is also of considerable practical importance, because in most of the applications of the Josephson effect at liquid nitrogen temperatures it is necessary to use junctions with absolute values of the characteristic voltage V_c not exceeding 1 mV (Ref. 286).

Naturally, at each stage of the proposed program of an investigation of direct-conduction junctions it is of fundamental importance to carry out a detailed comparison of the results obtained, particularly of the parameters γ_B and γ, representing the properties of SN junctions.

6.2. Structures with tunnel conduction

The advantage of junctions with tunnel conduction from the point of view of fundamental research on the Josephson effect in high-temperature superconductors is that in the case of these structures it should be possible to eliminate the influence of the properties of a spacer from the recorded characteristics of the junctions.

The first stage in the development of such tunnel conduction junctions would be the formation *in situ* of a single-crystal high-temperature superconducting film with an atomically smooth surface, a phase composition homogeneous across the thickness, and homogeneous superconducting properties, which should be passivated by an insulating layer. The main difficulties are prevention of chemical reactions at the interface between the superconducting film and the insulating coating (see Sec. 2.4). Some ways of tackling this problem have already been pointed out. For example, the photoemission data indicate that the superconductivity of a surface layer is not destroyed by thermal evaporation of CaF_2, which is an insulator with a strong ionic chemical binding and which can be sputtered and deposited in the form of a molecular beam on a cold high-temperature superconducting substrate.[83,89] Superconducting properties of the surface are also relatively little affected by the deposition of Bi, Al, and Si films in an atmosphere of ionized oxygen.[83] The sputtered materials are deposited onto the surface in the form of oxides supersaturating the interface with oxygen and thus preventing its diffusion out of a high-temperature superconductor.

The next stage is an investigation of small-area Josephson junctions of the SIS′ type formed from structures consisting of a high-temperature superconductor and an insulator, including an analysis of the dependences $I_c(H)$ and $V_c(T)$ and of the current-voltage characteristics of the junctions (excess current, dV/dI), followed by a comparison with the theoretical results deduced from the familiar models of asymmetric tunnel junctions.[287]

Unfortunately, at the present stage of the development of the technology of high-temperature superconductors it is not yet possible to realize the last stage, which is the fabrication of high-temperature superconducting tunnel junctions by deposition of an upper high-temperature superconductor electrode on an insulator. This problem may be solved by molecular epitaxy methods, for example, by replacement (during some stage of growth of a high-temperature superconducting film) of one of the elements forming this film with another which would modify considerably the transport properties of the original matrix but would not alter the period of the atomic lattice (in the case of yttrium ceramics one of the candidates for such an element can be, for example, praseodymium[288]). A comparison of the properties of such junctions with the results of the available theoretical models could make a major contribution to the understanding of the high-temperature superconductivity mechanism. In fact, the properties of such "ideal" tunnel junctions are practically independent (with the exception of the value of R_N) of the spacer material, so that their quasiparticle characteristics and the Josephson properties may be affected explicitly by deviations of the properties of high-temperature

superconductors from those predicted by the BCS theory.

Direct practical applications of tunnel Josephson structures with high values of the characteristic voltage V_c are very limited, since the frequency of plasma oscillations governing the hf properties of such junctions is estimated to be low (of the order of several hundreds of megahertz). However, an investigation of these junctions may open up ways for a decisive improvement in the transport properties of grain boundaries in high-temperature superconducting ceramics and thus make possible applications of high-current superconductivity.

It should be stressed that (at least in the case of the topic under discussion) the way to good physics lies only through the most modern technology.

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[1)] It was suggested in Ref. 17 that this difference is of fundamental importance and is due to the localization of free carriers in the surface layer. The theoretical calculations reported in Refs. 18 and 19 demonstrate that in some cases the density of states at the Fermi level $N(0)$ near the surface is indeed an order of magnitude lower than in a bulk material. However, this hypothesis requires additional experimental confirmation.

[2)] In the formation of the oxides of Ru, Os, and Ir with the formula MO_2 or of the oxide Rh_2O_3 it is necessary to break two or three CuO bonds, respectively, which is not favorable from the energy point of view.

[3)] An estimate[92] of the rf capacitance of the LaSrCuO/Al interface gives $C \approx 1.1$ nF, which corresponds to a thickness of ≈ 25 nm and a permittivity of ≈ 7.5 of the semiconducting layer.

[4)] The addition of small amounts of Ag to a ceramic leads in a number of cases to positive effects such as an increase in the critical current of a material,[117-119] an improvement in its mechanical[120] and surface[104] properties, and even an increase in the superconducting transition temperature.[121,122]

[5)] Effective repulsion of electrons in a spacer (corresponding to a negative value of the effective constant describing the interaction between them) has little influence on the results reported in Ref. 263.

[6)] A possible contribution to $(R_N)_{theor} \approx \rho_S l_\varepsilon = \rho_S \xi_S^* (2\pi T_c \tau_\varepsilon)^{1/2}$ due to the nonequilibrium nature of carriers in the electrodes[254] is of the same order of magnitude, which is due to the fact that the energy relaxation times τ_ε (estimated in Ref. 264 to be $\tau_\varepsilon \approx 80$ ps at $T = 1.6$ K and $\tau_\varepsilon \approx 1$ ps at $T = 77$ K) are much shorter than in low-temperature superconductors.

[7)] If $L \not\ll \xi_N^*$, then the role of the parameters γ and γ_B is played by the quantities $\gamma_M = \gamma L / \xi_N^*$ and $\gamma_{BM} = \gamma_B L / \xi_N^*$ (Refs. 258, 259, 268, and 269).

[8)] The presence of such abrupt interfaces may, in particular, lead to nonmonotonic dependences of the normal resistance and the critical current on the dimensions of a weak link.[270]

[9)] An inhomogeneity of the interface between a high-temperature superconductor and Au should give rise to a random redistribution of the current in an N film inside an SN electrode, which is ignored in the theory.

[10)] We cannot exclude the possibility that the process of resonance tunneling may be influenced significantly also by inelastic scattering of electrons. Unfortunately, we are not aware of any estimates of the influence of such scattering on the supercurrent.

