SQUID nature of microwave absorption in a high-$T_c$ superconducting Ho-Ba-Cu-0 single crystal

M.K.Aliev, G.R.Alimov, I.Kholbaev, T.M.Muminov, and B.A.Olimov

Institute of Applied Physics, Tashkent State University 700095, Tashkent, Uzbekistan

Abstract

A high-$T_c$, superconducting $Ho_1Ba_2Cu_3O_{7-x}$ single crystal with $T_c = 86.8K$ is investigated on a modified ESR spectrometer at temperatures $T > 78K$. A signal is observed, whose spectrum in the range of magnetic fields $H < 0.7Oe$ has the form of equivalent absorption lines with an interval $\Delta = 9 \times 10^{-3}Oe$. Detailed measurements of the dependence of the spectrum on the amplitude of the microwave field, the temperature, and the orientation of the single crystal are reported. It is established that the absorption spectrum exhibits a typical behavior inherent in SQUIDs with a critical current that decays linearly with increasing $T$. Three different techniques are used to determine the so-called hysteresis parameter of the postulated SQUID: $Li_c/\Phi_0$ ($L$ and $i_c$ are the inductance and critical current of the SQUID, and $\Phi_0$ is the quantum of magnetic flux). All three techniques give the same result: $Li_c(T = 79K)/\Phi_0 = 3.1 \pm 0.3$, attesting to the existence of a SQUID-like structure in the single crystal.

Keywords: SQUID; Magnetic-field modulation; Microwave absorption; High-$T_c$ superconductor

1 Introduction

Since the advent of high-temperature (high-$T_c$) superconductivity, the ESR spectrometer has found application for the investigation of microwave absorption in high-$T_c$ superconductors in addition to its conventional use. One of the most interesting phenomena discovered by means of ESR spectrometers is a periodic dependence of the microwave absorption in high-$T_c$ single crystals of the 1-2-3 type on the external magnetic field $H$ (the period $\Delta H \approx 10^{-2}Oe$) [1] - [8]. Despite consensus that this phenomenon is a macroscopic quantum effect, a single, unambiguous explanation has yet to be found for the microwave absorption mechanism itself. It has been hypothesized [4] - [6] that the phenomenon is attributable to the existence of structures resembling SQUIDs in high-$T_c$ superconductors. We now propose to confirm the validity of this hypothesis on the basis of quantitative self consistency, within the SQUID model, of the sum-total of experimental data obtained from more detailed measurements.

¹Corresponding author. e-mail: gleb@iaph.silk.org
2 Experimental Procedure

A RADIOPAN SE/X-2543 ESR spectrometer (ν ≈ 9GHz, P_{max} = 130mW) with a TE\(_{102}\) cavity was used in the experiment. A magnetic field was generated by Helmholtz coils. The cavity was positioned away from the electromagnet of the spectrometer and together with the Helmholtz coils was placed in a magnetostatic shield to achieve a hundredfold suppression of the earth’s magnetic field.

We designed a thermal regulation system capable of holding a sample at a steady temperature anywhere in the range 78K < T < 100K within ±0.1K error limits. The conventional field geometry for ESR spectrometers was used in the experiment: \(H \perp H_1\) (\(H\) is the static field, and \(H_1\) is the microwave field).

The investigated sample was a \(Ho_1Ba_2Cu_3O_{7-x}\) single crystal in the form of a \(1.0 \times 0.7 \times 0.1mm^3\) rectangular wafer. The plane of the wafer coincided with the crystallographic (ab) plane, and the crystallographic c axis was parallel to the shortest edge of the single crystal. The measurements were performed with the single crystal oriented so that \(c \perp H_1\), and the angle \(\varphi\) between \(c\) and \(H\) could be varied by rotating the single crystal about the direction of \(H_1\).

The microwave absorption signal was recorded by a modulation technique with the H field modulated at the frequency \(\nu_m = 100kHz\). From now on we denote this signal by "\(\partial R/\partial H\)" (\(R\) is the absorption), using quotation marks to underscore the conditional nature of this notation: In view of the steepness of the dependence \(R(H)\), in general the H-field modulation amplitudes used by us (\(h_m \geq 1.25mOe\)) were not small enough for the recorded signal to be interpreted as the derivative of the absorption in the strict sense.

Prior to each consecutive measurement of the signal spectrum the sample was heated above the critical transition temperature and then cooled to necessary temperature in zero field (\(H \sim 1mOe\)).

