Intrinsic radiation from high-T_c superconducting bridges with two-dimensional bulk diffusive weak links

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We have experimentally fabricated and investigated high-T_c superconducting bridges made from two-dimensional bulk weak links of diffusive type. For the first time, we have recorded intrinsic oscillations in these structures at wavelengths in the 8 mm range using an external mixer. The signal powers measured at the output of these systems had a value of 10^{-12} W for a typical bandwidth of a few gigaherz. We interpret our results in terms of a model involving the motion of hypervortices under the action of a Lorentz force.

I. INTRODUCTION

A transport current disrupts the superconducting state of a superconducting bridge in various ways, depending on the relation between its geometric dimensions (length L and width W) and the coherence length of the superconductor ξ.[1–3] Bridges with small dimensions ($L,W \ll \xi$) exhibit the Josephson effect, a phenomenon whose immediate manifestation is narrowband intrinsic Josephson oscillations of the sort observed in bridges made from indium and tin.[4,5] However, when the geometric dimensions of the bridge exceed ξ, the superconducting state becomes unstable with increasing current against penetration by Abrikosov vortices, even in the absence of an external magnetic field.[1–3] The periodic motion of these vortices under the action of the Lorentz force generated by the transport current leads to the appearance of an AC voltage across the sample. Although coherent effects, e.g., Josephson current steps in the voltage-current characteristics resulting from synchronization of the motion of vortices by an external magnetic field, have often been observed in experiment (see, e.g., Ref. 1), until recently no one had ever detected intrinsic oscillations from autonomous (i.e., unperturbed by external influences) superconducting bridges with large dimensions (i.e., $L,W > \xi$). It is likely that the reason for the smallness of these intrinsic oscillations, and thus the reason why they have never been recorded successfully in experiment, is strong pinning, which destroys the coherent motion of Abrikosov vortices in the bridge.

Recently, a number of papers have appeared (see, e.g., Refs. 6, 7) whose authors report observing intrinsic oscillations in bridges with large dimensions made from high-temperature superconductors. Coherent effects, including intrinsic oscillations, are observed in high-temperature superconducting bridges made from granular materials such as films and ceramics in those cases where the grains have Josephson links between them. For bridges in which the distribution of weak-link parameters exhibits exponential scatter, the current flow has a percolative character; this implies that for small currents in a large bridge only a single grain-to-grain link will be "working" out of the entire assembly of weak links. This phenomenon is observed in bridges made from nonoriented ceramic films of high-temperature superconductor.[8,9] For c-oriented granular films of $YBa_2Cu_3O_x$ we may expect effects that are characteristic of two-dimensional bulk Josephson junctions,[10] although difficulties in obtaining information on the scatter of weak-link parameters in high-temperature superconductors make the interpretation of measurement results ambiguous. We note that in high-temperature superconducting bridges carrying high current densities, in which the links between grains are large, effects are observed that are characteristic of thermally activated vortices.[10]

In this paper we present the results of a study of intrinsic oscillations in bridges made of artificially produced two-dimensional bulk high-temperature superconducting junctions of diffusive type,[11] which may be viewed as models of the phenomenon of high-temperature superconductivity in a granular system.

2. EXPERIMENTAL METHOD

We experimentally investigated several high-temperature superconducting sample bridges made from two-dimensional bulk diffusive weak links.[11] The basic structures were bridges made from $YBa_2Cu_3O_x$ (YBCO) films with dimensions $L = 10$ μm, $W = 1$–5 μm. We deposited bridges with thickness $d = 300$ nm onto a hot (600 to 700 °C) substrate made of MgO by the method of laser