[1]J. G. Bednorz and K. A. Müller, Rev. Mod. Phys. **60**, 585 (1988).
[2]A. I. Golovashkin, Usp. Fiz. Nauk **152**, 553 (1987) [Sov. Phys. Usp. **30**, 659 (1987)].
[3]L. P. Gor'kov and N. B. Kopnin, Usp. Fiz. Nauk **156**, 117 (1988) [Sov. Phys. Usp. **31**, 850 (1988)].
[4]J. Talvacchio, IEEE Trans. Components Hybrids Manuf. Technol. **CHMT-12**, 21 (1989).
[5]D. Sahu, A. Langner, T. F. George *et al.*, in Chemistry of High-Temperature Superconductors II (Proc. Symposium at 195th Meeting of American Chemical Society, Los Angeles, 1988), American Chemical Society, Washington, DC (1988), Chap. 1, p. 1 [ACS Symposium Series, Vol. 377].
[6]B. K. Chakraverty, M. Avignon, and D. Feinberg, J. Less-Common Met. **150**, 11 (1989).
[7]V. A. Labunov, V. E. Borisenko, and Yu. É. Voevodov, Zarubezh. Elektron. Tekh. No. 5, 3 (1989).
[8]I. É. Graboĭ, A. P. Kaul', and Yu. G. Metlin, *Progress in Science and Technology, Chemistry and Technology of High-Temperature Superconductors* [in Russian], Vol. 6, VINITI, Moscow (1988).
[9]K. K. Likharev, V. K. Semenov, and A. B. Zorin, Progress in Science and Technology, *New Possibilities for Superconductor Electronics* [in Russian], Vol. 1, VINITI, Moscow (1988).
[10]T. L. Hylton, A. Kapitulnik, M. R. Beasley *et al.*, Appl. Phys. Lett. **53**, 1343 (1988).
[11]É. B. Sonin, Pis'ma Zh. Eksp. Teor. Fiz. **47**, 415 (1988) [JETP Lett. **47**, 496 (1988)].
[12]A. F. Volkov, Pis'ma Zh. Eksp. Teor. Fiz. **49**, 86 (1989) [JETP Lett. **49**, 103 (1989)].
[13]K. K. Likharev, Usp. Fiz. Nauk **127**, 185 (1979); Rev. Mod. Phys. **51**, 101 (1979).
[14]K. K. Likharev and V. T. Ul'rikh, *Systems with Josephson Contacts* [in Russian], Moscow State University (1978).
[15]K. K. Likharev, *Introduction to the Dynamics of Josephson Junctions* [in Russian], Nauka, Moscow (1985).
[16]T. van Duzer and O. Turner, *Principles of Superconducting Devices and Circuits*, North-Holland, Amsterdam, 1981 [Russ. Transl., Radioisvyaz' M., 1984].
[17]R. G. Egdell and W. R. Flavell, Z. Phys. B **74**, 279 (1989).
[18]C. Calandra, G. Goldoni, F. Manghi, and R. Magri, Surf. Sci. **211/212**, 1127 (1989).
[19]C. Calandra, F. Manghi, T. Minerva, and G. Goldoni, Europhys. Lett. **8**, 791 (1989).
[20]R. J. Cava, B. Batlogg, R. B. van Dover *et al.*, Phys. Rev. Lett. **58**, 1676 (1987).
[21]I. K. Schuller, D. G. Hinks, M. A. Beno *et al.*, Solid State Commun. **63**, 385 (1987).
[22]J. A. Mydosh, Z. Phys. B **68**, 1 (1987).
[23]Z. Z. Wang, J. Clayhold, N. P. Ong *et al.*, Phys. Rev. B **36**, 7222 (1987).
[24]I. W. Chen, S. J. Keating, C. Y. Keating *et al.*, Solid State Commun. **63**, 997 (1987).
[25]P. Monod, M. Ribault, F. D'Yvoire *et al.*, J. Phys. (Paris) **48**, 1369 (1987).
[26]Yu Mei, C. Jiang, S. M. Green *et al.*, Z. Phys. B **69**, 11 (1987).
[27]P. P. Freitas and T. S. Plaskett, Phys. Rev. B **36**, 5723 (1987).
[28]A. T. Fiory, M. Gurvitch, R. J. Cava *et al.*, Phys. Rev. B **36**, 7262 (1987).
[29]L. R. Testardi, W. G. Moulton, H. Mathias *et al.*, Phys. Rev. B **36**, 8816 (1987).
[30]W. K. Kwok, G. W. Crabtree, A. Umezawa *et al.*, Phys. Rev. B **37**, 106 (1988).
[31]S. I. Park, C. C. Tsuei, and K. N. Tu, Phys. Rev. B **37**, 2305 (1988).
[32]R. J. Cava, B. Batlogg, C. H. Chen *et al.*, Phys. Rev. B **36**, 5719 (1987).
[33]G. Cannelli, A. Cantelli, F. Cordero *et al.*, Solid State Commun. **68**, 323 (1988).
[34]Y. Takeda, R. Kanno, O. Yamamoto *et al.*, Physica C (Utrecht) **157**, 358 (1989).
[35]K. N. Tu, N. C. Yeh, S. I. Park, and C. C. Tsuei, Phys. Rev. B **39**, 304 (1989).
[36]I. V. Aleksandrov, A. B. Bykov, I. P. Zibrov *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 449 (1988) [JETP Lett. **48**, 493 (1988)].
[37]I. V. Aleksandrov, A. P. Volodin, I. N. Makarenko *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **49**, 287 (1989) [JETP Lett. **49**, 327 (1989)].
[38]Y. Nakazawa and M. Ishikawa, Physica C (Utrecht) **158**, 381 (1989).
[39]E. Porschke and P. Meuffels, J. Less-Common. Met. **150**, 153 (1989).
[40]M. Oshima, Y. Yamada, T. Kawamura *et al.*, Jpn. J. Appl. Phys. Part 2 **27**, L2233 (1988).
[41]B. W. Veal, J. Z. Liu, A. P. Paulikas *et al.*, Physica C (Utrecht) **158**, 276 (1989).
[42]A. G. Schrott, S. L. Cohen, T. R. Dinger *et al.*, Proc. Topical Conf. on Thin Film Processing and Characterization of High-Temperature Superconductors, Anaheim, CA, 1987, in AIP Conf. Proc. No. 165, 349 (1988) [American Vacuum Society Series, No. 3].
[43]J. H. Thomas and M. E. Labib, Proc. Topical Conf. on Thin Film Processing and Characterization of High-Temperature Superconductors, Anaheim, CA, 1987, in AIP Conf. Proc. No. 165, 374 (1988) [American Vacuum Society Series, No. 3].
[44]V. I. Nefedov, A. N. Sokolov, M. A. Tyzykhov *et al.*, J. Electron Spectrosc. Relat. Phenom. **49**, 47 (1989).

