Stressed High Temperature Superconductor Films

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Abstract— **The goal of the project is to study and describe a new stressed state of High Temperature Superconducting (High-Tc) YBCO Films, to create of SQUIDs on the bases of these Films with maximal sensitivity. The problems of the project are: 1. The experimental studying of the stressed films growing by laser ablation method. 2. The studying of stressed film properties. 3. The making of the dc-SQUIDs with maximal sensitivity on the bases of the stressed YBCO films.**

I. INTRODUCTION

An analysis of the current literature on this question allows us to affirm that the subject of the project is actually.

The main planned bases results are: 1) It will be obtained new and more detailed data in the growing of the stressed YBCO films by laser ablation method. 2) Mechanism of critical current suppression at the Coulomb blockade on inter domain boundaries will be determined. 3. New experimental data of the stressed film properties, of the temperature dependence of critical current, the creep, the magnetic permeability depending on degree of the film stressing will be obtained. 4. The new experimental data of the stress domains by the tunneling spectroscopy method will be obtained. 5. The dc-SQUIDs of maximal sensitivity will be created on the bases of stressed films.

The main planned application results are: 1) The making of the HTS dc-SQUIDs on the bases of stressed films. 2) The creation of devices of high sensitive medical magnetometers and SQUID microscope.

II. Statement of the Problem

A big number of researchers became to work on the making of a SQUID (Superconducting Quantum Interference Device) at ones after the discovery of High-Tc ceramic superconductors at the end of 1986. Bulk ceramic $YBa_2Cu_3O_{7-\delta}$ (YBCO) RF-SQUIDs were created quite in 1987. These SQUIDs were created on the basis of a weak links Diem bridges that have a cross-section 50×50 μm2 in the best case. A preparation of them was conjugated with very big difficulties and, in addition, these bridges have collapsed 5~7 thermocycles. So the following works in this direction were focused on the SQUID creation on the basis of the thin High-Tc films. But this problem was proved to be complex one. The point is that the High-Tc films YBCO (precisely they have used most often of the SQUID making), growing by the laser ablation method, have a big range of superconducting and other physical parameters. The epitaxial, single crystalline films have the critical current density about 10^6 A/㎠. The value of the critical current density of the junction is 3 ㎃ at the width of a bridge in 3 mkm and the film thickness in 100 ㎚. In this case the parameter of the dc-SQUID $\beta=2I_cL/\Phi_0$ (Φ_0 is a quantum of magnetic flux, L is a inductance of the quantization loop) is equal to 300 for $L=10^{-10}$ H. The value of the parameter β must be about one for the SQUIDs with the high sensitivity. The value of L is determined of the SQUID geometry, and the quantization loop diameter is 20~30 ㎛ usually. This diameter gives for L the value about 10^{-10} H. So, the critical current of junction must be decreased for the decreasing of β. But the film structure is become granular and unstable to the thermocycling at the decreasing of the critical current density up to 10^4 /m². At present the creating of the film SQUIDs goes on the whole in the two directions: 1) with using of the step-edge junctions and 2) Bicrystal junctions [1]. These SQUIDs are very complicated for the making and require the expensive and complex equipment. Besides, the High-Tc film on the Bicrystal boundary and step-edge one grows with the low stability to a degenerating.

We propose other way to solve of the creating of the film SQUIDs with the high sensitivity. The main idea is to use so called stressed YBCO films. The stressed states in the High-Tc films growing by laser ablation method we were found in 1998 [16]. The films in these states have an unordinary temperature dependence of the critical current with the characteristic minimum at 55~57 K intervals. The critical current density of the films in the stressed states is changed over a wide range: from 10^3 to 10^5 A/㎠ at 77 K, moreover the values of the magnetic susceptibility and critical temperature are equals to the values of the single crystalline films [1]. Besides, the stressed films have the high stability to a degenerating. The parameter $\beta=2I_cL/\Phi_0$ in the SQUIDs being made on the basis of the stressed films is equal to about one, and the sensitivity of them by magnetic flux is $(2\cdot10^{-5} \sim 6\cdot10^{-6})\ \Phi_0/Hz^{1/2}$ [2]. The sensitivity by magnetic field with using of the flux concentrator in 1 ㎟ area is about $5\cdot10^{-14}$ $T/Hz^{1/2}$ [3]. This value is in agreement with the sensitivity of the dc-SQUIDs using the step-edge junction and bi-crystal junction.