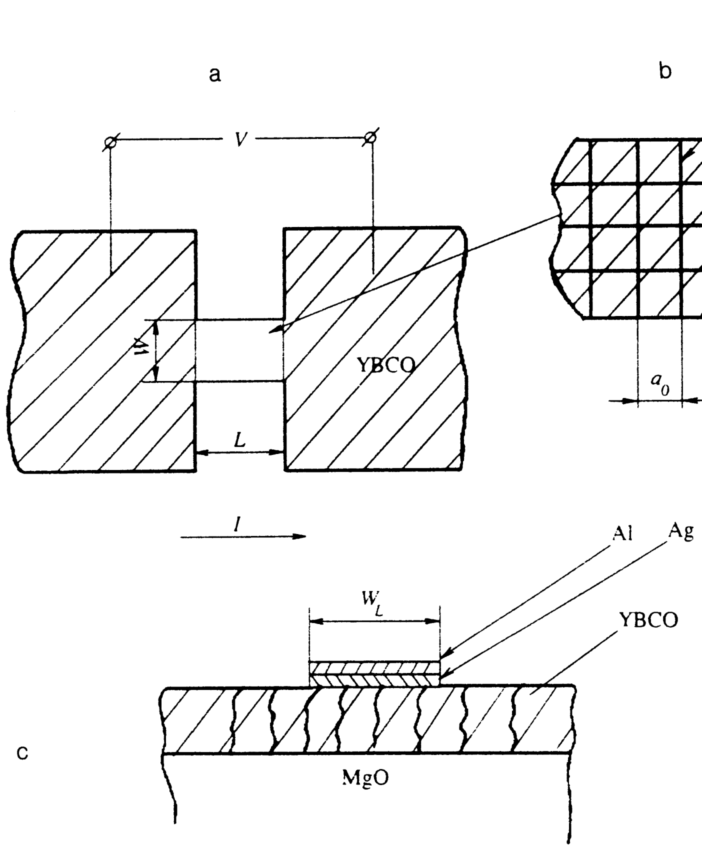

FIG. 1. (a)—Schematic illustration of a high-temperature superconducting bridge from above, with two-dimensional array of diffusive weak links; (b)—transverse cross section of one of the diffusive weak links. The structure measurements $L=10$ μm, $W=1-5$ μm, $d=30$ nm, $d_{Ag}=20$ nm, $d_{Al}=20$ nm, $a_0=0.5-0.8$ μm, $W_l=70$ nm.

sputtering. The films obtained were c-oriented, with critical temperatures T_c in the range 89 to 91 K. On top of the films we sputtered a grid of strips made of films of silver with thickness $d_{Ag}=20$ nm and aluminum with $d_{Al}=20$ nm; the periods of the grid were $a_0=0.5$ and 0.8 μm, the thickness of the strips $W_l=70$ nm. The total size of the grid of normal metal was 10 μm, with a width that varied from 4 to 8 μm. The completed structure (see Fig. 1) was fabricated using optical lithography, electron lithography, and ion doping.

The critical current density of each bridge $j_c=I_c/dW$ was calculated from the critical current I_c measured at a voltage $V\approx 5$ μV across the sample. The high critical current density $j_c>10^6$ A/cm^2 ($T=4.2$ K) immediately after ion etching indicated that there were no weak links within the film.[6] Heating a bridge up to a temperature of 200 to 300 °C caused j_c to decrease to values of 10^2 to 10^5 A/cm^2 due to silver diffusion along the grain boundaries in the YBCO films,[11] which decreased T_c to 30 to 50 K.[1)] Because of the small size ($a_1\approx d<W_l<a_0$) of the grains along whose boundaries the diffusion of normal metal took place, the annealing led to the formation of two-dimensional bulk superconducting regions (of size a_0) connected by narrow strips ($W_l<a_0$) made up of the strongly granularized film. Isolated diffusive junctions prepared on individual substrates exhibited Josephson steps in the voltage-current characteristics when subjected to external electromagnetic radiation, with an oscillatory dependence on the incident power; these steps indicated the presence of Josephson links.[11]

We measured the voltage-current characteristics and dV/dI as a function of I and V for various temperatures from 4.2 to 100 K and for various levels of excitation by an electromagnetic field in the millimeter-wave region. An external DC magnetic field (with $B<1$ mT) was applied perpendicular to the plane of the film. The sample was shielded from pickup noise by a screen made of permalloy, and all the measurements were made in a shielded room.

