Self-heating in a small mesa of BSCCO intrinsic Josephson junctions at very low temperatures

Minoru Suzuki, Yoshiharu Yamada, Itsuhiro Kakeya, Shintaro Kojima, and Kenkichi Anagawa
Department of Electronic Science and Engineering, Kyoto University, Kyotodaigaku-Katsura, Nishikyo-ku, Kyoto 615-8510, Japan
E-mail: suzuki@kuee.kyoto-u.ac.jp

Abstract.
Temperature rise due to self-heating at very low temperatures near 0.4 K has been numerically estimated for a 2 \( \mu m \) on a side and 3 nm-thick mesa of Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_{8+\delta}\) intrinsic Josephson junctions. In spite of very low thermal conductivities and specific heats of the materials constructing the mesa at these temperatures, the temperature rise is much less than 1 K at a usual current injection level. It is also found that the temperature rise shows a tendency to increase with the mesa size, which was also observed at higher temperatures. The temperature rise in the presence of the contact resistance is also estimated to be small when the contact resistivity is of the order of 1 \( \times 10^{-10} \) \( \Omega m^2 \). When the contact resistance is larger, the temperature rise becomes comparable with 1 K. The temperature rise in the presence of a voltage state junction is much less than 1 K at a critical current level. This implies that the saturation of the escape temperature of the recent switching probability experiments is totally unlikely to be due to simple heating characterized by the thermal equilibrium in phonons.

1. Introduction
Observation of the macroscopic quantum tunneling (MQT) \[1, 2, 3\] has been a novel subject of recent researches in intrinsic Josephson junctions (IJJs), which are naturally built in a crystal structure of high-\( T_c \) superconductors (HTSCs) \[4, 5\]. This is because it was pointed out that the MQT can be observed at a higher temperature than ever in the case of a Josephson junction made of an HTSC \[6\]. Indeed, the MQT crossover temperature was reported by Inomata et al to be approximately 1 K for an IJJ, which is one order of magnitude higher than previously \[7\]. It may be possible that the MQT crossover temperature becomes higher than 1 K if the Josephson critical current density \( J_c \) increases.

The MQT observation experiments in IJJs are usually conducted on mesa-structured samples or crank-shaped bridge samples, both made from a BSCCO single crystal using fine-processing techniques. Since these samples are in most cases characterized by a stack of IJJs connected in series, the switching to the voltage state occurs successively from one junction to another as the current increases. It is possible to observe the switching current probability distribution for each of these successive switching \[8\]. Let the switching in the absence of any voltage state junction in the stack be called \textit{the 1st switching} and that in the presence of only one voltage state junction in the stack be called \textit{the 2nd switching} and so on. The MQT was reported for the 1st switching for both types of sample.
The switching current distribution is characterized by the escape temperature $T_{\text{esc}}$, which is determined from the standard deviation of the switching current distribution and reflects the thermal excitation of the phase in the washboard potential model to the continuous motion in the junction phase dynamics [9]. For the 2nd switching, it was observed that $T_{\text{esc}}$ saturates at an extraordinarily high temperature of $\sim 8$ K and becomes temperature-independent in the temperature range below that [8, 10]. This behavior would appear that the MQT crossover temperature is raised up to this high temperature of $\sim 8$ K. However, evidence for the MQT, like energy level quantization, has not been provided so far. Rather, it was argued that this unusual behavior arises from self-heating due to current injection in the presence of a voltage state junction which lies in close contact with the stack.

The magnitude of $J_c$ for IJJs ranges from 100 to 2500 A/cm$^2$, which corresponds to a critical current $I_c$ of a few $\mu$A to 100 $\mu$A for a junction size of 2 $\mu$m on a side, a current level which leads to a dissipation of less than 1 $\mu$W. At temperatures above 4.2 K, the temperature rise caused by this energy dissipation does not usually amount to 0.1 K. However, at very low temperatures near 0.1 K, where the thermal conductivity and the specific heat decrease by more than two orders of magnitude, this is not necessarily the case. Since it is very difficult to measure the temperature rise experimentally for such samples at very low temperatures, we have employed detailed FDTD numerical calculation to estimate the temperature rise under various conditions. We have found that the temperature rise due to current injection is of the order of 0.1 K, which is not negligible in certain cases. However, it does not lead to a temperature rise of 1 K except under extraordinarily conditions.