[45]B. Kumar, R. S. Harmer, T. N. Wittberg *et al.*, J. Mater. Sci. **23**, 3879 (1988).
[46]G. N. A. van Veen, T. S. Baller, J. W. C. de Vries *et al.*, Physica C (Utrecht) **152**, 267 (1988).
[47]T. E. Os'kina, E. A. Soldatov, Yu. D. Tret'yakov *et al.*, Izv. Akad. Nauk SSSR Neorg. Mater. **25**, 134 (1989) [Izv. Inorg. Mater. (1989)].
[48]J. R. Gavaler Jr., A. I. Braginski, M. G. Forrester *et al.*, IEEE Trans. Magn. **MAG-25**, 803 (1989).
[49]F. L. Freire Jr, C. V. Barros Leite, B. K. Patnaik *et al.*, J. Appl. Phys. **65**, 400 (1989).
[50]R. B. Tripathi, S. Singh, S. M. Khullar *et al.*, Solid State Commun. **69**, 1165 (1989).
[51]J. Talvacchio, J. R. Gavaler, J. Greggi *et al.*, IEEE Trans. Magn. **MAG-25**, 2538 (1989).
[52]R. S. List, A. J. Arko, Z. Fisk *et al.*, Phys. Rev. B **38**, 11966 (1988).
[53]H. W. Zandbergen, R. Gronsky, and G. Thomas, Phys. Status Solidi A **105**, 207 (1988).
[54]X. M. Xie, T. G. Chen, and J. Huang, Phys. Status Solidi A **110**, 415 (1988).
[55]K. N. Tu, N. C. Yeh, S. I. Park, and C. C. Tsuei, Phys. Rev. B **39**, 304 (1989).
[56]H. U. Krebs and R. Wordenweber, J. Appl. Phys. **63**, 1642 (1988).
[57]M. G. Ramsey and F. P. Netzer, Mater. Sci. Eng. B **2**, 269 (1989).
[58]P. A. P. Lindberg, Z. X. Shen, I. Lindau *et al.*, Appl. Phys. Lett. **53**, 529 (1988).
[59]D. M. Hill, A. M. Meyer, J. H. Weaver *et al.*, Phys. Rev. B **38**, 11331 (1988).
[60]A. Enokihara, H. Higashino, S. Kohiki *et al.*, Jpn. J. Appl. Phys. Part 2 **28**, L452 (1989).
[61]Y. Tazoh, K. Aihara, K. Miyabara *et al.*, IEEE Trans. Magn. **MAG-25**, 2049 (1989).
[62]H. Akoh, F. Shinoki, M. Takahashi *et al.*, Jpn. J. Appl. Phys. Part 2 **27**, L519 (1988).
[63]H. Akoh, F. Shinoki, M. Takahashi, and S. Takada, IEEE Trans. Magn. **MAG-25**, 795 (1989).
[64]H. Akoh, F. Shinoki, M. Takahashi, and S. Takada, Bull. Electrotech. Lab. **53**, 74 (1989).
[65]H. Akoh, F. Shinoki, M. Takahashi, and S. Takada, Bull. Electrotech. Lab. **53**, 79 (1989).
[66]J. W. Ekin, T. M. Larson, N. F. Bergen *et al.*, Appl. Phys. Lett. **52**, 1819 (1988).
[67]R. S. Williams and S. Chaudhury, in Chemistry of High-Temperature Superconductors II (Proc. Symposium at 195th Meeting of American Chemical Society, Los Angeles, 1988), American Chemical Society, Washington, DC (1988), Chap. 22, p. 291 [ACS Symposium Series, Vol. 377].
[68]M. K. Kelly, S. W. Chan, K. Jenkin II *et al.*, Appl. Phys. Lett. **53**, 2333 (1988).
[69]M. K. Kelly, P. Barboux, J. M. Tarascon *et al.*, Phys. Rev. B **38**, 870 (1988).
[70]H. P. Geserich, B. Koch, G. Scheiber *et al.*, Physica C (Utrecht) **153–155**, 661 (1988).
[71]M. Garriga, U. Venkateswaran, K. Syassen *et al.*, Physica C (Utrecht) **153–155**, 643 (1988).
[72]M. Garriga, J. Humlicek, M. Cardona *et al.*, Solid State Commun. **66**, 1231 (1988).
[73]H. M. Meyer III, T. J. Wagener, D. M. Hill *et al.*, Appl. Phys. Lett. **51**, 1118 (1987).
[74]Y. Gao, T. J. Wagener, J. H. Weaver *et al.*, Appl. Phys. Lett. **51**, 1032 (1987).
[75]H. M. Meyer III, D. M. Hill, S. G. Anderson *et al.*, Appl. Phys. Lett. **51**, 1750 (1987).
[76]D. M. Hill, H. M. Meyer III, J. H. Weaver *et al.*, Phys. Rev. B **36**, 3979 (1987).
[77]D. M. Hill, Y. Gao, H. M. Meyer III *et al.*, Phys. Rev. B **37**, 511 (1988).
[78]Y. Gao, T. J. Wagener, J. H. Weaver *et al.*, Phys. Rev. B **37**, 515 (1988).
[79]Y. Gao, I. M. Vitomirov, C. M. Aldao *et al.*, Phys. Rev. B **37**, 3741 (1988).
[80]T. J. Wagener, Y. Gao, I. M. Vitomirov *et al.*, Phys. Rev. B **38**, 232 (1988).
[81]C. Laubschat, M. Domke, M. Prietsch *et al.*, Europhys. Lett. **6**, 555 (1988).
[82]H. M. Meyer III, D. M. Hill, J. H. Weaver *et al.*, Appl. Phys. Lett. **53**, 1004 (1988).
[83]D. M. Hill, H. M. Meyer III, J. H. Weaver *et al.*, Appl. Phys. Lett. **53**, 1657 (1988).
[84]H. M. Meyer III, D. M. Hill, T. J. Wagener *et al.*, Phys. Rev. B **38**, 6500 (1988).
[85]C. Laubschat, M. Domke, M. Prietsch *et al.*, Physica C (Utrecht) **153–155**, 141 (1988).
[86]Y. Gao, T. J. Wagener, C. M. Aldao *et al.*, J. Appl. Phys. **64**, 1296 (1988).