III. Method of Solving Problems

1. Stressed YBCO film

To grow high quality thin YBCO films by laser ablation method we must understand, first of all, processes going on the substrate surface at the absorption of laser pulses. Our experiments have showed that the power density of the laser radiation *Wpc* = $2.5 \cdot 10^8$ W/㎠ is boundary one. The cluster mechanism of the particle break-off from substrate YBCO is realized at *Wp* > *Wpc*, which is changed on the drop mechanism at *Wp* < *Wpc*. We are developed a theory of the cluster and drop mechanisms [4].

The stressed YBCO films have been deposited by laser ablation method. As a substrate we used single-crystal plates of $LaAlO_3$ (100). We used a pulsed Nd:YAG laser (wavelength λ= 1.06 ㎛, pulse length τ =20 ns , repetition race υ=12 Hz). The substrate temperature was adjusted at temperature in the range 810~840℃, and the oxygen partial pressure in the vacuum chamber was about 0.1~0.6 mbar during the deposition. The power density of laser radiation on the target surface varied from $3 \cdot 10^8$ W/㎠ to $8 \cdot 10^8$ W/㎠. The studied films were made in the shape of long strips of width about 10~40 ㎛ by means of focused ultraviolet laser beam. The critical current was measured by a four-probe method. The 1 ㎶ criterion was used for the critical current.

The stressed states of growing HTS YBCO films arise at the rapid rate of cooling [28]. A main cause of arising of the mechanical stress in the films is a difference of parameters of the YBCO structure and substrate material. This difference of the YBCO and $LaAlO_3$ crystals are equal to about 1 %. At the rapid rate of cooling about 1.5~2.5 deg./s the mechanical stresses in a film are not able relax and they are frozen in the superconducting material. Dependences of the critical current density in accordance with time of the holding in the furnace at difference cooling rates are shown in Fig. 1.

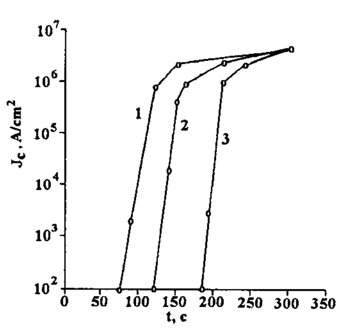

Fig. 1. Dependences of the critical current density Jc vs. time of the holding in the furnace at difference cooling rates. (1-2.5 deg./s, 2-2.2 deg./s, 3-1.6 deg./s).

The stress degree of films depends on the thickness of them (see Fig.2).

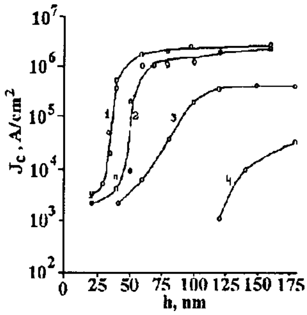

Fig. 2. Dependences of the critical current density Jc vs. thickness of films at difference hardening time: 1-300 s, 2-180 s, 3-90 s, 4-80 s.

Our studying of the stressed HTS films by the tunneling microscopy indicates that film structure consists of stress domains. We have measured tunnel I-V characteristics between a film and a needle of the scanning microscope [29]. A boundary between domains has a deformation potential well, in which an electron may by localized. Therefore the tunnel I-V characteristics will be have peaks. The typical I-V characteristic is shown in Fig. 3.

