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THE BASES FOR THE DEVELOPMENT OF HIGH-TEMPERATURE INTEGRATED SQUID-SYSTEMS
I. Josephson Junctions

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Introduction

In [1] a review was published on the development, investigation and applications of SQUIDs made from bulk polycrystalline superconducting ceramics. It was emphasized in the above paper that the high-temperature SQUIDs development aims, similarly to that of conventional niobium SQUIDs, to fabricate a thin-film device with a planar superconducting coil above, coupling SQUID with the outer world. It was stated, however, that due to the extremely small coherence length of new materials and their layer structure (strong anisotropy of the superconducting properties) the development of high quality thin-film SQUIDs is not the question of the near future. Fortunately practical work proved this statement to be groundless. The principal obstacles on the way to practical SQUID fabrication have been overpassed:

- effective methods of growth of epitaxial thin-films without the defects have been developed;
- the principles for artificial Josephson contacts fabrication have been elaborated;
- the methods for building the reproducible Josephson structures of good enough quality with direct conductance were developed;
- the technique of growth of epitaxial multilayer structures of superconductor-insulator-superconductor (SIS) has been developed, which permitted to form the input coils and flux transformers without the excessive magnetic noise.

At present a tendency can be seen to consider the high $T_c$ SQUIDs as the complete analogs of low-temperature (LTSC) ones operating only in liquid nitrogen. Thus the concept of HTSC-based system building is taken from the LTSC-system, i.e. high $T_c$ SQUIDs are matching the standard electronic equipment made for helium cryogenic supply. Actually the operation ability at liquid nitrogen temperature and higher gives to the SQUIDs a new qualitative status. This new quality comes from the fact that their operating temperature overlaps the range of operating temperatures of semiconducting elements.

For example, recent experiments have shown that besides the magnetic measurements high $T_c$ SQUIDs permit to considerably (in 1-2 orders of magnitude) rise the sensitivity level in the field of electrical measurements, which at a time is provided by semiconducting elements [2].
This level increase can be effectuated by creating such basic measurement devices applied practically in all measuring systems and determining their major metrological characteristics as super-low-noise operation amplifiers, rf-amplifiers, high-sensitive comparators, converters of physical quantities into electric ones etc. Naturally, HTSC SQUIDs can produce a serious impact in the measurement technique development (not to mention the development of the next generation technique) only if all the above mentioned and not mentioned basic devices would be built in a form of fully integrated circuit of special destinations. Thus the overlap of operation temperature range of the new superconducting and semiconducting materials makes possible to put a question about a formation and development of a new field of science and technology, namely of a hybrid high-temperature superconductor-semiconductor (SE) microelectronics.

Finally, the hybrid microelectronics of the nitrogen cooling level must rest upon the possibility of forming the HTSC and SE elements on the common crystal. This approach is justified from the point of view of the micro miniaturization, insensitivity to external interferences and expenses decrease mostly at considerable manufacturing volumes. On the way of single crystalline hybrid devices development there are, however, some unsolved problems caused by the fact that oxide superconductors in comparison with semiconductors have rather great and complicated atomic lattice. Thus, the growth technique of the epitaxial HTSC films and SE materials and forming from them complicated structures differs considerably. For instance, in the process of growth of HTSC film in order to achieve high quality the substrate temperature should be maintained significantly higher than in the case with SE. Besides, the great difference in the coefficients of thermal expansion (CTE) takes place. For example, the single crystalline silicon substrates widely applied in SE microelectronics have the CTE \(3.8 \times 10^{-6}/^\circ\text{C}\), and for YBaCuO CTE\(=16 \times 10^{-6}/^\circ\text{C}\). Thus, critical thickness of YBaCuO film on Si without the fractures cannot be more than 50 nm [3]. For comparison the London penetration depth, which should be exceeded by the thickness of the film in the majority of practical cases, is \(\lambda_L=200 \text{ nm}\) [4].

We should not exclude the possibility that the solution of the problem of matching of HTSC and SE technologies will take a certain time. Having this in mind, we should not try probably to set the maximum problem at once but to begin with the development of double-crystal microcircuits:
to form the superconducting passive and active elements on the first crystal and semiconducting on the other one, respectively. The adoption of this intermediate stage into the common program of nitrogen microelectronics development would enable to use in the works even today the powerful semiconductors enterprises and thus to speed up the practical HTSC-SQUID-systems development, which are now the most required especially in the technique of physical experiment and in metrology.

The purpose of this review is to generalize the main results in the HTSC and LTSC SQUIDs field, which could be taken as a basis of the new branch of microelectronics development. This task could be considered fulfilled and the work performed not in vain if the present paper will help in a certain measure to the specialists to see more clearly the common perspective or to save their time and will provide the progress in the new interesting field of science and technique, namely, microelectronics of the nitrogen cooling level.

2. HTSC Weak Links

2.1. Josephson effect: main relations.

Resistively shunted junction model (RSJ).