The critical temperature of the investigated sample, determined from the position of the superconducting transition peak observed in the temperature dependence of the signal in fields \(H > 30Oe\) with high modulations of the H field, had a value \(T_c = 86.8 \pm 0.2K\) (for more on the superconducting transition peak see Refs. \([9, 10]\)).

3 Experimental Results

For low field modulations \(h_m = 10^{-3} - 10^{-2}Oe\) and microwave power
inputs to the cavity exceeding the threshold value determined for a given temperature, the observed signal oscillates as the field \( H \) is varied. The period of the signal oscillations with respect to \( H \) does not depend on the microwave power and changes only when the crystal is rotated. The minimum oscillation period is attained at the angle \( \varphi = 90^\circ \), when it has the value \( \Delta H = 9 \times 10^{-3} Oe \). The field dependence of the signal becomes irregular in the vicinity of \( H \approx 0.7 Oe \), where a comparison of the spectra for forward and backward scans shows that hysteresis effects, having been negligible near \( H = 0 \), intensify as the retrace point in scanning approaches the indicated value of the field.

Unlike the oscillation period, the amplitude and the \( H \) dependence of the form change abruptly as the microwave power is varied. In Fig. 1a this behavior is reflected by the display of several graphs of the field dependence of the signal near \( H=0 \) at \( T=79 \) K and \( \varphi = 90^\circ \), plotted for various values of the microwave power. It is evident from the figure that, as the microwave power is increased, the amplitude of the signal oscillations increases from zero (curve 1a), passes through a maximum (curve 4a), and then decays to zero.

Fig. 1. Evolution of the absorption spectrum as the microwave power is increased at \( T=79 \) K. a) Variation of the spectrum of the \( \partial R/\partial H \) signal; b) corresponding absorption spectrum \( R(H) \) in the SQUID model. The spectra are numbered in sequence as the microwave power is uniformly increased from -18.4 dB to -16.5 dB (0 dB corresponds to \( P_{\text{max}} = 130 \) mW).

Fig. 2. Oscillation amplitude of \( \partial R/\partial H \) signal vs microwave field at \( T=79\)K (a) and vs temperature at \( P = -14.8 \) d8 (b). \( H_1^{\text{max}} \) is the amplitude of the microwave field at \( P_{\text{max}}=130 \) mW (0 db), the dashed lines correspond to zero signal level, and the amplitudes are given in arbitrary units.
With a further increase in the microwave power the amplitude once again increases (curve 8a) and, as shown by subsequent measurements, the indicated dependence repeats periodically, showing up as one new series after another. We have traced 15 such series in detail.

We now call attention to the change in the form of the dependence of the signal. It is evident from Fig. 1a that one of the distinguishing features of this dependence is found in the "shoulders," i.e., the sloping parts of the curves connecting the maxima and minima of the signal. Whereas the shoulders of curves 2a and 3a occur to the left of the maxima, those of curves 5a and 6a have already shifted to the right of them. In this sense curve 4a represents a transition stage in that it has a symmetric profile. In this sense curve 4a represents a transition stage in that it has a symmetric profile. The shoulders of curve 8a, which launches a new series of spectra, are once again to the left of the maxima. A careful examination of the curves reveals that this change in their profile is associated with movement of the maxima and minima as the microwave power is increased, the maxima shifting to the left, and the minima to the right. This movement of the extrema is clearly evident in curves 2b-6b, where the vertical bars indicate the positions of the maxima and minima of the signal, which correspond to the vertical bars forming the left and right boundaries, respectively, of the hatched part of the curves. Using these curves, we can also readily conclude that the intervals between the maxima and minima of the signal increase uniformly from zero to the oscillation period $\Delta H$ within a single series (curves 1-7). And one final, important detail: Curve 8a(b), which is the start of a new series of spectra, is shifted a half-period, i.e., $\Delta H/2$, relative to the corresponding curve 2a(b) in the first series. We have observed this shift in transition from one series to the next in all 15 of the measured series.