[87]E. Weschke, C. Laubschat, M. Domke *et al.*, Z. Phys. B **74**, 191 (1989).
[88]H. M. Meyer III, D. M. Hill, T. J. Wagener *et al.*, J. Appl. Phys. **65**, 3130 (1989).
[89]H. M. Meyer III, D. M. Hill, J. H. Weaver *et al.*, in Chemistry of High-Temperature Superconductors II (Proc. Symposium at 195th Meeting of American Chemical Society, Los Angeles, 1988), American Chemical Society, Washington, DC (1988), Chap. 21, p. 280 [ACS Symposium Series, Vol. 377].
[90]K. Mizushima, M. Sagoi, T. Miura *et al.*, Jpn. J. Appl. Phys. Part 2 **27**, L1489 (1988).
[91]D. B. Schwartz, P Mankiewich, R. E. Howard *et al.*, IEEE Trans. Magn. **MAG-25**, 1298 (1989).
[92]K. Takeuchi, Y. Okabe, M. Kawasaki *et al.*, Jpn. J. Appl. Phys. Part 2 **26**, L1017 (1987).
[93]K. Kaneto and K. Yoshino, Jpn. J. Appl. Phys. Part 1 **26**, 1842 (1987).
[94]Y. Tzeng, J. Electrochem. Soc. **135**, 1309 (1988).
[95]R. Caton, R. Selim, A. M. Buoncristiani *et al.*, Appl. Phys. Lett. **52**, 1014 (1988).
[96]T. J. Richardson and L. C. Jonghe, Appl. Phys. Lett. **53**, 2342 (1988).
[97]J. van der Maas, V. A. Gasparov, and D. Pavuna, Nature (London) **328**, 603 (1987).
[98]Y. Tzeng, A. Holt, and R. Ely, Appl. Phys. Lett. **52**, 155 (1988).
[99]I. Sugimoto, Y. Tajima, and M. Hikita, Jpn. J. Appl. Phys. Part 2 **27**, L864 (1988).
[100]J. W. Ekin, A. J. Panson, and B. A. Blankenship, Appl. Phys. Lett. **52**, 331 (1988).
[101]K. Mizushima, K. Sagoi, T. Miura *et al.*, Appl. Phys. Lett. **52**, 1101 (1988).
[102]A. D. Wieck, Appl. Phys. Lett. **52**, 1017 (1988).
[103]A. D. Wieck, Appl. Phys. Lett. **53**, 1216 (1988).
[104]S. Yokoyama, T. Yamada, Y. Kubo *et al.*, Cryogenics **28**, 734 (1988).
[105]L. R. Tessler, U. Dai, N. Hess *et al.*, J. Phys. D **21**, 1652 (1988).
[106]J. D. Katz, J. O. Willis, M. P. Maley *et al.*, J. Appl. Phys. **65**, 1792 (1989).
[107]M. Suzuki, T. Fujii, K. Mori *et al.*, Jpn. J. Appl. Phys. Part 1 **27**, 2003 1988).
[108]M. P. Maley, J. O. Willis, J. D. Katz *et al.*, IEEE Trans. Magn. **MAG-25**, 2053 (1989).
[109]J. R. Gavaler *et al.*, in High-Temperature Superconductors II (Symposium, Boston, MA, 1987), Materials Research Society, Pittsburgh, PA (1988), p. 193 [Materials Research Society Symposium Proc. Vol. 99].
[110]Y. Suzuki, T. Kusaka, T. Aoyama *et al.*, Appl. Phys. Lett. **54**, 666 (1989).
[111]S. Jin, M. E. Davis, T. H. Tiefel *et al.*, Appl. Phys. Lett. **54**, 2605 (1989).
[112]E. H. Rhoderic, *Metal–Semiconductor Contacts*, Clarendon Press, Oxford, 1978 [Russ. Transl. Radioisvyaz', M., 1982].
[113]C. A. Chang, Appl. Phys. Lett. **52**, 924 (1988).
[114]C. A. Chang, J. Appl. Phys. **64**, 1991 (1988).
[115]F. H. Streitz, M. Z. Cieplak, Gang Xiao *et al.*, Appl. Phys. Lett. **52**, 927 (1988).
[116]S. Jin, R. C. Sherwood, T. H. Tiefel *et al.*, Appl. Phys. Lett. **52**, 1628 (1988).
[117]R. G. Sharma, Y. S. Reddy, S. R. Jha *et al.*, Pramana **30**, L75 (1988).
[118]D. Pavuna, H. Berger, M. Affronte *et al.*, Solid State Commun. **68**, 535 (1988).
[119]P. N. Peters, R. C. Sisk, E. W. Urban *et al.*, Appl. Phys. Lett. **52**, 2066 (1988).
[120]N. C. Soni, R. Prasad, A. Mohan *et al.*, Pramana **30**, L335 (1988).
[121]Y. Nishi, S. Moriya, and S. Tokunada, J. Mater. Sci. Lett. **7**, 596 (1988).
[122]K. Tsuchida, Y. Miura, H. Tsudo, *et al.*, J. Less-Common. Met. **146**, L19 (1989).
[123]J. Moreland, R. H. Ono, J. A. Beall *et al.*, Appl. Phys. Lett. **54**, 1477 (1989).
[124]K. Hoshino, H. Takahara, and M. Fukutomi, Jpn. J. Appl. Phys. Part 2 **27**, L1297 (1988).
[125]C. X. Ren, G. L. Chen, Y. Zheng *et al.*, IEEE Trans. Magn. **MAG-25**, 2463 (1989).
[126]Y. Ichikawa, H. Adachi, T. Mitsuyu *et al.*, Jpn. J. Appl. Phys. Part 2 **27**, L381 (1988).
[127]H. Koinuma, K. Fukuda, T. Hashimoto *et al.*, Jpn. J. Appl. Phys. Part 2 **27**, L1216 (1988).
[128]C. T. Cheung and E. Ruckenstein, J. Mater. Res. **4**, 1 (1989).
[129]M. Gurvitch and A. T. Fiory, Appl. Phys. Lett. **51**, 1027 (1987).
[130]A. Mogro-Campero, B. D. Hunt, L. G. Turner *et al.*, Appl. Phys. Lett. **52**, 584 (1988).
[131]J. Narayan, N. Biunno, R. Singh *et al.*, Appl. Phys. Lett. **51**, 1845