Numerous experiments in the low temperature physics have shown that the dynamics of practically all types of weak links at certain relations of geometric sizes to the coherence length (or lengths) of the materials from which they are composed obey to equations proposed by Josephson for the description of the process of tunneling between two superconducting electrodes separated by a thin insulating barrier:

\[
\begin{align*}
I &= I_c \sin \varphi + [\sigma_0(V,T) + \sigma_1(V,T) \cos \varphi] V \\
V &= \frac{\hbar}{2e} \times \frac{d\varphi}{dt}.
\end{align*}
\]

where \( V \) is the voltage across the junction, \( I \) is the current flowing through the junction, \( I_c \) is the critical value of \( I \), \( \varphi \) is the difference in the phase of the wave function across the junction, \( \sigma_0, \sigma_1 \) voltage- and temperature-dependent conductivities.

Bringing together the system (2.1) into one equation and supposing that \( \sigma_1 / \sigma_0 = 0 \), \( 1 / \sigma_0 = R_o \), we obtain the expression:
\[ I = I_c \sin \varphi + \frac{h}{2e} \times \frac{1}{R_0} \times \frac{d\varphi}{dt}, \]  
(2.2)

which is the basis for creation of a resistively shunted model of Josephson junction (RSJ) [5,6]:

\[ I = I_c \sin \varphi + \frac{h}{2e} \times \frac{1}{R_N} \times \frac{d\varphi}{dt} + \frac{h}{2e} \times \frac{d^2 \varphi}{dt^2} + I_n, \]  
(2.3)

where \( C \) is the capacitance across the junction, \( R_N \) is the resistance formed by \( R_0 \) in parallel with artificial external shunt resistance (in (2.3) \( R_N << R_0 \) is the case of strongly shunted tunnel junction).

RSJ model is represented schematically in Fig.1. \( I_n \) is the thermal noise current generated by \( R_N \) with spectral density of \( 4k_B T R_N \).

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Fig.1. Resistive shunted model of the Josephson junction.

Although the RSJ model is suitable for the description of all types of weak links, S-N-S structures included, it is naturally that the behavior of real junction can differ considerably from that predicted by the equation (2.3). For these junctions more sophisticated models have been elaborated [7]. The practice shows, however, that in order to obtain high quality of a systems with Josephson junctions one should attain in most cases their correspondence to the RSJ model (2.3).

The consistent improvement of the technology of Josephson junction preparation is impossible without understanding of their microscopical structure. Unfortunately, at present there are more questions about the interpretation of the experimental data than the answers and, moreover, sometimes the existing answers are ambiguous. For the microstructure analysis the follows most important parameters are determined.
The characteristic voltage $V_c(T) = I_c(T)R_n$, where $R_n$ is measured at $T$ to exceed slightly $T_c$.

For tunnel structures provided that the thickness of the isolated layer $d$ is much less than the free path length in the superconducting electrodes and much more than interatom distance \(\text{(weak transparency of the barrier!!!)}\) we have according to [8]

$$V_c(T) = \frac{\pi \Delta(T)}{2 \times \frac{\Delta(T)}{e} \text{th} \frac{2k_bT}{\Delta(T)}}, \quad (2.4)$$

where $\Delta(T)$ is the gap energy of the superconducting electrodes close to barrier, $e$ is the charge of electron;

for the S-N-S structures when $d \geq 3\xi_n$ and $T \approx 0.3T_c$, characteristic voltage can be written respectively as [8,9]

$$V_c(T) \approx \frac{2\Delta(T)}{e} \exp(-d_n/\xi_n), \quad (2.5)$$

where $d_n$ is the thickness of normal metal barrier, $\xi_n$ is its normal coherent length.

For tunnel junction, when the voltage across it exceeds $\frac{2\Delta(T)}{e}$, the current-voltage characteristic has the following typical form

$$I_N(V) = \frac{V}{R_n}, \quad (2.6)$$

while for the S-N-S junctions it is

$$I_N(V) = \frac{V}{R_n} + I_{ex}, \quad (2.7)$$

where $I_{ex} = \frac{\Delta(T)}{R_n e} \left(\frac{\pi^2}{4} - 1\right)$ is related to excess current [10].

On the quasiparticle branch of VCC of junctions the following parameters are tested as well:

- the current gap Shapiro steps, which must be observed in $V_n = \text{nhf}/2e$ points, where $f$ is an external irradiation frequency;

- sub-gap structures as a result of resonant self-excitations in the junctions with a small attenuation that is characteristic of S-I-S type of weak links [11].