Figure 2a shows the dependence of the amplitude of the signal oscillations on the amplitude of the microwave field $H_1$ ($H_1 \sim P^{1/2}$, where $P$ is the microwave power input). The ends of each of the vertical lines drawn in this figure signify the maximum and minimum values of the signal as a function of $H$ at the corresponding value of $H_1$. The formation of the above-discussed series is clearly evident from the figure. Of special note is the interesting fact that the threshold values of $H_1$ with which the series begin and which we denote from now on by $H_1^{(n)}$ ($n = 1, 2, \ldots$ enumerates the series) are separated by equal intervals $\Delta H_1$ and can be expressed by the arithmetic progression

$$H_1^{(n)} = H_1^{(1)} + (n - 1)\Delta H_1,$$

where $H_1$ is the threshold of the first series and is simultaneously the absolute...
signal-generation threshold. It is also evident from the figure that the maximum signal of the series does not show any overall tendency to increase or decrease with increasing sequence number \( n \), but merely oscillates in the nature of large-scale modulations with respect to \( H_1 \). Since the measurements were performed over a wide range of microwave power, we found it necessary to work with both square-law and linear detection regimes. The first nine series shown in Fig. 2a have been obtained in an almost square-law regime, where the dependence of the recorded signal on the microwave power \( P \) is known to correspond to the true \( P \) dependence for \( \Delta R \sim R(H + h_m) - R(H - h_m) \).

The next six series were measured directly in a near-linear regime. Here the maximum signal is observed to decay from one series to the next. Not to be dismissed is the possibility of attributing this decay to the instrumental distortion factor \( -1/2 \), which is well known in ESR spectroscopy and is inherent in the \( P \) dependence of the signal when linear detection is used.

The investigation of the temperature dependence of the signal spectrum in the interval \( 78K < T < T_c \) gives the following results. The oscillation period \( \Delta H \) remains constant as the temperature is varied in this interval. The thresholds \( H_1^{(n)} \) shift uniformly toward lower (higher) values of \( H_1 \) as the temperature is raised (lowered), so that the interval between thresholds \( \Delta H_1 \) also remains constant. As \( T \) increases, the signal spectrum for a given \( H_1 \) goes through the same evolutionary phases with the formation of series observed as \( H_1 \) increases at a fixed temperature \( T \) (Fig. 1). The formation of temperature series is distinctly perceptible in Fig. 2b, which shows the temperature dependence of the signal oscillation amplitude at a fixed \( H_1 \) (the vertical lines in the figure have the same significance as in Fig. 2a except that now they correspond to different temperatures). To distinguish between the two types of series from now on, we designate them as a \( H_1 \) series (series of spectra ordered on \( H_1 \)) and a \( T \) series (series of spectra ordered on \( T \)).

It is evident from a comparison of Figs. 2a and 2b that the main qualitative difference between the \( T \) series and the \( H_1 \) series is that the maximum signal of the \( T \) series decreases monotonically toward higher temperatures with increasing sequence number. It is noteworthy that the temperature at which the signal vanishes, \( T_g = 85.2K \), is considerably lower than the critical temperature \( T_c = 86.8K \). Also remarkable is the approximate equality of the intervals between thresholds of the \( T \) series with \( \Delta = 1.1 - 1.3K \). It has been established that the temperature thresholds shift uniformly toward lower (higher) temperatures as \( H_1 \) increases (decreases), where a negative (positive) shift in the case of sufficiently large variations of \( H_1 \) is accompanied by the emergence (disappearance) of new (existing) series at a constant
temperature $T_g$. In the case of sufficiently low values of $H_1$ we observe an absolute temperature threshold for the appearance of a signal; as $H_1$ increases, this threshold shifts toward lower temperatures until it attains liquid nitrogen level, after which it is not longer observable. This is the case depicted in Fig. 2b, where the first observable low-temperature threshold is the threshold of the third T series. We conclude, therefore, that the threshold of the T series can be expressed, as in the case of the $H_1$ series, by an arithmetic progression.

$$T^{(n)} = T^{(1)} + (n - 1)\Delta T,$$

where $n = 1, 2, 3,..., N$ ($N$ is the highest sequence number, which depends on $H_1$), and $T^{(1)}$ is simultaneously the threshold of the first T series and the absolute temperature threshold of signal generation at a given $H_1$.

As we mentioned at the outset, the signal oscillation period $\Delta H$ in our experimental geometry depends on the angle $\varphi$ between the crystallographic $c$ axis and the direction of the field $H$. By rotating the single crystal about the direction of the microwave field $H_1$ and measuring the signal oscillation period $\Delta H$ for various angles $\varphi$ we have established the functional relation

$$\Delta H(\varphi) = \Delta H(90^\circ)/\sin \varphi,$$

where $\Delta H(90^\circ) = 9 \times 10^{-3} Oe$. This fact indicates that a preferred direction parallel to the crystallographic (ab) plane exists in the single crystal and that the external field influences the absorption signal in such a way that only its projection onto this direction is effective.