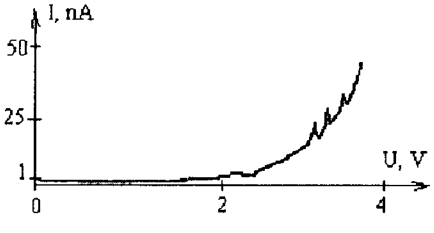

Fig. 3. Typical tunnel I-V characteristic

In Fig. 4 coordinates of dots on the scan where the I-V characteristics have peaks as in Fig. 3 are shown.

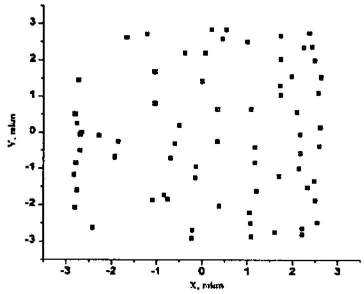

Fig. 4. Coordinates of dots with the tunnel I-V characteristics of domain boundaries.

The distance between two neighboring dots apparently is a size of domain. In the Fig. 5 the dependence of an average size of domain in accordance with the critical current density is shown.

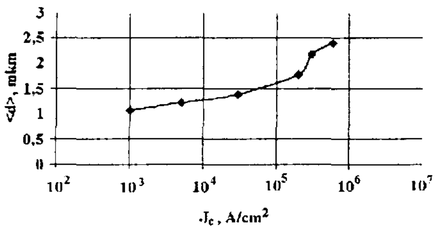

Fig. 5. The dependence of an average size of domain vs. the critical current density Jc.

It is seen from Fig. 5 that the average size of domain increases at the increasing of critical current density, i.e. at the decreasing of the stress power.

The stressed HTS YBCO films have unusual temperature dependence of the critical current density. In the temperature interval of 55~57 K it have the minimum [23,25,27,28]. In Fig. 6 the typical temperature dependence of the critical current density is shown.

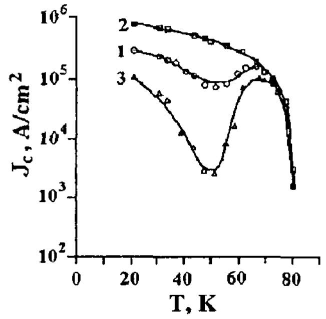

Fig. 6. Typical temperature dependence of the critical current density for the stressed HTS YBCO film at the different number of thermocycles n (1- n=0, 2- n=70, 3- n=140).

This unusual behavior of the curve of temperature dependence of the critical current density is explained with the Coulomb blockade on the domain boundaries, where electrons are localized. These domain boundaries are like a Josephson junction of an unknown type.

Fig. 7. The critical current density Jc of the stressed film vs. number thermocycles n. (Initial value of Jc = $3\cdot10^5$ A/cm^2)

Our studying has shown that the stressed films are more stable to the thermocycling than the films with the granular structure. The stressed films having the value of the critical current density Jc = $3\cdot10^5$ A/cm^2 are the more stable. These films can bear more than 500 thermocycles. In Fig. 7 results of the thermocycling of the stressed film with the initial value Jc = $3\cdot10^5$ A/cm^2 are shown.

2. SQUIDs on the stressed HTS films

SQUIDs on the basis of the stressed HTS YBCO films are made by the photolithography technology using a dry etching method [11,20,24,37,39]. This method allows us to get micro bridges with the width about 3~4 μm. The thickness of films was equal to 100 nm.

The SQUID design has a flux concentrator (see Fig. 8). An asymmetry of the dc-SQUID arms plays an important role, but it is not succeed to exclude completely by preparation. Equations of the dc-SQUID with regard to the asymmetry have the form:

$$(1)\quad V=\frac{1}{2}(\phi_1+\phi_2)$$

$$(2)\quad i_L=\frac{2\Phi_e}{\beta}-\frac{\phi_2-\phi_1}{\pi\beta}$$

$$(3)\quad \phi_1=\frac{1}{i_{c1}}(\frac{i}{2}-i_L-(1-\alpha)\sin\phi_1-i_{1f})$$

$$(4)\quad \phi_2=\frac{1}{i_{c2}}(\frac{i}{2}+i_L-(1+\alpha)\sin\phi_1-i_{2f})$$