At $T=77K$ it is very incentive to measure the VCC with high current and voltage resolution in a neighboring region of $I_c$. As is shown in [12, 13] in HTSC Josephson junctions with a reduced energy gap in superconductive electrodes near the barrier an excessive quasi constant
voltage $V_{ct}$ and noise $V_{ex}$, possibly caused by the thermoactivated slip of the phase, are observed. As according to [14] even for the undistorted superconductor lattice, without the oxygen deficiency in the interface area S-I, the value of energy gap near $T_c$ $\Delta_1(T)$ can be less than one in distant unperturbed layers $\Delta(T)$ due to the extremely small coherence length:

$$\Delta_1(T) \equiv \Delta(T) \left(1 - T/T_c\right)^{1/2} \xi(0)/\alpha$$  \hspace{1cm} (2.8)

where $\xi(0)$ is the coherence length at $T=0$ and $\alpha$ is a constant of the lattice, then with the degradation of the transparency of the interface region due to the lattice distortion, stoichiometry disturbance and other reasons, the increment of $V_{ct}$ and $V_{ex}$ is expected. It should be added that if the excessive noise $V_{ex}$ exceeds the white noise level from $R_n$ it manifests itself in SQUIDs, worsening their energy resolution. Therefore, the $V_{ex}$ control is very desirable. It would be interesting to match $V_{ct}$ and $V_{ex}$ with the critical current density through the junction $J_{c}^{w1}$ and the distribution homogeneity degree of $J_{c}^{w1}$ in the junction. The homogeneity of the junction can be interpreted by the critical current dependence on the external magnetic field $I_c(H)$. At characteristic sizes of a weak link $s<\lambda_j$ (where $\lambda_j = \left[h/(2\mu_0 eJ_c(2\lambda_L + d))\right]^{1/2}$ is Josephson penetration depth) to the homogeneous distribution of the $J_{c}^{w1}$ corresponds $I_c(H)$ as a Fraunhofer's diffraction picture:

$$I_c(H) = I_{co} \cdot \frac{\sin(H/H_0)}{H/H_0},$$ \hspace{1cm} (2.9)

where $H_0 = \Phi_0 w(d+2\lambda_L), \Phi_0 = 2.07 \times 10^{-15}$ Wb is flux quantum, $w$ is the width of the junction, $d$ is the thickness of the barrier.

An important factor at the analysis of the junction microstructure is a temperature dependence of critical current near $T_c$. According to the Ambegaokar-Baratoff theory for the S-I-S type junction it should be expected $I_c(T) \alpha (1-T/T_c)$ provided the conditions before (2.4) are satisfied and for the SNS type junction $I_c(T) \alpha (1-T/T_c)^2$ [7]. It should be emphasized, however, that with the account of (2.8) the Ambegaokar-Baratoff equation will look like [12]:

$$I_c(T) = \frac{\pi \Delta^2(0)}{4e R k_b T_c} \left(1 - T/T_c\right)^2.$$  \hspace{1cm} (2.10)

It means that in Josephson junctions of SIS type with electrodes from HTSC materials the possibility is not excluded of observing $I_c(T) \alpha (1-T/T_c)^2$.

The last parameter we would like to mention is the relation between...
the supercurrent and the phase difference of the order parameter \( I_\phi(\phi) \) since this parameter is a very subtle instrument for the determination of quality of Josephson junctions. The \( I_\phi(\phi) \) function itself is included into the resistive model (into (2.3) one is taken \( I_\phi(\phi)=\sin\phi \)) and thus by the appearance of stationary and nonstationary voltage-current characteristics one can interpret its deviation from the sine law. We shall remind, however, that for the LTSC a method is elaborated for determination of \( I_\phi(\phi) \) in explicit form. In this case the junction is included into rf SQUID operating in the nonhysteresis mode. The advantage of this method is the possibility to measure \( I_\phi(\phi) \) with a good accuracy for the most interesting case in practice - junctions with \( I_c \) smaller than few tens of micro amperes at liquid nitrogen temperature, when VCC of the autonomous junctions is strongly diffused by the thermal noise [16].

The alternative for Josephson junction are weak links with the behaviour similar to Josephson's due to coherent movement of the vortex in the direction perpendicular to transport current (flux-flow weak links) [7]. This is characteristic of the junctions with width of \( w>\lambda_j \). They can reveal current steps as well at the external SHF radiation but the VCC of flux-flow weak links differs much from VCC given by the resistive model [17].

2.2. Types of HTSC weak links

If we refer the problems which one has to solve when creating a hybrid high temperature superconductor-semiconductor technology then the most complicated will be the problem of a thin film Josephson junction forming. The technique must not only provide the possibility of the fabrication of Josephson junction with certain electric parameters but in addition has to satisfy all the requirements existing usually for microelectronics elements, namely:

- controllability. Which means that setting a certain technological regime one can predict main parameters of the junction;
- reproducibility of the main parameters from sample to sample;
- their long-term stability;
- high reliability at thermocycling.

In addition as the final purpose it is desirable to create a tunnel Josephson structure operating at liquid nitrogen temperature. Similarly to low temperature superconducting electronics, tunnel junctions are
preferably to be used in analog and most of all in digital devices, as
being switched to normal state their voltage fall ΔV is close to a gap
value, which is estimated to be about 32 mV. Such a ΔV would permit to
easily match HTSC elements with semiconductors. The attempts (for example
[18]) to use for high temperature superconductors the same methods as for
niobium technology in insulating barrier forming appeared to be
unsuccessful. It is likely that creating the tunnel structure one has to
struggle for each atomic layer, i.e. the barrier must be grown epitaxially
in order to attain a nearly ideal coincidence of its atomic lattice with
that of HTSC electrodes. In opposite situation, as it was already
mentioned, the distortion of the lattice in the neighbouring to the
barrier layers will lead to the suppression of the order parameter, \( V_c \)
decrease and coherence length reduction. The latter is especially
undesirable, as even at maximum coherence length in a plane a-b \( \xi=(1+2)nm \)
[4] a problem is to be solved of dielectric barrier permeability
decreasing, not to mention the problem of microshorts.