4 Discussion of the results and conclusions

All the experimental results obtained in our work can be explained on the hypothesis that a superconducting ring with a weak link, i.e., a SQUID, exists in the single crystal. The first evidence in support of this hypothesis can be found in the form of the absorption spectrum $R(H)$ and its evolution as the microwave power is increased, as discerned from the SQUID model and shown in Fig. 1b in accordance with the measured $\partial R/\partial H$ signal spectra. The fact that the $\partial R/\partial H$ signals in the extreme spectra of each $H_1$ series are vanishingly small can be attributed to the fact that the modulation amplitude by virtue of its finiteness greatly exceeds the width of the "absorption line" of the spectrum $R(H)$ at the beginning of the series, and greatly exceeds the width of the "gap" between them at the end of the series. The formation of the spectra of the $H_1$ series is attributable to the actual mechanism of
microwave power absorption in the SQUID when it operates in a hysteresis regime. This mechanism consists in the fact that each entry or exit of a fluxon in a SQUID ring, stimulated by microwave field oscillations, has a jumplike behavior and is accompanied by energy dissipation in the weak link. The sequence number \( n \) in an \( H_1 \) series in the SQUID model indicates the number of successively entering (departing) fluxons involved in the formation of the absorption maxima of the spectra \( R(H) \) of the given series (in this sense the minima correspond to \( n-1 \) fluxons) within one oscillation period. Remarkably, the increase in the absorption from one series to the next does nothing more than raise the homogeneous ”background” of the spectrum \( R(H) \), whereas the intensity of the part of the spectrum that varies with \( H \), i.e., the ”absorption line,” remains unchanged. This fact accounts for the observed approximate invariance of the maximum of the ”\( \partial R/\partial H \)” signal with increasing sequence number of the series. It is evident from Fig. 1b that the indicated homogeneous ”background” is formed as a result of the spreading of the ”absorption line” at the end of each series, and it must therefore be cumulative with increasing sequence number of the series.

It follows from the SQUID model that the centers of the ”absorption line” in the spectra of consecutive series must be shifted relative to one another by a half-period, where the center of one line in series with even \( n \) must be situated at the point \( H = 0 \). Both of these conjectures are consistent with our measurements.

Finally, according to the SQUID model,

\[
\Delta H = \Phi_0 /[2S \cdot \cos (\mathbf{H}, \mathbf{n})],
\]

(\( \Phi_0 \) is the quantum of magnetic flux, \( S \) is the area of the SQUID, and \( \mathbf{n} \) is the normal to the face of the SQUID); this result agrees with our observed relation (3), provided only that we consider \( \mathbf{n} \) to be situated in the crystallographic (ab) plane.

We now attempt to verify quantitatively the validity of the SQUID model of microwave absorption. For the SQUID in this case we invoke the linear theory of Silver and Zimmerman [11]. According to this theory, the thresholds of the \( H_1 \) -series must be described by Eq. (4), where the quantities \( \Delta H_1 \), and \( H_1^{(1)} \) in it are expressed as follows in terms of the basic SQUID parameters:

\[
\Delta H_1 = \Phi_0 /[2S \cdot \cos (\mathbf{H}_1, \mathbf{n})],
\]

\[
H_1^{(1)}(T) = \Delta H_1 \cdot [2Li_c(T) - \Phi_0]/\Phi_0,
\]

where \( L \) and \( i_c \) are the inductance and critical current of the SQUID, respectively.
We make the following departure in connection with Eqs. (4) and (5). Our experimental geometry is such that the direction of \( n \) cannot be determined exactly. The experimental data expressed by Eq. (3) permit only the statement that the vector \( n \) is situated in the \((ab)\) plane. However, there is an indirect technique for amplifying the specification of this vector. When the single crystal is oriented with \( \varphi \equiv (\hat{H}, c) = 90^\circ \), the \((ab)\) plane is congruent with the \((\hat{(H_1, H)})\) plane, so that \( \cos(\hat{H}, n) = \sin(\hat{H_1}, n) \). It then follows from (4) and (5) that

\[
\tan(\hat{H}, n) = \Delta H/2\Delta H_1.
\]