In order to make the measurements in the millimeter range, we placed the samples at the center of the flattened part of the transition from a 7.2×3.4 mm^2 waveguide to a 7.2×0.1 mm^2 waveguide. The signal power arriving at the sample was measured using a superheterodyne receiver consisting of a balanced mixer made up of beam-lead diodes followed by amplifiers at the intermediate frequency and a spectrum analyzer. The noise temperature of the receiver had the value $T_R=2000$ K at a frequency 35 GHz over a bandwidth of 3 MHz. The sample was isolated from the heterodyne signal by three waveguide gates, which provided 60 dB of isolation. In order to increase its sensitivity, the receiver was operated in a modulation mode, i.e., the input signal was modulated at a frequency of 1 kHz and the output signal at the intermediate detection frequency was fed to a synchronous detector at the modulation frequency. In this mode, we used a crystal detector in place of the spectrum analyzer, which allowed us to further increase the bandwidth of the receiver signal up to 400 MHz. The frequency at which the sample was best matched to the waveguide was determined based on the behavior of the external radiation.

TABLE I. Parameters of bridges at $T=4.2$ K.

Label	L, μm	W, μm	a_0, μm	R_N, Ω	I_c, μA	λ_j, μm	R_0, Ω	R_1, Ω
GZ1.3	8.2	5.5	0.5	80	16	8	48	72
GZ2.1	10	0.8	0.8	44	10	4	20	35
GZ2.3	9.0	5.0	0.8	5.2	190	2.3	2	3.2
MW2.3	9.9	1.6	0.8	35	12	5.6	17	30

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Critical current and *IV* characteristics of the bridges

Table I gives the parameters of several samples we investigated at $T=4.2$ K. The geometric dimensions of the bridges were measured using an optical microscope, while the structure of the film and dimensions of the grid were monitored by using a scanning electron microscope. The Josephson penetration depth Λ_J, which is an important parameter of Josephson structures, was estimated from the expression for a distributed Josephson junction of sandwich type:

$$\lambda_J=\sqrt{\Phi_0/2\pi\mu_0\, j_c t_{\text{eff}}}\,, \tag{1}$$

where $t_{\text{eff}}=t+2\lambda_L$ is the effective penetration depth of the magnetic field along the current, and $\lambda_L=0.2$ μm is the London penetration depth for YBaCuO; $\Phi_0=h/2e$ is the flux quantum.

Direct evidence of the multiconnected nature of the bridge is the fact that the function $I_c(B)$ is quasiperiodic, with a characteristic period with respect to magnetic field $B_1=\Phi_0/S_1$ determined by the area of the largest superconducting closed loop (for the bridge GZ2.3, $S_1=19$ μm^2; see Ref. 13). Harmonics at Φ_0/nS_1 were also observed in the function $I_c(H)$; however, their amplitudes varied irregularly as B increased, which was probably due to the effect of the edges of the bridge and the scatter in the parameters of the weak links. For $B_2\approx465$ μT ($S_2=4.4$ μm^2) I_c was observed to increase, i.e., $I_c(B_2)>I_c(0)$. For small fields $B<B_2$ the function $I_c(B)$ was quite reproducible over many measurements; at higher values of the external field, flux trapping occurred.

The dependence of the critical current on magnetic field can be explained by means of a model based on two-dimensional bulk superconducting regions coupled by Josephson weak links.[14] If the energy of the Josephson links is large,