Considerable success has been achieved on the way of the tunnel
structure creation: the problems have been principally solved of epitaxial
growth not only of HTSC thin films [4, 19] but also first epitaxial S-I-S
multilayer structures appeared although with a thick insulating layer [3,
20, 21]. However, to build a practical tunnel junction satisfying to all
the cited requirements will take some time. From the other hand as is
known from the experiments with bulk polycrystalline ceramics, SQUIDs with
high energy resolution can be built on the junctions with nontunnel
conductance as well. Moreover, using the standard methods of information
reading from SQUIDs one has to shunt the tunnel junctions [22] in order to
eliminate hysteresis of volt-current characteristics, which in turn leads
to \( V_c \) decrease. Thus the investigation are carried out also within the
frame of other structures. We refer first of all to the nearest analogs of
S-I-S structures - the S-N-S and S-SE-S structures (SE is a
semiconductor), where the requirements to the barrier are not so demanding
as its thickness must correlate with its normal coherence length \( \xi_n \) [7],
the structures with an artificial intergrain boundary and different kinds
of microbridges. In the technology of fabrication of HTSC junctions with
spontaneous conductivity considerable progress has been achieved, so we
shall review some of these junctions in this section.

As it is already published and are constantly appearing a number of
papers dedicated to HTSC weak links, a classification of this weak links is given in fig.2. It might be not so perfect but it will help us to orient ourself in the flood of publications.

Fig.2. Classification of HTSC weak links.

2.2.1. Weak links on the single intergrain boundary

This type of weak links is arisen from the following experimentally proved fact. In the textured thin film with a c axis, ideally aligned perpendicularly to the substrate plane, a decrease of the critical current density is observed if a misorientation of axes in a basal plane takes place [23]. When a misorientation angle $\theta$ (fig.3) exceeds a certain
critical value the boundary separating the misoriented parts of the film

Fig. 3. Schematic drawing of bicrystal. The axes of crystals are misoriented in basal plane (angle $\theta$) and along $c$-axis directions (angle $\varphi$).

starts to operate as a weak link. It was found afterwards in [24] that a weak-linked behaviour can have also boundaries between single crystal films misoriented in other planes, for instance at $c$ axis as shown in fig. 3 (angle $\varphi$). The quantitative results on the critical current density $J_c$ dependence on different angles of misorientation were first reported in [23, 24] and then were precised repeatedly, for example in [25]. A plot $J_c(\theta)$ made with the data from [23] is shown in fig. 4. 3 can be clearly

Fig. 4. The dependence of the critical current density flowing through the boundary of misoriented in basal plane bicrystal on misorientation angle $\theta$. 
1. A small angle boundary $\theta < 5^\circ$. The bridge formed on this boundary demonstrates a strong coupling between the grains as can be derived from the dependence of its critical current density $J_c^{g \text{b}}$ on the external field, which is completely identical to the field dependence of critical currents densities $J_c^{g \text{b}}(H)$ of the neighbouring grains themselves, forming the boundary;

2. $(5^\circ < \theta < 20^\circ)$ - a transition region from the strong coupling to a weak-coupled behaviour;

3. $\theta > 20^\circ$ - the most interesting for us region of large misorientation angles, when $J_c^{g \text{b}}$ decrease reaches its saturation and a small sized weak links begins to manifest Josephson properties.

At present one cannot say that the mechanism providing a weak-coupled behaviour is exactly understood. Its geometric interpretation looks cogent enough. According to [24, 26] the observations using electron microscope and Auger-spectroscopy of high resolution show that in the intergrain boundary there are non-superconducting dislocations with the centers in points of maximum mismatch of atomic lattices due to the final $\theta$. With misorientation angle increment the dislocation density grows and as shown in [24] at very $\theta = 20^\circ$, which corresponds to the minimum $J_c^{g \text{b}}$, the normal "cores" of the dislocations overlap completely each other. Thus at $\theta > 20^\circ$ grain boundary can be regarded as a region with a completely distorted and disordered lattice.