It is evident from Figs. 1 and 2a that for the indicated orientation of the single crystal \( \Delta H = 9 \cdot 10^{-3} Oe \) and \( \Delta H_1 = 2,4 \cdot 10^{-2} \cdot H_1^{max} \). Approximating \( H_1^{max} \) roughly by its calculate value in the case of the unloaded cavity, \( H_1^{max} \approx 1,6 Oe \), we find that

\[
\tan(\hat{H}, n) \approx 10^{-1}
\]

The smallness of the resulting number implies that the vector \( n \) lies in practically the same direction as the vector \( \hat{H} \). In our experiment, for the given orientation of the single crystal, its two small faces parallel to the \( c \) axis were perpendicular to \( \hat{H} \). It is reasonable to infer, therefore, that the vector \( n \) is perpendicular to these faces and, accordingly, the plane of the SQUID ring is parallel to it. Setting \( \cos(\hat{H}, n) \approx 1 \) in (4), we can also determine the area of the SQUID:

\[
S \approx \frac{\Phi_0}{\Delta H} \approx 2 \cdot 10^{-3} \text{mm}^2.
\]

A comment needs to be interjected at this point to avoid misunderstanding. In the experiment we have a situation similar to the case \( \hat{H_1} \perp n, \hat{H} \parallel n \). If these exact conditions were met, then observing a SQUID signal would require the input of infinite microwave power, because Eqs. (3) and (4) give divergent quantities in this case. In reality, however, there is always a small error in the mounting of the sample in the holder. The value of \( \tan(\hat{H}, n) \approx 10^{-1} \) found by us corresponds to \( \sim 5^\circ \), which is fully admissible in the mounting of the sample in view of its small dimensions. This is why we have obtained finite values of \( \Delta H_1 \), in the experiment, which are nonetheless large enough to ensure high accuracy in the determination of this quantity. It must be noted that the indicated error does not in any way affect the conclusions that follow, because the equations used by us are general.

The existence of the T series of absorption spectra is also readily explained in the SQUID model. The critical current of Josephson junctions is
known to decrease monotonically as the temperature increases. Accordingly, it follows from Eqs. (3) and (1) that the threshold values $H_1^{(n)}$ must shift uniformly toward lower values with increasing temperature, so that the absorption spectrum for a fixed $H_1$ goes through sequential stages of evolution in the same way as then $H_1$ is increased at a fixed temperature. Obviously, the threshold values $T^{(n)}$ for a given $H_1$ are given by the equation

$$H_1^{(n)}(T^{(n)}) = H_1.$$  \hspace{1cm} (7)

It follows from (7) that equation (2) describing our experimentally determined thresholds of the T series is valid in the SQUID model if the critical current $i_c$ decreases with increasing temperature according to the linear law

$$i_c(T) = \alpha \cdot (T^* - T) \hspace{1cm} (8)$$

($\alpha$ and $T^*$ are constants), where the quantities $\Delta T$ and $T^{(1)}$ in (2) are now given by the expressions

$$\Delta T = \Phi_0 / 2L\alpha,$$  \hspace{1cm} (9)

$$T^{(1)}(H_1) = T^* - \Delta T \cdot (1 + H_1/\Delta H_1).$$  \hspace{1cm} (10)

The amplitude of the signal oscillations is expressed as follows in the SQUID model:

$$\left(\partial R/\partial H\right)^{max}_{\Delta} \sim 2\nu[2Li_c(T) - \Phi_0] \cdot \Phi_0/2L,$$  \hspace{1cm} (11)

from which it follows that the intensity of the signal must decay as the temperature increases. The practically linear decay of the signal observed in Fig. 2b corresponds to condition (8). The temperature $T_g$ at which the signal is observed to vanish has a special significance as the temperature for which

$$Li_c(T_g)/\Phi_0 = 1/2$$  \hspace{1cm} (12)

(At $T > T_g$ the SQUID already operates in the zero-hysteresis regime, for which the given absorption mechanism no longer functions). Equation (12) with (8) and (9) leads to the relation

$$T^* = T_g + \Delta T.$$  \hspace{1cm} (13)

