Supercond. Sci. Technol. 7 (1994) 313–316. Printed in the UK

Analysis of Josephson radiation from $YBa_2Cu_3O_7$ thin-film Josephson junctions

G Kunkel, M Bode, F Wang, M Siegel, W Zander, J Schubert and A I Braginski

Institut für Schicht- und Ionentechnik, Forschungszentrum Jülich, D-52425 Jülich, Germany

Received 7 December 1993

Abstract. We have investigated the Josephson radiation from different types of $YBa_2Cu_3O_7$ (YBCO) thin-film Josephson junctions: step-edge junctions (SEJs), biepitaxial junctions and SNS junctions with N = Au. The radiation was detected using a non-resonant radiometer system with a receiving frequency of 11–12 GHz. The current–voltage characteristics were measured simultaneously with the radiation spectra in the temperature range 4.2–90 K. All junctions exhibited a large emission peak at a voltage which was related to the frequency through the second Josephson relation. Typically, for high temperatures, and therefore small critical currents, the measured radiation linewidth agreed well with the theoretical predictions. At lower temperatures the experimental linewidths deviated from the theoretical values due to additional noise sources in the junctions. Some of the SEJs showed a non-monotonic dependence of the linewidth on temperature. It is suggested that such SEJ data may be discussed in terms of a model which treats the SEJ as an interferometer consisting of a parallel array of random Josephson junctions.

1. Introduction

In the past years, different types of Josephson junction with high-T_c superconductors have been developed [1]. For practical use in cryoelectronic devices such as SQUIDs, arrays and rapid single-flux quantum (RSFQ) circuits, the junctions have to be optimized with regard to their Josephson behaviour. The most sensitive method for the analysis of the Josephson properties is the direct measurement of the Josephson radiation.

The step-edge junctions (SEJs) were fabricated by pulsed-laser deposition of YBCO thin films on $LaAlO_3$ substrates with a steep step [2]. The biepitaxial junctions were made on MgO substrates with a CeO_2 seed layer [3]. The SNS junctions were prepared on steep steps by depositing YBCO and Au layers by means of directional sputtering as described in [4]. The YBCO films were patterned either by Ar-ion beam etching or by inhibit patterning. The widths of the junctions varied from $w = 2$ to 32 μm. The YBCO film thickness was about 100 to 200 nm.

2. Experimental details

The Josephson radiation was detected using a non-resonant radiometer system. The junctions were mounted inside a horn at the end of an X-band waveguide. The signal was preamplified and mixed down with a local oscillator at 10 GHz. The intermediate-frequency IF signal versus bias was either monitored by a tuned UHF receiver at a fixed frequency, or the spectral distribution was analysed. The junctions were shielded from external spurious signals by low-pass filters and surrounded with mumetal. The I–V curves were measured by the four-point technique and were recorded simultaneously with the radiation spectra in the temperature range 4.2–90 K.

3. Results and discussion

A typical measurement of the radiation from a biepitaxial junction is shown in figure 1. The frequency was fixed at 11 GHz and both the I–V curve and the radiation spectrum were recorded at 4.2 K. The larger emission peak occurs at a voltage which is related to the frequency through the second Josephson equation: $2eV = h\nu$. The second peak shown in figure 1 corresponds to the second harmonic of the Josephson generation. The generation of harmonics is expected within the resistively shunted junction (RSJ) model for detection frequencies lower than the characteristic frequency of the junction [5].