What is the microscopic nature of the grain boundary? May be it is an inhomogeneous SNS contact or an inhomogeneous SIS tunnel structure without a gap in the density of quasiparticle states, or a parallel massive of ballistic point contacts, or more complicated structures as, for example, the SNINS and so on. At present this question remains open. The discussions on this subject can be found in practically all papers on HTSC weak links, for example in [9, 11, 12, 14, 24, 26, 27, 29 and others]. The most important for us is that, according to numerous experiments, in the large-angle intergrain boundaries an misorientation angle $\theta$, critical current density $J_c^{g \text{b}}$, normal resistance $R_N$ and boundary area $A$ are connected by a single-valued functional dependence (scaling behaviour). If $\rho_{n} = R_{n} A$ then

$$J_c^{g \text{b}} \rho_{n} \propto \left( \frac{1}{\rho_{n}} \right)^{K},$$

(2.11)
where $\kappa = 0.75$ in [27] and $\kappa = 0.85$ in [28],

$$V_C = I_R \alpha(I_C)^{0.6} \quad [27].$$

(2.12)

From (2.11) and (2.12) a conclusion can be derived that based on the intergrain boundary Josephson junctions can be formed by a controlled method.

At present three types of weak links formed on the intergrain boundaries can be marked out. All this weak links are single-layer structures, have similar electric parameters and differ only by the methods of forming the substrates on which the film is epitaxially grown. We shall briefly touch the three types of weak links, point out their advantages and deficiencies and will give their main performances.

**Bicrystalline weak links**

The artificial boundary in that type of weak links is formed by the epitaxia growth of a thin film on a bicrystalline substrate the two halves of which have misoriented crystalline lattices (fig.5). Preparing bicrystalline substrates of a good quality is a rather complicated task. The most used are two ways [24,25]:

- hot pressing at $T_{pr}$ considerably lower the melting point of preliminary thoroughly polished two single-crystals. For SrTiO$_3$ $T_{pr} \approx 1450^\circ$;
- synthesis of a common sample from two seeded single-crystals at $T_s > T_{pr}$ (for SrTiO$_3$ $T_s \approx 1650^\circ$). In the latter case the bicrystall is formed by the migration of the initial boundaries of the seeded crystals to a distance of several hundreds of microns.

The process effectuated by the first method requires less time and is easier in realization. However, it harbours a danger of crystal structure deformation while pressing.

Evidentially the bicrystalline weak links are not so promising for the integrated technology. They can be practically applied only in simple circuits with few Josephson junctions in it, for instance in single SQUIDs. It is connected with the fact that the local position of the superconductor's elements is preset by the boundary line of the substrate. And besides this the preparation of a high quality bicrystalline substrate is a very complicated and expensive process.

These disadvantages have been overcome in the weak links formed on the bi-epitaxial films.
Bi-epitaxial weak links

This type of the weak links development was stimulated by the observation of the existence of two axis orientations in the basal plane (with θ=45°) of the YBaCuO c-oriented epitaxial thin films, when they are deposited at different temperatures on the substrates with a crystalline lattice not well matching with a YBaCuO lattice. It can be taken zirconium stabilized by yttrium [30] or sapphire [31] as an example of such a substrate.

The main idea of a bi-epitaxial grain boundary forming consists in using additional seed and buffer layers growing epitaxially on the substrate. The materials of these additional layers are usually selected in the way that one part of them grows without - but another one with define angle towards major symmetry axes of substrate. In further, these layers serve as the substrates for the HTSC film while their separation boundary is a base for intergrain junction nucleating. It is obvious, that when applying a standard photolitography, one can form Josephson junctions with this approach in any local places on the substrate.

A schematic view of an example of bi-epitaxial weak link structure is shown in fig. 5 [31]. First it was precipitated 3-30 nm of epitaxial MgO upon the r-plane of the sapphire substrate. Then a standard photoresist mask was deposited in a way that after an ion or chemical etching the MgO would be removed from the half of the substrate. An epitaxial 10-100 nm buffer layer of SrTiO₃ was grown above both upon sapphire surface and the MgO seed layer. At an oxygen pressure of 100-200 mT and a substrate temperature 710-760°C a SrTiO film grows in two orientations separated by

Fig.5. Schematic drawing of the structure of the bi-epitaxial weak links.
a boundary with $\theta=45^\circ$ along the transition line from MgO to sapphire. Under standard conditions an YBaCuO layer grown epitaxially after the SrTiO repeats the obtained intergrain boundary. At the end of the procedure a weak link of required sizes is lithographically patterned. The investigations in [30-32] have shown that it is possible to eliminate all large-angle grain boundaries from the film save the artificially grown one. This conclusion was derived from the critical current density measurement in both halves of the bi-epitaxial film, which by the way was $(1-3)10^6 A/cm^2$ at $T=77K$.

As the bi-epitaxial weak links preparation is based only on the standard photolithography and they can be placed in any point of a substrate this technique can be adopted in future as a base in the integral superconducting electronics. However, it requires more work to be done for its development. It is connected with the fact that bi-epitaxial junctions have the most low values of $V$ ($(0.1-1)mV$ at $4.2K$) and critical current density $(J^b_c=(10^2-10^3)A/cm^2$ at $T=77K$) among the junctions on intergrain boundary because of the large misorientation angle $\theta=45^\circ$. There is a hope, however, that in the nearest future the approaches will be found which allow to improve electrical characteristics. At present the intensive work is performed in this direction [33].