where V is a SQUID potential normalized to $V_c=\hbar/2e\,\tau_c$, time t normalized to $\tau_c=\hbar/2eR_1I_{c1}=\hbar/2Er_2I_{c2}$, ϕ_1 and ϕ_2 are phase differences of wave function on the arms of SQUID, i and i_L are bias and circular currents respectively normalized to (I_1 and I_2 are currents on the corresponding arms of SQUID, I_{c1} and I_{c2} are critical currents on the corresponding arms of SQUID), i_1, i_2, i_{1f} and i_{2f} are critical and noisy currents on the corresponding arms normalized to I_c. Φe is an external magnetic flux through the SQUID normalized to the quantum of flux. β is a modulation parameter, α is a asymmetry parameter.

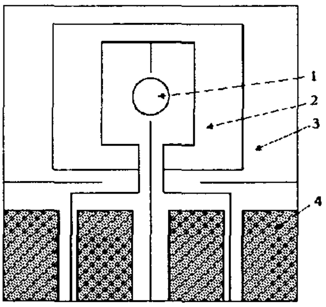

Fig. 8. The dc-SQUID design. (1 quantization contour; 2 flux concentrator; 3 induction coil; 4 golden contact areas.

Voltage-flux characteristic of SQUID and scheme of dc-SQUID are shown in Fig. 9.

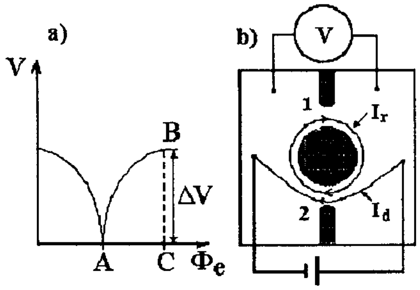

Fig. 9. a) Voltage-flux characteristic of SQUID; and b) Scheme of dc-SQUID.

The SQUID sensitivity S is defined as the following:

$$S = (1+\frac{1}{2}i_b^2)^{1/2}\frac{2R_D\sqrt{k_BT}}{\Gamma}\frac{1}{\sqrt{Hz}} \qquad (5)$$

where $R_D = R\frac{i_b}{\sqrt{i_b^2-1}}$ is a differential resistance, $i_b = \frac{i_b}{i_c}$, i_b is a bias current. The resistance R is defined from I-V characteristic of the SQUID. The parameter Γ characterizes amplitude of the SQUID voltage per half of flux quantum.

Parameters Γ and α were measured experimentally and numerically by the solving Eqs. (1)~(4). In Fig. 10 the calculated values of the parameter Γ depending on the asymmetry parameter α are shown [17]. It is seen the increasing of parameter decreases Γ.

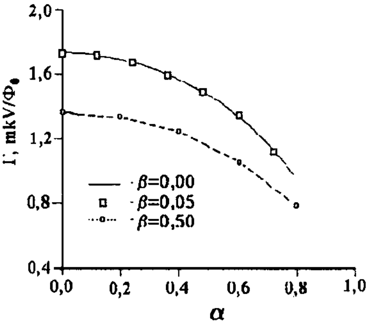

Fig. 10. Dependence of the parameter Γ vs. the asymmetry parameter α.

Table 1. experimental data

No	I_c, μA	△V, V	Γ, μV/Φ_0	S,
1	21	1.5	0.33	5.9×10^{-6}
2	50	2.0	0.44	4.5×10^{-6}
3	160	0.4	0.08	2.45×10^{-5}

Thus, as it is seen from the Table, the SQUIDs on basis of the stressed films have the sensitivity not lower than step-edge junction and Bicrystal junction SQUIDs, but simpler in the making and more long-lived. We can maintain at present that the proposing way in creating the SQUIDs on the basis of the stressed High-Tc YBCO films makes possible to develop the technology of an industrial manufacture devises and systems of the various purpose. One of the interesting areas of use are the SQUID microscopy, medicine, industry of oil extraction and so on.

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