Substituting the experimentally determined values of $T_g = 85.2 \pm 0.1K$ and $\Delta T = 1.2 \pm 0.1K$, we find that $T^* = 86.4 \pm 0.2K$. This value of $T^*$ practically coincides with the measured critical temperature $T_c = 86, 8 \pm 0, 2$ consistent with the theory of Josephson junctions [12].
Using equations, written above can easily obtain three expressions for the "hysteresis parameter" $L_i(T)/\Phi_0$ in terms of various sets of experimentally determined quantities:

$$[(N - n) + 1]/2 \leq L_i(T^{(n)})/\Phi_0 < [(N - n) + 2]/2,$$

where $T^{(n)}$ denotes the threshold temperatures, and $N$ is the maximum sequence number of the $T$ series observed for some specific value of $H_1$;

$$L_i(T)/\Phi_0 = 1/2[1 + (T_g - T)/\Delta T];$$

$$L_i(T)/\Phi_0 = 1/2[1 + H_1^{(1)}(T)/\Delta H_1].$$

We can use Eqs. (14) - (16) to test the self-consistency of our experimental data. For example, in Fig. 2b the first visible threshold of the $T$ series corresponds to $T= 78.2$ K, a simple computation of the total number of subsequent thresholds yields $(N-n)=5$, and hence, according to (14), we have

$$L_i(T = 78.2K)/\Phi_0 = 3.0 \div 3.5.$$  (17)

For comparison we give the result of estimating the hysteresis parameter obtained at the same temperature from Eq.(15) using the experimental data for $\Delta T$ and $T_g$ ($\Delta T = 1.2 \pm 0.1 K$, and $T_g = 85.2 \pm 0.1 K$):

$$L_i(T = 78.2K)/\Phi_0 = 3.5 \pm 0.3.$$  (18)

Clearly, the results of both estimates agree.

Continuing the test for self-consistency of our experimental data, we now determine the hysteresis parameter by means of (16), using the data from Fig. 2a: $T=79$ K and $H_1^{(1)}/\Delta H_1 = (12.1 \pm 0.3)/(2.4 \pm 0.1)$. As a result of simple calculations we obtain

$$L_i(T = 79K)/\Phi_0 = 3.0 \pm 0.2.$$  (19)

On the other hand, it is readily verified that Eq. (15) gives at $T=79$ K

$$L_i(T = 79K)/\Phi_0 = 3.1 \pm 0.3.$$  (20)

We see, therefore, that our experimental data are quantitatively self-consistent within the framework of the SQUID model. In our opinion, this fact is the most conclusive evidence in favor of the SQUID nature of microwave absorption in type 1-2-3 high-$T_c$ superconducting single crystals.
References

[1] S.V. Bogachev, G.A. Emel’chenko, V.A. Il’in et al., JETP Lett. 47, 203 (1988).

[2] K.W. Blazey, A.M. Portis, K.A. Muller, F.H. Holtzberg, Europhys. Lett. 6 (1988) 457.

[3] A.A. Bugai, A.A. Bush, I.M. Zaritskii et al., JETP Lett. 46, 228 (1988).

[4] A.A. Konchits, I.M. Zaritskii, A.A. Bugat et al., Sverkhprovod. Fiz. Khim. Tckh. 2, 25 (1989).

[5] H. Vichery, F. Beuneu, and P. Lejay, Physica C 159, 823 (1989).

[6] J. Martinek and J. Stankowski, Phys. Rev. B50 (1994) 3995.

[7] G.S. Patrin, G.A. Petrakovskil, K.A. Sablina, and Yu.N. Ustyuzhanin, Sverkhprovod. Fiz. Khim. Tekh. 4, l913 (1991) [Supercond. Phys. Chem. Technol. 4, 1822 (1991)].

[8] V.V. Troitskii, M.A. Krykin, Yu. A. Yazlovetskaya et al., Sverkhprovod. Fiz. Khim. Tekh. 6, 728 (1988).

[9] B.F. Kim, J. Bohandy, K. Moorjani, F.J. Adrian, J. Appl. Phys. 63 (1988) 2029.

[10] M.K. Aliev, J. Wawryshchuk, S.P. Wolosyaniy,T.M. Muminov, B. Olimov and I. Kholbaev, Fiz. Tverd. Tela (Leningrad) 31 (1989) 254. [Sov. Phys. Solid State 31, l621 (1989)].

[11] A.H. Silver and J.E. Zimmerman, Phys. Rev. 157, 317 (1967).

[12] A. Barone and G. Paterno, Plysics and Applications of the Josephson Effect, Wiley, New York (1982).