$$E_J=\hbar j_c^g/2e>16\pi^3\lambda_L^2/(\Phi_0^2 a_0)$$

(where j_c^g is the density of critical current), then the processes that take place in the two-dimensional interior are the same as for the case of a uniform type-II superconductor. When there is a weak link between superconducting regions ($j_c^g<10^6$ A/cm^2 for YBCO) the situation changes; in particular, the penetration depth of a weak magnetic field into the film (the size of a vortex) is determined[15,16] by λ_J, and for small magnetic fields the structure of the vortex differs considerably from that of an Abrikosov vortex in a uniform superconductor. Because of their large electromagnetic radii, such vortices are called hypervortices.[15] Although they do not have regions with suppressed order parameter, their dynamic properties are in many ways analogous to Josephson vortices. The core of the vortex, defined so that a circuit around any path enclosing it causes the phase of the superconducting wave function to change by 2π, has a radius equal to a_0. According to theoretical calculations,[14] as the magnetic field increases the uniform superconducting state becomes unstable at a field $B_g=\Phi_0 a_0/\lambda_J^2\lambda_L$ against penetration by hypervortices, which decay into Josephson vortices at a field $B_J=\Phi_0/a_0\lambda_L$; at a field $B_A=\Phi_0/\lambda_L^2$ penetration of Abrikosov vortices into the superconducting regions is observed.

In our experiment, the characteristic magnetic fields B_1 and B_2 are considerably smaller than those of the fields B_J and B_A, which correspond to decay of the hypervortices. Instead, the magnetic field period B_1 observed in the experiments is related to the geometry of the bridge (i.e., the appearance of currents circulating around a loop with area $\lambda_J W=11.5$ μm^2), while the observed increase in I_c for $B\approx B_2$ indicates that two hypervortices penetrate the bridge ($2\lambda_J^2\lambda_L/a_0=3.3$ μm^2).

In the inset to Fig. 2 we show the IV characteristics of bridge MW2.3 at $T=4.2$ K. These IV characteristics show no hysteresis over a wide temperature range. The presence of an excess current in the IV characteristics (i.e., a shift of the IV characteristics at large voltages relative to Ohm's law), which is typical for weak links with directed conductivity, indicates that there is no tunneling character to the system conductivity. At low temperatures, the IV characteristics of the bridge consist of a series of segments with practically constant values of differential resistance R_d separated by portions which are unstable and subject to hysteresis in which R_d changes.

For $L,W\gg\xi$ the resistive state of the bridge at a prespecified current is caused by the penetration and periodic motion of vortices under the action of the Lorentz force.[2,3] Magnetic measurements indicate that the bridge film is multiconnected, while the low current density $j_c=2.5\cdot10^4$ A/cm$^2<10^6$ A/cm^2 points to the existence of weak links which determine the current transport in the bridge. Since the original film was c-oriented and the condition $L,W>a_0>W_L>a_1$ was satisfied, it is entirely correct to use a model of a two-dimensional array of Josephson weak links; in this model, the resistive state occurs as the current increases due to penetration into the bridge and the motion of the hypervortices.[6] At currents close to I_c, the IV char-

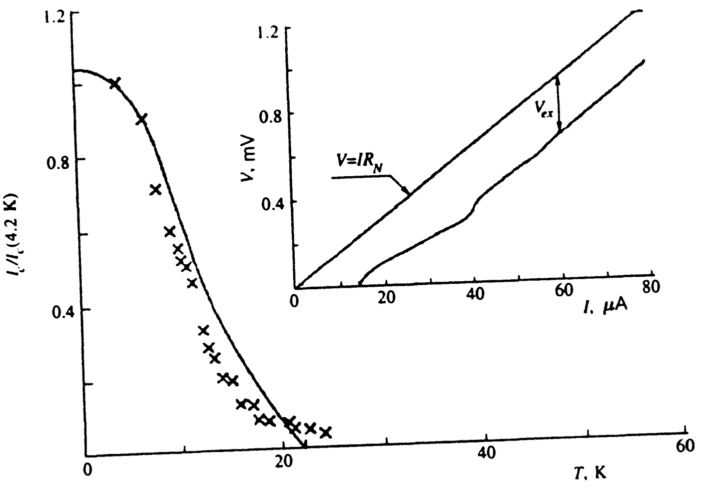

FIG. 2. Dependence of the normalized value of the critical current of the bridge on temperature. The solid curve is a theoretical calculation of the critical current for an SNS Josephson junction of length 3ξ, whose critical temperature was chosen from the condition of best agreement with experiment. In the inset we show the IV characteristics of bridge MW2.3 at a temperature $T=4.2$ K.