**Step-edge junctions**

As it was mentioned above the misorientation not only in a basal plane but also along any other planes leads to a weak-link behaviour. The fact of the critical current density decrease on the step MgO substrates reported by many researches (for example [34]) became a precondition for a step-edge junctions development. The idea of the method can be clearly seen in fig. 6 [35]. First a step with a preset inclination angle and height is formed at the single-crystalline substrate via ion or chemical etching. Afterwards an epitaxial superconducting film is grown above. The step in the substrate leads to a two grain boundaries forming near the top and the foot of the step. These boundaries determine the properties of the microbridge which is perpendicular to the step.

With the step-edge junctions a greater $V_c$ value can be achieved in comparison with that of the bi-epitaxial ones because their $J^b_c$ can be easily changed by three orders. It is effectuated by three parameters:

- changing of a step slope angle;
- height of the step;
- relation of film thickness to step height.

It was obtained experimentally with step-edge junctions the highest values of critical current density \( J_{cb} = 10^5 \text{A/cm}^2 \) at \( 77K \) [36]) and \( I_c R_N \) product \((5-8)\text{mV} \) at \( T=77K \) for \( \text{TlCaBaCuO} \) [37]) among all types of weak links. However, at the same time a strong dependence of \( J_{cb} \) on three quoted factors will create probably additional difficulties in attaining a good controllability and reproducibility.

As the best characteristics to date were obtained on the SQUIDs with step-edge junction it would be of interest to study technological procedures of their fabrication. These methods are described in detail in [37-39]. There is reported that following relations can be taken as optimal: a height of the step made via ion etching, \( h=0.3-0.4 \ \mu\text{m} \), a slope angle of the step with the substrate \( \approx 60^\circ \) and a film thickness about \( h/2 \).

Thus, we have considered all known to date approaches of junction fabrication on the artificially grown intergrain boundaries. Their principal advantages and deficiencies are given for illustration in table 1 and the main parameters in table 2. In addition to the tables we shall make some remarks:

a) intergrain boundaries have normal resistance not changing in a wide temperature range;

b) step edge junctions with the artificially added capacitance reveal
knee-like hysteretic VCC from which follows that $R_0 \approx 5000\Omega$ and gap-like structure at $V_c = 35mV (T < T_c)$;

These facts are serious arguments in favor of a thesis that grain boundary forms nevertheless an insulating barrier and possibly by decreasing a scattering factor in an interface region (to increase $\Delta_i(T)$), a larger more $V_C$ value will be obtained.

c) VCC almost of all the types of grain boundary weak links are in a very good agreement with a RSJ (1.3) [36];

d) and, finally, in recent works, e.g., in [24, 37, 47], the field dependence of critical current of Josephson junctions $I_c(H)$ coincides with high accuracy with (1.9), if we take into consideration an effect of magnetic flux focusing at $H_o$ calculation [48]. This means that it is possible to attain a good homogeneity of the boundary.

2.2.2. Multilayer weak links

2.2.2.1. Heteroepitaxial structures

Even not taking into account a high temperature of the substrate at film deposition, it can be seen from table 1 that developed technologies

<table>
<thead>
<tr>
<th>Type of weak link</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>bicrystal</td>
<td>reproducibility, reliability, controllability, large $V_c, J_c$</td>
<td>weak integration</td>
</tr>
<tr>
<td>bi-epitaxial</td>
<td>reproducibility, controllability, high integration</td>
<td>small $V_c, J_c^b$, weak reliability</td>
</tr>
<tr>
<td>step-edge junctions</td>
<td>reliability, large $V_c, J_c^b$</td>
<td>weak reproducibility, controllability</td>
</tr>
</tbody>
</table>
of grain boundary weak links preparation have not provided the achievement of high electrical parameters and the satisfaction with the major requirements of integral technology simultaneously. Particularly, it will be a serious problem to solve that of development of a process of the junction surface passivation not changing its electrical parameters. Hence, now alternative structures are being developed and investigated, especially that of multilayer structures with artificially grown barrier. They are important not only because they probably will be free from the above cited deficiencies but also because we hope in course of the works on the artificial growth of the barrier to create a classical tunnel junction operating at liquid nitrogen temperatures.

From that point of view the use dielectrics dopped with metals as a material for the barrier is of major interest. In [41] it was suggested to use SrTiO3:Nb. The advantage of SrTiO3:Nb rests on two reasons: first - its crystalline lattice matches well with YBaCuO and second - that its conductivity is determined completely by the level of doping with niobium, which partially replaces Ti. One can approach a problem of insulating barrier fabrication by gradually decreasing Nb concentration in SrTiO3:Nb and developing the technology of heteroepitaxial structures growth.

S-SE-S type structures are interesting as Josephson junction with non-hysteretic VCC as well. As shown in [49] a semiconducting barriers with low state density (weak conductivity) permit to attain comparatively high \( V_c \) values even at a small coherence length in high temperature superconducting electrodes. At conductivity of semiconductor \( \sigma_{SE} \leq 0 \),

\[
V_c \rightarrow \frac{\pi}{2} \frac{\Delta^2(T)}{e}
\]

The S-SE-S junctions are fabricated mainly in two configurations:
- edge junction with c-oriented HTSC film electrodes (fig.7);
- vertical sandwich, where a axes of the superconducting electrodes are perpendicular to the substrate plane (fig.8).