(1987).
[132]S. Y. Lee, B. Murdock, D. Chin, and T. van Duzer, Proc. Topical Conf. on Thin Film Processing and Characterization of High-Temperature Superconductors, Anaheim, CA, 1987, in AIP Conf. Proc. No. 165, 427 (1988) [American Vacuum Society Series, No. 3].
[133]P. Madakson, J. J. Cuomo, D. S. Yee, J. Appl. Phys. **63**, 2046 (1988).
[134]N. P. Bansal, R. N. Simons, and D. E. Farrell, Appl. Phys. Lett. **53**, 603 (1988).
[135]J. J. Cuomo *et al.*, in Chemistry of High-Temperature Superconductors II (Proc. Symposium at 195th Meeting of American Chemical Society, Los Angeles, 1988), American Chemical Society, Washington, DC (1988), p. 141 [ACS Symposium Series, Vol. 377].
[136]S. H. Lion *et al.*, in Chemistry of High-Temperature Superconductors II (Proc. Symposium at 195th Meeting of American Chemical Society, Los Angeles, 1988), American Chemical Society, Washington, DC (1988), p. 79 [ACS Symposium Series, Vol. 377].
[137]O. Michikami, H. Asano, and Y. Katoh, Rev. Electr. Commun. Lab. **36**, 579 (1988).
[138]H. Nakajima, S. Yamaguchi, K. Iwasaki *et al.*, Appl. Phys. Lett. **53**, 1437 (1988).
[139]M. V. S. Lakshmi, K. Ramkumar, and M. Satyam, J. Phys. D **22**, 373 (1989).
[140]M. J. Cima, J. S. Schneider, S. C. Peterson *et al.*, Appl. Phys. Lett. **53**, 710 (1988).
[141]A. Mogro-Campero, L. G. Turner, and G. Kendall, Appl. Phys. Lett. **53**, 2566 (1988).
[142]J. S. Tsai, Y. Kubo, and J. Tabuchi, Phys. Rev. Lett. **58**, 1979 (1987).
[143]S. Imai, T. Tozawa, G. Oya *et al.*, Jpn. J. Appl. Phys. Part 2 **27**, L552 (1988).
[144]S. Imai *et al.*, Extended Abstracts of Intern. Superconductivity Electronics Conference, Tokyo, 1989 (ISEC '89), Jpn. Soc. Appl. Phys., Tokyo (1989), p. 493.
[145]S. Kita, H. Tanabe, T. Takahashi *et al.*, Jpn. J. Appl. Phys. Part 2 **26**, L1353 (1987).
[146]S. Zhao, H. Tao, Y. Chen *et al.*, Chin. Phys. Lett. **5**, 249 (1988).
[147]J. Kuznik, M. Odehnal, S. Safrata, and J. Endal, J. Low-Temp. Phys. **69**, 313 (1987).
[148]A. Barone, A. di Chiara, G. Peluso *et al.*, Phys. Scr. **37**, 910 (1988); Phys. Rev. B **36**, 7121 (1987).
[149]T. Nishino, H. Hasegawa, H. Nakane *et al.*, Jpn. J. Appl. Phys. Part 2 **26**, L674 (1987).
[150]J. Kuznik, M. Odehnal, S. Safrata, and J. Endal, J. Low-Temp. Phys. **72**, 283 (1988).
[151]M. A. Gijs *et al.*, Preprint (1988).
[152]W. R. McGrath, H. K. Olsson, T. Claeson *et al.*, Europhys. Lett. **4**, 357 (1987).
[153]H. C. Yang, Physica B (Utrecht) **148**, 439 (1987).
[154]W. Eidelloth, F. S. Barnes, S. Geller *et al.*, IEEE Trans. Magn. **MAG-25**, 939 (1989).
[155]T. Yamashita, A. Kawakami, T. Nishihara *et al.*, Jpn. J. Appl. Phys. Part 2 **26**, L671 (1987).
[156]O. P. Balkashin, I. K. Yanson, and Yu. A. Pilipenko, Fiz. Nizk. Temp. **14**, 697 (1988) [Sov. J. Low Temp. Phys. **14**, 382 (1988)].
[157]N. H. Andersen, J. Johannsen, and M. T. Levinsen, Phys. Scr. **37**, 138 (1988).
[158]S. I. Vedeneev, I. P. Kazakov, A. P. Kir'yanov *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **47**, 159 (1988) [JETP Lett. **47**, 194 (1988)].
[159]A. Nakayama and Y. Okabe, Extended Abstracts of Intern. Superconductivity Electronics Conference, Tokyo, 1989 (ISEC '89), Jpn. Soc. Appl. Phys., Tokyo (1989), p. 36.
[160]W. Eidelloth, F. S. Barnes, Z. Z. Sheng, and A. M. Hermann, Appl. Phys. Commun. **8**, 191 (1988).
[161]C. C. Camerlingo, R. Cristiano, M. Russo *et al.*, Phys. Lett. A **128**, 508 (1988).
[162]A. Inoue, K. Takeuchi, H. Ito *et al.*, Jpn. J. Appl. Phys. Part 2 **26**, L1443 (1987).
[163]A. Nakayama, A. Inoue, K. Takeuchi *et al.*, IEEE Trans. Magn. **MAG-25**, 799 (1989).
[164]A. Nakayama, A. Inoue, K. Takeuchi, and Y. Okabe, Jpn. J. Appl. Phys. Part 1 **26**, 2055 (1987).
[165]A. Barone, A. Di Chiara, G. Peluso *et al.*, Nuovo Cimento D **9**, 727 (1987).
[166]J. S. Tsai, I. Takeuchi, J. Fujita *et al.*, Physica C (Utrecht) **157**, 537 (1989).
[167]Y. Katoh, K. Tanabe, H. Asano, and O. Michikami, Jpn. J. Appl. Phys. Part 1 **26**, 1777 (1987).
[168]Y. Katoh, H. Asano, K. Tanabe, and O. Michikami, Jpn. J. Appl. Phys. Part 2 **26**, L2136 (1987).
[169]I. Iguchi, H. Watanabe, Y. Kasai *et al.*, Jpn. J. Appl. Phys. Part 2 **26**, L645 (1987).
[170]M. A. M. Gijs, J. W. C. de Vries, and G. M. Stollman, Phys. Rev. B **37**, 9837 (1988).