2. Model and calculations

The model of the present calculation is a mesa structure fabricated on a surface of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (BSCCO) single crystal. The structure and the configuration of the materials are similar to the those described earlier [11]. The plan view and the cross-sectional one are shown in Fig. 1. The differences from the previous calculations are the lack of a He gas layer and the segmentation size of the Au subcell. Table 1 lists the dimensions of the mesa structure and the

![Figure 1. Plan view (left) and cross sectional view (right) of a small mesa structure for the model in the present numerical calculation.](image-url)
Table 1. Dimensions of the mesa structure and the cell size used for the numerical calculations.

|                | x-size (μm) | y-size (μm) | z-size (μm) |
|----------------|-------------|-------------|-------------|
| mesa           | 2           | 2           | 0.003       |
| BSCCO pedestal | 1000        | 1000        | 40          |
| BSCCO cell     | 38.5        | 38.5        | 5.71        |
| submesa cell   | 5.5         | 5.5         | 0.381       |
| Au electrode   | 1000        | 100         | 0.35        |
| Au subcell     | 2.56        | 2.56        | 0.35        |
| SiO cell       | 38.5        | 38.5        | 0.25        |
| Stycast layer  | 1000        | 1000        | 20          |
| Stycast cell   | 38.5        | 38.5        | 4           |

cell sizes. The differential equation to be solved is the Fourier’s law represented by

\[
c_{p}\rho \frac{dT}{dt} = \nabla(\bar{\kappa}\nabla T) + q(t),
\]

where \( T \) is the temperature, \( c_p \) is the specific heat, \( \rho \) is the density, \( \bar{\kappa} \) is the anisotropic thermal conductivity tensor, and \( q(t) \) is the heat source representing self-heating. In the calculation of Eq. (1), the \( T \)-dependent \( c_p \) and \( \kappa \) values are used for Au [12, 13], SiO, BSCCO [14, 15, 16, 17, 18], and Stycast (epoxy resin as a glue). Since the data for Stycast and SiO at very low temperatures is lacking, the \( c_p(T) \) and \( \kappa(T) \) data for epoxy-resin [19] and vitreous SiO2 [20] is used. The \( T \) dependence of \( c_p \) and \( \kappa_{ab} \) is shown for BSCCO and Au in Fig. 2 and Fig. 3, representing a typical temperature dependence in a very low temperature range. Since these two materials are the mesa itself, the pedestal under the mesa, and the Au thin film electrode in contact with the mesa, the temperature rise of the mesa is primarily determined by these temperature dependent values. The most significant difference from the previous self-heating calculation [11] is found in the magnitudes of the thermal conductivity. Both the thermal conductivity and the specific heat are smaller than those at 10 K by more than two orders of magnitude. Because of this small values, the temperature rise tends to become significant even when the current injection is not large. At the same time, the diffusion coefficient \( D = \sqrt{\kappa/c_p\rho} \) increases by more than 2 orders of magnitude at temperatures near 0.1 K. The increase in \( D \) implies that a larger area centering at the mesa is heated at very low temperatures.

In the calculation, the temperature rise in the 1st switching is estimated based on the dissipation due to the contact resistance \( R_{\text{cont}} \) between the Au electrode and the surface CuO2 double layer. A half of the heat generated at the contact interface is used to raise the temperature of Au electrode and the other half is used to heat the mesa. In the 2nd switching, the temperature rise is calculated based on the energy dissipation due to the injected current multiplied by the voltage branch spacing of 24 mV, which is converted to a value for the effective resistivity in the calculation. The base temperature \( T_0 \) is set to 0.4 K.

In the numerical calculation, values for \( \kappa(T) \) and \( c_p(T) \) were calculated for all the constituent materials by the spline interpolation method at every heat cycle of a \( 2 \times 10^{-11} \) s or less interval. The time division for the FDTD calculation is much less than this time interval for the reason described previously[11].
Figure 2. Temperature dependence of the thermal conductivity in the ab-plane $\kappa$ and specific heat $c_p$ for BSCCO [15, 16, 17, 18]. Marks are the data used for the spline interpolation method.

Figure 3. The temperature dependence of the thermal conductivity $\kappa$ and specific heat $c_p$ for Au [12, 13]. The notations are the same in Fig. 2.

3. Results and discussion

3.1. Mesa size dependence

Figure 4 shows the temperature rise due to self-heating as a function of time for various mesa lateral sizes from 0.5 to 22 $\mu$m on a side at an injection current density of 2 kA/cm$^2$ and a contact resistivity of $4 \times 10^{-6}$ $\Omega$cm$^2$. It is readily seen that the magnitude of the temperature rise increases with the junction lateral size. This is somewhat contradictory to the usual sense, in which the temperature rise is proportional to the injected power density. However, the result implies that the temperature rise is primarily determined by the temperature of the Au electrode, which is in close contact with the mesa. Since the power decreases with decreasing junction area, the temperature rise of the Au electrode is suppressed. This is the reason why the temperature rise increases with the junction size.

Another feature found in this result is the fast response of the temperature rise. The temperature rise is closely related with the diffusion length. Since the diffusion coefficient becomes very large at very low temperatures, the diffusion length becomes comparable with
3.2. Contact resistance dependence

The mesa type structure is forced to have a three-terminal type electrode configuration and reducing the contact resistivity is important. Usually, a contact resistivity of less $4 \times 10^{-6} \text{Ωcm}^2$ is necessary to observe current-voltage characteristics in which the influence of the contact resistance is sufficiently small to recognize. Figure 6 shows the time-evolution of the temperature rise at various contact resistivities. The junction size is fixed to be 2 μm on a side and the injection current density is 2 kA/cm$^2$. When $\rho_{\text{cont}}=4 \times 10^{-6} \text{Ωcm}^2$, the temperature rise is much less than 0.1 K. However, when $R_{\text{cont}}$ is significantly large, the temperature increases to $\sim 1$ K in an area comparable to 1 mm$^2$ due to a very large diffusion length of $\sim 5$ m$^2$/s for Au below 1 K.