From the point of view of microshorts avoiding and self capacitance decreasing the edge junctions are preferable.

Besides SrTiO:Nb as a -SE- layer PrBaCuO is tested [42, 43] and non-superconducting YBaCuO grown at a lowered substrate temperature (520–540°C) [40].

The best results to date among multilayer structures have been
achieved in edge junctions with N-YBaCuO [40]. Their stationary VCC are consistent with a RSJ model (2.3), normal resistance is inversely proportional to the barrier area and the critical current density $j_c \propto \exp(d / \xi_n)$, where according to [40] $\xi_n \approx 20\text{Å}$. All this facts and most of all the experimentally defined value of $\xi_n$ assumes a good homogeneity of junction and absence of microshorts. Taking into account that a minimal thickness attained for a reliable SE-barrier is 2nm one can predict promising perspectives for heteroepitaxial structures.

Principal parameters for the best S-SE-S junctions are given in table 2.

2.2.2.2. Multilayer structures with the non-epitaxial barrier

This types of structures related to the junctions where the role of the barrier plays their own native oxide layer or layer formed by the plasma processing of one of the HTSC electrodes and normal metal barrier junctions based on the proximity effect as well.

In [18, 45] is shown that the junctions based on their own oxide and fluorinated barriers might have high electrical parameters (table 2). However, the questions connected with the nature of this barrier, controllability and reproducibility from sample to sample still remain open.

S-N-S structures are traditional for low temperature superconductivity. Their nature was well studied [7]. Hence, immediately after the discovery of the HTSC a proximity effect near S-N boundary was investigated [50]. Because of high reaction ability of the oxide superconductors, only Ag, Au or Ag-Au were tested as N layer. In recent papers on proximity effect [51, 52] it has been shown that it is possible to attain good homogeneity of S-N interface. A fabrication of S-N-S weak links, which demonstrate Josephson properties and agree with a RSJ model (2.3) is reported in [44, 53, 54]. Unfortunately, these weak links have shown $V_c$ considerably lower the value, which could be expected from the
proximity effect. Probably it would be connected with the fact that the S-N transition region has strong centers of quasiparticle scattering decreasing $\Delta(T)$. It is proved by the fact that normal resistance of S-N-S junctions is by 2-3 orders higher than that of the N layer.

The problems of permeability of S-N regions are discussed with more detail and with quantitative calculations in [55].

Principal parameters of the best YBaCuO/YBaCuO+CF$_4$/YBaCuO and YBaCuO/Ag/YBaCuO junctions are given in table 2.

<table>
<thead>
<tr>
<th>Type of weak link</th>
<th>$I_{R, mV}$ at 4.2K</th>
<th>$I_{R, mV}$ at 77K</th>
<th>$T_c$, K</th>
<th>$J_{C, A/cm^2}$ at 4.2K</th>
<th>Width of weak link, $\mu$m</th>
<th>Barrier thickness, nm</th>
<th>Film thickness, nm</th>
<th>Substrate material</th>
<th>Reference</th>
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<tr>
<td>bicrystal</td>
<td>1-2</td>
<td>0.1-0.2</td>
<td>90</td>
<td>$10^4-10^5$</td>
<td>0.25-2</td>
<td>-</td>
<td>300</td>
<td>SrTiO$_3$</td>
<td>[13]</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.04</td>
<td>90</td>
<td>$10^3$</td>
<td>4</td>
<td>-</td>
<td>200</td>
<td>Y-ZrO$_2$</td>
<td>[25]</td>
</tr>
<tr>
<td>bi-epitaxial</td>
<td>0.4</td>
<td>-</td>
<td>88</td>
<td>$10^2-10^3$</td>
<td>40</td>
<td>-</td>
<td>250</td>
<td>Al$_2$O$_3$</td>
<td>[32]</td>
</tr>
<tr>
<td></td>
<td>0.15-0.35</td>
<td>0.01</td>
<td>85</td>
<td>400</td>
<td>20-50</td>
<td>-</td>
<td>250</td>
<td>SrTiO$_3$, LaAlO$_3$, MgO, Y-ZrO$_2$</td>
<td>[33]</td>
</tr>
<tr>
<td>step-edge junctions:</td>
<td>-</td>
<td>2-5</td>
<td>100</td>
<td>$10^3-10^4$</td>
<td>5-10</td>
<td>-</td>
<td>200</td>
<td>LaAlO$_3$</td>
<td>[37]</td>
</tr>
<tr>
<td>YBaCuO</td>
<td>0.5-0.2</td>
<td>0.02</td>
<td>90</td>
<td>$10^2-10^3$</td>
<td>5</td>
<td>-</td>
<td>200</td>
<td>SrTiO$_3$, LaAlO$_3$</td>
<td>[35]</td>
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<tr>
<td>YBCO/N-YBCO/YBCO</td>
<td>0.66</td>
<td>&lt;0.1</td>
<td>85</td>
<td>$6.5\times10^3$</td>
<td>10-15</td>
<td>2-10</td>
<td>150-300</td>
<td>LaAlO$_3$</td>
<td>[40]</td>
</tr>
<tr>
<td>edge junctions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>YBCO/SrTiO: Nb/YBCO</td>
<td>1-3</td>
<td>-</td>
<td>80</td>
<td>$12$</td>
<td>50-200</td>
<td>25</td>
<td>200</td>
<td>MgO</td>
<td>[41]</td>
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<tr>
<td>YBCO/PrBCO/YBCO</td>
<td>0.07-0.22</td>
<td>-</td>
<td>85</td>
<td>$10^4$</td>
<td>10-20</td>
<td>30-150</td>
<td>200</td>
<td>SrTiO$_3$</td>
<td>[42]</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>YBCO/YBCO+CF$_4$/</td>
<td>0</td>
<td>-</td>
<td>84</td>
<td>-</td>
<td>40</td>
<td>-</td>
<td>200</td>
<td>SrTiO$_3$</td>
<td>[43]</td>
</tr>
<tr>
<td>YBCO/YBCO</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YBCO/Ag/YBCO</td>
<td>0.07-0.22</td>
<td>-</td>
<td>87</td>
<td>-</td>
<td>5</td>
<td>300</td>
<td>250</td>
<td>LaAlO$_3$</td>
<td>[44]</td>
</tr>
<tr>
<td>step edge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>YBCO/YBCO+CF$_4$/</td>
<td>0</td>
<td>-</td>
<td>84</td>
<td>-</td>
<td>40</td>
<td>-</td>
<td>200</td>
<td>SrTiO$_3$</td>
<td>[45]</td>
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Thus, we have reviewed all main approaches of making weak links known to date. Each of them can be potentially adopted as a basic one in superconductive microelectronics. To conclude this section we shall summarize: further investigations in the field of HTSC weak link technology has a very strong basis, which permits to start works on projecting analogous systems with Josephson contacts of integrated design.