[171]M. G. Blamire, G. W. Morris, R. E. Somekh *et al.*, J. Phys. D **20**, 1330 (1987).
[172]M. Naito, D. P. E. Smith, M. D. Kirk *et al.*, Phys. Rev. B **35**, 7228 (1987).
[173]A. Fournel, I. Oujia, J. P. Sorbier *et al.*, Europhys. Lett. **6**, 653 (1988).
[174]D. Esteve, J. M. Martinis, C. Urbina *et al.*, Europhys. Lett. **3**, 1237 (1987).
[175]T. Matsui, K. Takeuchi, A. Nakayama *et al.*, Extended Abstracts of Intern. Superconductivity Electronics Conference, Tokyo, 1989 (ISEC '89), Jpn. Soc. Appl. Phys., Tokyo (1989), p. 222.
[176]J. Moreland, J. W. Ekin, L. F. Goodrich *et al.*, Phys. Rev. B **35**, 8856 (1987).
[177]*Novel Superconductivity* (Proc. Intern. Workshop on Novel Mechanisms of Superconductivity, Berkeley, CA, 1987, ed. by S. A. Wolf and V. Z. Kresin), Plenum Press, New York (1987), p. 1105.
[178]A. T. A. M. De Waele, R. T. M. Smokers, R. W. van der Heijden *et al.*, Phys. Scr. **37**, 840 (1988).
[179]A. T. A. M. De Waele, R. T. M. Smokers, R. W. van der Heijden *et al.*, Phys. Rev. B **35**, 8858 (1987).
[180]J. Niemeyer, N. D. Kataria, M. R. Dietrich *et al.*, Z. Phys. B **69**, 1 (1987).
[181]B. I. Verkin, S. I. Bondarenko, E. M. Dmitriev *et al.*, Fiz. Nizk. Temp. **13**, 995 (1987) [Sov. J. Low Temp. Phys. **13**, 568 (1987)].
[182]T. Ryhanen and H. Seppa, IEEE Trans. Magn. **MAG-25**, 881 (1989).
[183]H. Nakane, T. Nishino, M. Hirano *et al.*, Jpn. J. Appl. Phys. Part 2 **26**, L1581 (1987).
[184]T. Komatsu, K. Imai, K. Matusita *et al.*, Jpn. J. Appl. Phys. Part 2 **26**, L1148 (1987).
[185]T. Yamashita, A. Kawakami, T. Nishihara *et al.*, Proc. Eighteenth Intern. Conf. on Low Temperature Physics, Kyoto, 1987, in Jpn. J. Appl. Phys. **26**, Suppl. 3, Part 2 (Contributed Papers), 1149 (1987).
[186]H. K. Olsson, W. R. McGrath, T. Claeson *et al.*, J. Appl. Phys. **62**, 4923 (1987).
[187]T. Hatano *et al.*, Extended Abstracts of Intern. Superconductivity Electronics Conference, Tokyo, 1989 (ISEC '89), Jpn. Soc. Appl. Phys., Tokyo (1989), p. 233.
[188]J. S. Tsai, Y. Kubo, and J. Tabuchi, Jpn. J. Appl. Phys. Part 2 **26**, L701 (1987).
[189]J. Moreland, L. F. Goodrich, J. W. Ekin, *et al.*, Appl. Phys. Lett. **51**, 540 (1987).
[190]J. Moreland, A. F. Clark , L. F. Goodrich *et al.*, Phys. Rev. B **35**, 8711 (1987); J. Moreland, J. W. Ekin, L. F. Goodrich *et al.*, Phys. Rev. B **35**, 8856 (1987); J. Moreland, A. F. Clark , H. C. Ku, and R. N. Shelton, Cryogenics **27**, 227 (1987).
[191]G. J. Cui, X. F. Meng, S. G. Wang *et al.*, Solid State Commun. **64**, 321 (1987).
[192]A. Sugishita, M. Yanagisawa, and I. Iguchi, Jpn. J. Appl. Phys. Part 2 **26**, 1472 (1987).
[193]N. P. Gerasimov, V. I. Krzhimovskiĭ, A. S. Katkov *et al.*, Pis'ma Zh. Tekh. Fiz. **14**, 1683 (1988) [Sov. Tech. Phys. Lett. **14**, 733 (1988)].
[194]X. F. Meng, Y. D. Dai, H. M. Jiang *et al.*, Solid State Commun. **63**, 853 (1987).
[195]P. H. Wu, Q. H. Cheng, S. Z. Yang *et al.*, Jpn. J. Appl. Phys. Part 2 **26**, L1579 (1987).
[196]Y. Higashino, T. Takahashi, T. Kawai *et al.*, Jpn. J. Appl. Phys. Part 2 **26**, L1211 (1987).
[197]N. X. Shen, P. H. Wu, S. Z. Yang *et al.*, IEEE Trans. Magn. **MAG-25**, 915 (1989).
[198]Fan Changxin, Sun Lin, Miao Bocai, and Liu Jun, Solid State Commun. **64**, 689 (1987).
[199]T. Yang, L. Dong, Z. Q. Sun *et al.*, IEEE Trans. Magn. **MAG-25**, 970 (1989).
[200]A. A. Shablo, A. V. Lukashenko, S. I. Bondarenko *et al.*, Fiz. Nizk. Temp. **14**, 653 (1988) [Sov. J. Low Temp. Phys. **14**, 361 (1988)].
[201]Lu Li, Duan Hong-min, and Zhang Dian-lin, Phys. Rev. B **37**, 3681 (1988).
[202]D. Robbes, Y. Monfort, M. Lam Chok Sing *et al.*, Nature (London) **331**, 151 (1988); D. Robbes, M. Lam Chok Sing, Y. Monfort *et al.*, Appl. Phys. Lett. **54**, 1172 (1989).
[203]J. Song, P. H. Wu, Q. H. Cheng *et al.* IEEE Trans. Magn. **MAG-25**, 911 (1989).
[204]N. D. Kataria, V. S. Tomar, A. K. Gupta *et al.*, J. Phys. C **21**, L523 (1988).
[205]A. I. Akimov, B. B. Boĭko, S. I. Borovitskiĭ *et al.*, Fiz. Nizk. Temp. **15**, 535 (1989) [Sov. J. Low Temp. Phys. **15**, 301 (1989)].
[206]V. S. Tomar, A. K. Gupta, M. Johri *et al.*, J. Phys. C **20**, L1017 (1987).
[207]R. L. Peterson and J. W. Ekin, Phys. Rev. B **37**, 9848 (1988).
[208]N. V. Zavaritskiĭ and V. N. Zavaritskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **47**,