3.3. Time evolution of the temperature rise

Figure 7 shows the time evolution of the temperature rise for both the 1st and the 2nd switching when the junction size is 2 μm on a side and the injection current density is 2 kA/cm$^2$ (80 μA). This current density is observed for a slightly overdoped BSCCO samples and is a little larger than usual $J_c$ for optimal or underdoped BSCCO IJJ samples. The value is selected to estimate the upper bound of the temperature rise due to self-heating. We can safely conclude that if $R_{\text{cont}}$ is less than $4 \times 10^{-6} \text{Ωcm}^2$, the temperature rise is no higher than 0.1 K at the 1st switching in the presence of contact resistance.
3.4. Temperature rise in the 2nd switching

Figure 8 shows the temperature rise in the 2nd switching at various injection currents. It is clearly seen from this result that the temperature rise is no higher than 1 K. The experimental results which should be compared with the present numerical calculation are those reported by Ota and coworkers [10]. In the experiments, the escape temperature $T_{esc}$ is approximately 7 K, which is much higher than the numerical results. This comparison implies that the observed large value for $T_{esc}$ is not due to simple heating characterized by the phonon thermal equilibrium. Rather, it may be related to the electronic temperature, which can be raised by the quasiparticle injection due to nonequilibrium effect.

4. Conclusions

Detailed numerical calculation of the self-heating has been conducted for a small mesa structure consisting of a stack of IJJs. It is found that the temperature rise is of the order of 0.1 K and...
The results imply that an unusually large value for $T_{esc}$ observed in the 2nd switching in recent switching probability measurements in IJJs is not ascribable to simple heating, where phonons are in thermal equilibrium. Rather it may be related with an increase in the electronic temperature rise due to the injection of quasiparticle current.

Acknowledgments
We have benefited from discussions with Prof. A. Maeda, Prof. H. Kitano, and Dr. K. Ota.

References
[1] Inomata K, Sato S, Nakajima K, Tanaka A, Takano Y, Wang H B, Nagao M, Hatano H and Kawabata S 2005 Phys. Rev. Lett. 95 107005
[2] Jin X Y, Lisenfeld J, Koval Y, Lukashenko A, Ustinov A V and Müller P 2006 Phys. Rev. Lett. 96 177003
[3] Li S X, Qiu W, Han S, Wei Y F, Zhu X B, Gu C Z, Zhao S P and Wang H B 2007 Phys. Rev. Lett. 99 037002
[4] Kleiner R, Seinmeyer F, Kunkel G and Müller P 1992 Phys. Rev. Lett. 68 2394 – 2397
[5] Oya G, Aoyama N, Irie A, Kishida S and Tokutaka H 1992 Jpn. J. Appl. Phys. 31 L829–L831
[6] Kawabata S, Kashiwaya S, Asano Y, and Tanaka Y 2004 Phys. Rev. B 70 132505
[7] Voss R and Webb R A 1981 Phys. Rev. Lett. 47 265–268
[8] Kashiwaya H, Matsumoto T, Shibata H, Kashiwaya S, Eisaki H, Yoshida Y, Kawabata S and Tanaka Y 2008 J. Phys. Soc. Jpn. 77 104708
[9] Tinkham M 1996 Introduction to Superconductivity, Second Edition (McGraw-Hill, Inc.)
[10] Ota K, Hamada K, Takemura R, Ohmaki M, Machi T, Tanabe K, Suzuki M, Maeda A and Kitano H 2009 Phys. Rev. B 79 134505
[11] Suzuki M, Yamada Y, Tajitsu E and Kojima S 2007 IEEE Trans. Appl. Supercond. 17 594–597
[12] Martin D L 1966 Phys. Rev. 141 576–582
[13] Lide D R (ed) 1992 CRC Handbook of Chemistry and Physics 1992-1993 73rd Edition (CRC Press Inc. London)
[14] Loram J W, Luo J L, Cooper J R, Liang W Y and Tallon J L 2000 Physica C 341-348 831–834
[15] Crommie M F and Zettl A 1990 Phys. Rev. B 41 10978 –10982
[16] Crommie M F and Zettl A 1991 Phys. Rev. B 43 408–412
[17] Behnia K, Belin S, Aubin H, Rullier-Albenque F, Ooi S, Tamegai T, Deluzet A and Batail P 1999 J. Low Temp. Phys. 117 1089–1098
[18] Ando Y, Takeya J, Abe Y and Kapitulnik A 2000 Phys. Rev. B 62 626–630
[19] Kelham S and Rosenberg H M 1981 J. Phys. C: Solid State Phys. 14 1737–1749
[20] Zeller R and Pohl R O 1971 Phys. Rev. B 4 2029–2041