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# SUBJECT CATEGORIES
## OF THE JINR PUBLICATIONS

<table>
<thead>
<tr>
<th>Index</th>
<th>Subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>High energy experimental physics</td>
</tr>
<tr>
<td>2.</td>
<td>High energy theoretical physics</td>
</tr>
<tr>
<td>3.</td>
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</tr>
<tr>
<td>4.</td>
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</tr>
<tr>
<td>5.</td>
<td>Mathematics</td>
</tr>
<tr>
<td>6.</td>
<td>Nuclear spectroscopy and radiochemistry</td>
</tr>
<tr>
<td>7.</td>
<td>Heavy ion physics</td>
</tr>
<tr>
<td>8.</td>
<td>Cryogenics</td>
</tr>
<tr>
<td>9.</td>
<td>Accelerators</td>
</tr>
<tr>
<td>10.</td>
<td>Automatization of data processing</td>
</tr>
<tr>
<td>11.</td>
<td>Computing mathematics and technique</td>
</tr>
<tr>
<td>12.</td>
<td>Chemistry</td>
</tr>
<tr>
<td>13.</td>
<td>Experimental techniques and methods</td>
</tr>
<tr>
<td>14.</td>
<td>Solid state physics. Liquids</td>
</tr>
<tr>
<td>15.</td>
<td>Experimental physics of nuclear reactions at low energies</td>
</tr>
<tr>
<td>16.</td>
<td>Health physics. Shieldings</td>
</tr>
<tr>
<td>17.</td>
<td>Theory of condensed matter</td>
</tr>
<tr>
<td>18.</td>
<td>Applied researches</td>
</tr>
<tr>
<td>19.</td>
<td>Biophysics</td>
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</tbody>
</table>
Полушкин В.Н. Д13-92-339
Основы для разработки высокотемпературных сквидовских систем в интегральном исполнении. Часть I. Джозефсоновские переходы

Рассмотрено современное состояние дел в области создания интегральных высокотемпературных джозефсоновских переходов и сквидов. Проанализированы перспективы использования новых датчиков для построения сверхвысокочувствительной измерительной аппаратуры. Показано, что ВТСП-сквиды способны оказывать серьезное влияние на общее развитие информационно-измерительной техники, так как на их основе может быть создан ряд базовых микроэлектронных устройств нового поколения.

Работа выполнена в Лаборатории нейтронной физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1992

Перевод автора

Polushkin V.N. D13-92-339
Part I. Josephson Junctions

The current state of high-$T_c$ superconducting thin-film Josephson junctions and SQUIDs developing is reviewed. The prospects of application of new devices in supersensitive measurement apparatus are analyzed. It is shown that high $T_c$ SQUIDs are able to influence further development of information and measurement engineering as on their base the series of microelectronic elements and devices of new generation can be built.

The investigation has been performed at the Laboratory of Neutron Physics, JINR.

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