334 (1988) [JETP Lett. **47**, 400 (1988)].
[209]T. J. Witt, Phys. Rev. Lett. **61**, 1423 (1988).
[210]K. Moriwaki, Y. Enomoto, and T. Murakami, Jpn. J. Appl. Phys. Part 2 **26**, L521 (1987).
[211]R. H. Koch, C. P. Umbach, G. J. Clark *et al.*, Appl. Phys. Lett. **51**, 200 (1987).
[212]B. Hauser, M. Diegel, and H. Rogalla, Appl. Phys. Lett. **52**, 844 (1987).
[213]H. Nakane, Y. Tarutani, T. Nishino *et al.*, Jpn. J. Appl. Phys. Part 2 **26**, L1925 (1987).
[214]A. I. Golovashkin, A. L. Gudkov, S. Krasnosvobodtsev *et al.*, IEEE Trans. Magn. **MAG-25**, 943 (1989).
[215]A. I. Golovashkin, S. I. Krasnosvobodtsev, I. V. Kucherenko *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 27 (1988) [JETP Lett. **48**, 27 (1988)].
[216]R. H. Ono, J. A. Beall, M. W. Cromar *et al.*, IEEE Trans. Magn. **MAG-25**, 976 (1989).
[217]B. Hauser, B. Klopman, D. Blank *et al.*, IEEE Trans. Magn. **MAG-25**, 919 (1989).
[218]T. Kobayashi, K. Hashimoto, U. Kabasawa *et al.*, IEEE Trans. Magn. **MAG-25**, 927 (1989).
[219]I. S. Gergis, J. A. Titus, P. H. Kobrin *et al.*, Appl. Phys. Lett. **53**, 2226 (1988).
[220]Y. Higashino *et al.*, Extended Abstracts of Intern. Superconductivity Electronics Conference, Tokyo, 1989 (ISEC '89), Jpn. Soc. Appl. Phys., Tokyo (1989), p. 218.
[221]T Yamashita, A. Kawakami, S. Noge *et al.*, IEEE Trans. Magn. **MAG-25**, 923 (1989).
[222]T. Yamashita, A. Kawakami, S. Noge *et al.*, Jpn. J. Appl. Phys. Part 2 **27**, L1107 (1988).
[223]S. Noge, T. Yamashita, Z. Wang *et al.*, Extended Abstracts of Intern. Superconductivity Electronics Conference, Tokyo, 1989 (ISEC '89), Jpn. Soc. Appl. Phys., Tokyo (1989), p. 504.
[224]B. Hauser, B. B. G. Klopman, G. J. Gerritsma *et al.*, Appl. Phys. Lett. **54**, 1368 (1989).
[225]I. Takeuchi, J. S. Tsai, H. Tsuge *et al.*, Jpn. J. Appl. Phys. Part 1 **27**, 2265 (1988).
[226]P. Chaudhari, J. Mannhart, D. Dimos *et al.*, Phys. Rev. Lett. **60**, 1653 (1988).
[227]D. Dimos, P. Chaudhari, J. Mannhart *et al.*, Phys. Rev. Lett. **61**, 219 (1988).
[228]J. Mannhart, P. Chaudhari, D. Dimos *et al.*, Phys. Rev. Lett. **61**, 2476 (1988).
[229]E. Wiener-Avnear, J. E. Cooper, G. L. Kerber *et al.*, IEEE Trans. Magn. **MAG-25**, 935 (1989).
[230]G. C. Hilton, R. A. Schweinfurth, and D. J. Van Harlingen, IEEE Trans. Magn. **MAG-25**, 931 (1989).
[231]A. E. White, K. T. Short, R. C. Dynes *et al.*, Appl. Phys. Lett. **53**, 1010 (1988).
[232]Y. Katoh, M. Asahi, H. Asano *et al.*, Jpn. J. Appl. Phys. Part 2 **27**, L1110 (1988).
[233]R. H. Koch, W. J. Gallagher, B. Bumble *et al.*, Appl. Phys. Lett. **54**, 951 (1989).
[234]H. Tanabe, S. Kita, Y. Yoshizako *et al.*, Jpn. J. Appl. Phys. Part 1 **26**, 1961 (1987).
[235]A. Z. Lin, H. Q. Li, F. W. Liu *et al.* Jpn. J. Appl. Phys. Part 2 **27**, L1204 (1988); A. Z. Lin, H. Q. Li, L. Tang *et al.*, IEEE Trans. Magn. **MAG-25**, 885 (1989).
[236]I. Iguchi, A. Sugishita, and M. Yanagisawa, Jpn. J. Appl. Phys. Part 2 **26**, L1021 (1987).
[237]C. W. Yuan, B. R. Zhao, Y. Z. Zhang *et al.*, J. Appl. Phys. **64**, 4091 (1988).
[238]S. I. Vedeneev, S. N. Maksimovskiĭ, I. B. Molchanov *et al.*, Pis'ma Zh. Tekh. Fiz. **15**(7), 80 (1989) [Sov. Tech. Phys. Lett. **15**, 281 (1989)].
[239]S. Kita, H. Tanabe, and T. Kobayashi, IEEE Trans. Magn. **MAG-25**, 907 (1989).
[240]Z. Wen, Y. Kanke, and I. Iguchi, Extended Abstracts of Intern. Superconductivity Electronics Conference, Tokyo, 1989 (ISEC '89), Jpn. Soc. Appl. Phys., Tokyo (1989), p. 109.
[241]S. Wang, G. Cui, Y. Dai *et al.*, IEEE Trans. Magn. **MAG-25**, 893 (1989).
[242]M. Matsuda *et al.*, Extended Abstracts of Intern. Superconductivity Electronics Conference, Tokyo, 1989 (ISEC '89), Jpn. Soc. Appl. Phys., Tokyo (1989), p. 497.
[243]B. A. Aminov *et al.*, Sverkhprovodimost' (KIAE) **2**(7), 91 (1989) [Superconductivity **2**(7), (1989)].
[244]B. A. Aminov *et al.*, Sverkhprovodimost' (KIAE) **2**(6), 47 (1989) [Superconductivity **2**(6), (1989)].
[245]L. E. Amatuni, A. A. Akhumyan, K. I. Konstantinyan *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **49**, 559 (1989) [JETP Lett. **49**, 647 (1989)].
[246]T. Shiota *et al.*, Preprint (1989).
[247]S. Kominami, Y. Tarutani, M. Hirano *et al.*, Extended Abstracts of Intern. Superconductivity Electronics Conference, Tokyo, 1989 (ISEC '89), Jpn. Soc. Appl. Phys., Tokyo (1989), p. 202.
[248]V. Ambegaokar and A. Baratoff, Phys. Rev. Lett. **10**, 486 (1963).
[249]I. O. Kulik and A. N. Omel'yanchuk, Pis'ma Zh. Eksp. Teor. Fiz. **21**, 216 (1975); **25**, 465 (1977) [JETP Lett. **21**, 96 (1975); **25**, 437 (1977)].
[250]S. N. Artemenko, A. F. Volkov, and A. V. Zaĭtsev, Zh. Eksp. Teor. Fiz. **76**, 1816 (1979) [Sov. Phys. JETP **49**, 924 (1979)].