acteristics are determined by the time it takes for a vortex to overcome the edge barrier; according to Ref. 3, $V\sim\sqrt{I}$. This is observed in experiment for $I\approx I_c$. Irregularities in the structure itself (on the order of a_0) turn out to have a weak effect on the motion of the vortices: for $I>I_c$, each vortex moves viscously, with a velocity proportional to the current density at the location the vortex is found. As a result, the IV characteristics have a linear portion with resistance R_0. For bridge MW2.3 we estimate $R_0^{\text{th}}=22\ \Omega$ based on the formula $R_0^{\text{th}}=R_N\lambda_J/L$, which exceeds somewhat the experimental value of 17 Ω; possibly this is due to an overestimate of the value of λ_L we have chosen and used to calculate λ_J. As the current increases, we observe a sharp kink in the IV characteristics and a transition after a linear region $R_d=R_0$ to the linear portion $R_d=R_1>R_0$. This shape of the IV characteristics is observed in the majority of samples we measured.

In the experiment, because the length L is large, i.e., $L>\lambda_J$, several vortex rows appear as the current in the bridge increases. According to numerical calculations,[17,18] for a two-dimensional array of Josephson junctions the length $L>\lambda_J$ at which the first row of vortices is created occurs near nonuniformities of the two-dimensional array due to a local increase in the current density. In this case the process of vortex creation is analogous to the process that occurs at edges. As the current increases, subsequent rows appear next to the first row at distances comparable to λ_J, leading to discrete increases in R_d for the linear portions observed in the experiment. However, these increases in R_d are not by multiples of R_0, which is probably connected with strong mutual interactions among the vortex rows.

The temperature dependence of the normalized value of the critical current $I_c(T)/I_c(4.2\text{ K})$ for bridge MW2.3 is shown in Fig. 2. In the low-temperature limit we observe a function $I_c(T)$ that is typical of weak links. At a current

$$I_c>I>I_t=\pi d\frac{2e}{\hbar}g$$

the penetration of vortices is prevented by a potential barrier at the edge of the film, which disappears at a current

$$I=I_c=\pi d\frac{2e}{\hbar}g\frac{W}{a_{\text{eff}}},$$

where a_{eff} is the effective dimension of the vortex core, which equals ξ for Abrikosov vortices[3] and a_0 for a two-dimensional array of Josephson junctions.[14–16] Since W, d, and a_0 do not depend on temperature, and the only quantity in $I_c(T)$ that changes with temperature is $g\approx\hbar j_c^g a_0/2e$, the temperature dependence $I_c(T)$ measured in the experiment (Fig. 2) is proportional to the temperature dependence of the weak-link critical current. The agreement between theoretical (see the review by Likharev[19]) and experimental $I_c(T)$ functions indicates that Josephson junctions in the two-dimensional bulk are characterized by a nontunneling conductivity that is close to that of an SNS junction. The nonlinear dependence $I_c\propto(T_{c0}-T_c)^n$ (where $n=1.5$ to 2) near T_c is most likely caused by the suppression of phase coherence in the two-dimensional array by temperature fluctuations, which can cause I_c to decrease by 20% even for $ekT/\hbar I_c=0.1$ (see Refs. 16, 18).