[251]S. N. Artemenko, A. F. Volkov, and A. V. Zaĭtsev, Solid State Commun. **30**, 771 (1979).
[252]A. V. Zaĭtsev, Zh. Eksp. Teor. Fiz. **78**, 221 (1980) [Sov. Phys. JETP **51**, 111 (1980)].
[253]I. V. Zaĭtsev, Zh. Eksp. Teor. Fiz. **86**, 1742 (1984) [Sov. Phys. JETP **59**, 1015 (1984)].
[254]A. D. Zaikin, Tr. Fiz. Inst. Akad. Nauk SSSR **174**, 45 (1986) [Proc. (Tr.) P. N. Lebedev Phys. Inst. Acad. Sci. USSR **174** (1986)].
[255]A. V. Zaĭtsev and G. A. Ovsyannikov, Extended Abstracts of Intern. Superconductivity Electronics Conference, Tokyo, 1989 (ISEC '89), Jpn. Soc. Appl. Phys. Tokyo (1989), p. 210.
[256]A. I. Larkin and Yu. N. Ovchinnikov, Zh. Eksp. Teor. Fiz. **51**, 1535 (1966) [Sov. Phys. JETP **24**, 1035 (1967)].
[257]N. R. Werthamer, Phys. Rev. **147**, 255 (1966).
[258]A. A. Golubov, M. Yu. Kupriyanov, and V. F. Lukichev, Fiz. Nizk. Temp. **10**, 799 (1984) [Sov. J. Low Temp. Phys. **10**, 418 (1984)].
[259]A. A. Golubov and M. Yu. Kupriyanov, Zh. Eksp. Teor. Fiz. **96**, 1420 (1989) [Sov. Phys. JETP **69**, 805 (1989)].
[260]K. K. Likharev, G. M. Lapir, and V. K. Semenov, Pis'ma Zh. Tekh. Fiz. 2, 809 (1976) [Sov. Tech. Phys. Lett. **2**, 316 (1976)].
[261]M. Yu. Kupriyanov, Fiz. Nizk. Temp. **7**, 700 (1981) [Sov. J. Low Temp. Phys. **7**, 342 (1981)].
[262]A. A. Zubkov and M. Yu. Kupriyanov, Fiz. Nizk. Temp. **9**, 548 (1983) [Sov. J. Low Temp. Phys. **9**, 279 (1983)].
[263]M. Yu. Kupriyanov, K. K. Likharev, and V. F. Lukichev, Zh. Eksp. Teor. Fiz. **83**, 431 (1982) [Sov. Phys. JETP **56**, 235 (1982)].
[264]E. M. Gershenzon, M. E. Gershenzon, G. N. Gol'tsman *et al.*, Extended Abstracts of Intern. Superconductivity Electronics Conference, Tokyo, 1989 (ISEC '89), Jpn. Soc. Appl. Phys., Tokyo (1989), p. 214.
[265]Z. G. Ivanov, M. Yu. Kupriyanov. K. K. Likharev *et al.*, Fiz. Nizk. Temp. **7**, 560 (1981) [Sov. J. Low Temp. Phys. **7**, 274 (1981)].
[266]M. Yu. Kupriyanov and V. F. Lukichev, Fiz. Nizk. Temp. **8**, 1045 (1982) [Sov. J. Low Temp. Phys. **8**, 526 (1982)].
[267]M. Yu. Kupriyanov and V. F. Lukichev, Zh. Eksp. Teor. Fiz. **94**(6), 139 (1988) [Sov. Phys. JETP **67**, 1163 (1988)].
[268]A. A. Golubov, M. Yu. Kupriyanov, and V. F. Lukichev, Mikroelektronika (Akad. Nauk SSSR) **12**, 342 (1983).
[269]M. Yu. Kupriyanov, Sverkhprovodimost (KIAE) **2**(8), 5 (1989). [Superconductivity **2**(8), (1989)].
[270]A. L. Gudkov, M. Yu. Kupriyanov and K. K. Likharev, Zh. Eksp. Teor. Fiz. **94**(7), 319 (1988) [Sov. Phys. JETP **67**, 1478 (1988)].
[271]M. Yu. Kupriyanov, Extended Abstracts of Intern. Superconductivity Electronics Conference, Tokyo, 1989 (ISEC '89), Jpn. Soc. Appl. Phys. Tokyo (1989), p. 534.
[272]C. Kittel, *Introduction to Solid State Physics*, 4th ed., Wiley, N. Y., 1971 [Russ. transl., Nauka, M., 1978].
[273]R. G. Chambers, Proc. R. Soc. London Ser. A **215**, 481 (1952).
[274]S. I. Beloborod'ko and A. N. Omel'yanchuk, Abstracts of Papers presented at Second All-Union Conf. on High-Temperature Superconductivity, Kiev, 1989 [in Russian], Vol. 2, p. 236.
[275]R. O. Zaĭtsev, Abstracts of Papers Presented at Second All-Union Conf. on High-Temperature Superconductivity, Kiev, 1989 [in Russian], Vol. 1, p. 45.
[276]L. I. Glazman and K. A. Matveev, Zh. Eksp. Teor. Fiz. **94**(6), 332 (1988) [Sov. Phys. JETP **67**, 1276 (1988)].
[277]A. V. Tartakovskiĭ, M. V. Fistul', M. É. Raĭkh *et al.* Fiz. Tekh. Poluprovodn. **21**, 603 (1987) [Sov. Phys. Semicond. **21**, 370 (1987)].
[278]I. M. Lifshits and V. Ya. Kirpichenkov, Zh. Eksp. Teor. Fiz. **77**, 989 (1979) [Sov. Phys. JETP **50**, 499 (1979)].
[279]L. G. Aslamazov and M. V. Fistul', Zh. Eksp. Teor. Fiz. **83**, 1170 (1982) [Sov. Phys. JETP **56**, 666 (1982)].
[280]A. I. Larkin and K. A. Matveev, Zh. Eksp. Teor. Fiz. **93**, 1030 (1987) [Sov. Phys. JETP **66**, 580 (1987)].
[281]A V. Tartakovskiĭ and M. V. Fistul', Zh. Eksp. Teor. Fiz. **94**(9), 353 (1988) [Sov. Phys. JETP **67**, 1935 (1988)].
[282]A. F. Andreev, Zh. Eksp. Teor. Fiz. **46**, 1823 (1964) [Sov. Phys. JETP **19**, 1228 (1964)].
[283]L. N. Bulaevskiĭ, V. V. Kuziĭ, and A. A. Sobyanin, Pis'ma Zh. Eksp. Teor. Fiz. **25**, 314 (1977) [JETP Lett. **25**, 290 (1977)].
[284]L. N. Bulaevskiĭ, V. V. Kuziĭ, and A. A. Sobyanin, Solid State Commun. **25**, 1053 (1978).

[285]L. I. Glazman and K. A. Matveev, Pis'ma Zh. Eksp. Teor. Fiz. **49**, 570 (1989) [JETP Lett. **49**, 659 (1989)].
[286]K. K. Likharev, Preprint (1989).
[287]L. Soderholm and G. L. Goodman, J. Solid State Chem. **81**, 121 (1989).
[288]U. Poppe, P. Prieto, J. Schubert *et al.*, Solid State Commun. **71**, 569 (1989).

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