3.2. Intrinsic electromagnetic radiation

When an external electromagnetic field is present, we observe harmonic and subharmonic Josephson steps on the IV characteristics at voltages $V_{m,n}$ connected with the frequency of the external excitation f_e by the Josephson relation:

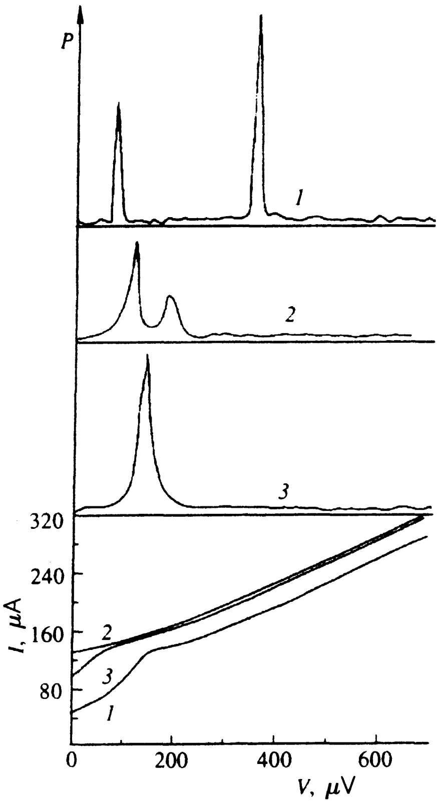

FIG. 3. Dependence of the radiated power on voltage for bridge GZ2.3 and the corresponding IV characteristics for the following values of the external magnetic field: 60 μT (*1*), 260 μT (*2*), and 290 μT (*3*) for $T=4.2$ K. The IV characteristics *2* and *3* are shifted upward along the current axis by 25 μA.

$$V_{m,n}=\frac{n}{m}\frac{hf_e}{2e},\tag{2}$$

where n,m are integers. The dependence of the amplitude of these steps on the power $I_{1,2\ldots}(P)$ has a maximum, and then falls off monotonically with increasing power of the external probe, in contrast to small-size uniform Josephson junctions, in which $I_{1,2\ldots}$ oscillates with increasing P. The absence of secondary maxima in the functions $I_{1,2\ldots}(P)$ was observed previously in large-size bridges made of tin, in which coherent motion of Abrikosov vortices takes place.[1]

Figure 3 shows a family of bridge IV characteristics and the voltage dependence of the radiated power $P(V)$ at a frequency 35 GHz for various magnetic fields. The function $P(V)$ differs from the corresponding function observed in single Josephson junctions.[4,5] At small B, the voltage at which the first oscillation peak occurs is related to the oscillation frequency by Eq. (2) with $m=1$ and $n=1$. The almost-linear portion of the IV characteristic with $R_d=R_0=$const in this range of voltages ($V=60$ to 70 μV) indicates a single row of vortices is contained in the bridge, whose oscillations are being recorded at the receiver frequency $f=35$ GHz. Each vortex row picks up an AC component of the voltage with frequency

$$f=Nv/b,\tag{3}$$

where b is a characteristic parameter of the vortex lattice ($b\sim W$), and N is the number of vortices in the row. Since the transit of each vortex containing a magnetic flux quantum Φ_0 causes the quantum-mechanical phase difference between the superconducting end regions to change by 2π, the oscillation frequency and voltage for a single vortex row are related by the Josephson equation (2). The second radiation peak in the function $P(V)$, which is observed for the segment of the IV characteristics with $R_d=R_1$, indicates the presence of several vortex rows in the bridge. The voltage position of the second peak is not related to the frequency of the receiver by Eq. (2). According to Ref. 17, subsequent rows of vortices should appear in the immediate vicinity of the first row and interact strongly with it. However, it is clear from experiment (Fig. 3) that there is no increase in the oscillation power from the bridge with increasing N, probably because of the antiphase character of the oscillations in adjacent rows. Application of a weak magnetic field causes the IV characteristics of the bridge to change, and both peaks in the function $P(V)$ are found to shift in voltage.

Changing the frequency of the receiver also causes both radiation peaks to shift in voltage, in good agreement with the Josephson Eq. (2) with $m=n=1$. Consequently, by measuring the width of the curve $P(V)$ in voltage ΔV we obtain the width of the oscillation line $\Delta f=2e\Delta V/h$. For sample GZ2.3, the minimum value, equal to $\Delta f=2.2$ GHz, depends significantly on R_d and T. A typical power recorded at the input of the mixer above the cryostat was 10^{-12} W.

Figure 4 shows the temperature dependence of the oscillation linewidth of the first peak normalized by R_d^2 for $B=0$. In this figure we show the functions obtained using a resistive model of the Josephson junction, taking into account only the effect of Nyquist noise:

$$\Delta f=4\pi\Phi_0^2kT\,\frac{R_d^2}{R}\left(1+\frac{I_c^2}{2I^2}\right)\tag{4}$$

for $R=R_N=5.2\ \Omega$ and the experimental values of the remaining parameters. The dashed curve corresponds to $R=R_0$. It is clear that within the limits of experimental accuracy there is agreement between the experiment and Eq. (4) when we use for R (the source of fluctuations) the resistance $R_0<R_N$, corresponding to the regime of viscous flow of the vortices. The assumption that thermal fluctuations have a decisive influence is confirmed by the increase in Δf according to the law $\Delta f/T\propto R_d^2$ as R_d^2 is increased by two orders of magnitude.

4. CONCLUSION

Thus, in this paper we have developed a method for obtaining high-temperature superconducting bridges made from $YBa_2Cu_3O_x$ with artificially created two-dimensional bulk diffusive weak links. The results of our electrophysical measurements show that our samples are well described by a model of a two-dimensional array of superconducting grains linked by Josephson contacts with a nonexponential spread in parameters. For small magnetic fields, a resistive

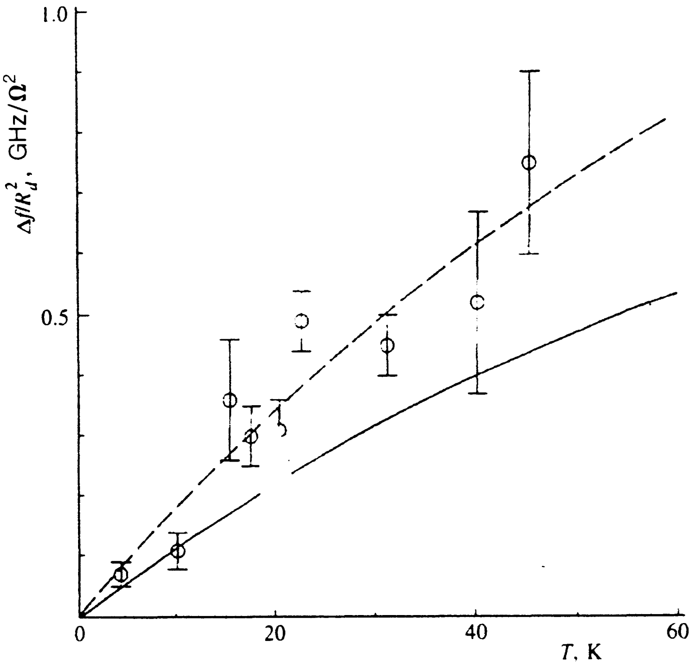

FIG. 4. Temperature dependence of the ratio of the width of the oscillation line to the squared differential resistance for bridge GZ2.3. The solid curve corresponds to a calculation within the framework of the resistive model (4), taking into account only thermal noise; the dashed curves are for the case where we used the resistance R_0 as the normal resistance of the junction, which corresponds to the regime of viscous motion of vortices in the bridge.

state is realized in these bridges due to the viscous motion of large-radius vortices (hypervortices) under the action of the Lorentz force. The shape of the dependence of the intrinsic oscillation power on the bias voltage is caused by the motion of several rows of vortices in the bridge. We observed a change in the position of the oscillation peaks with respect to voltage with increasing magnetic field. The width of the oscillator line is in good agreement with calculations for isolated Josephson junctions, taking into account only thermal fluctuations.

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[1)]In films that are close to single-crystal in character, with high current densities $j_c > 10^7$ A/cm^2, and coated with Al and Ag films, heating up to 300 °C did not cause a decrease in the critical parameters, probably due to the strong coupling of the grains in the plane $a-b$ (see Ref. 12).

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