0953-2048/94/050313+04$19.50

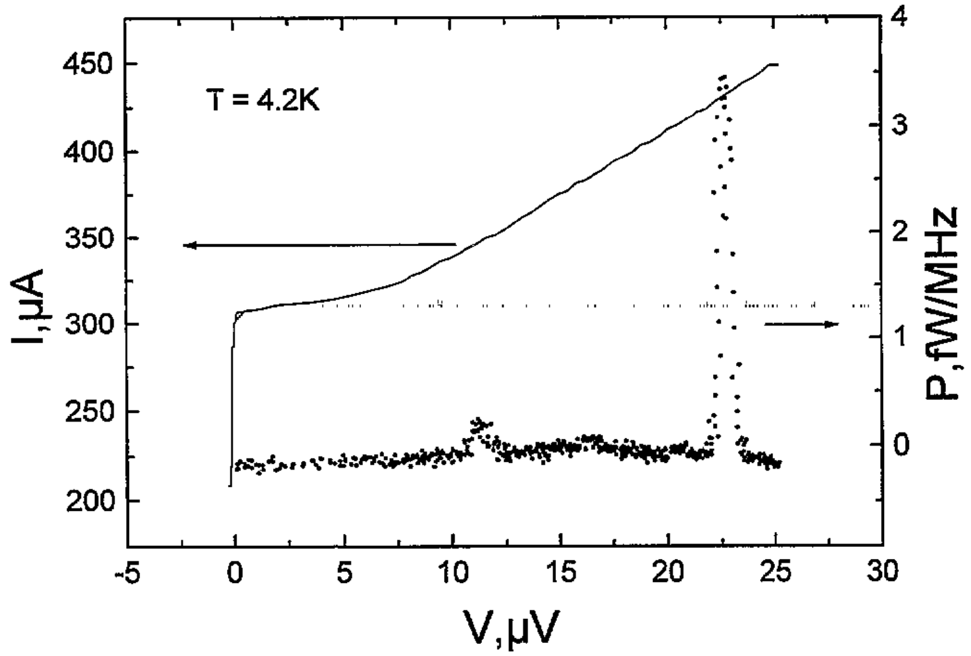

Figure 1. The radiation and *I–V* curve of a biepitaxial junction ($w = 16$ μm) at 4.2 K. The two peaks at 11.4 and 22.7 μV are related to the detection frequency of 11 GHz by $neV = h\nu$.

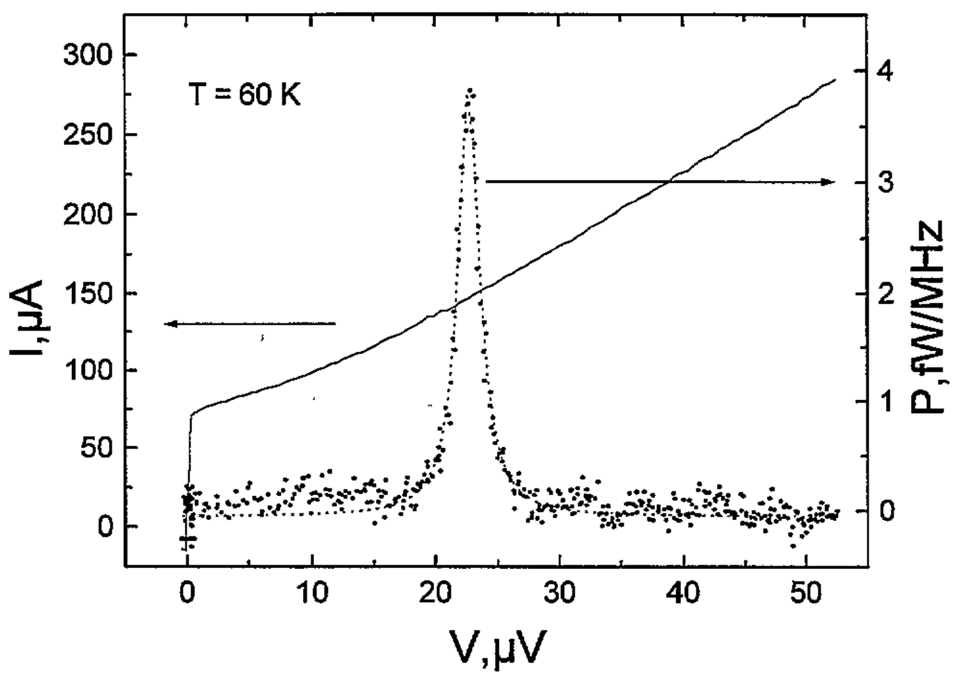

Figure 2. Radiation and *I–V* curve of a 16 μm wide SNS junction at 60 K and 11 GHz. The broken curve shows the Lorentzian fit.

The measured linewidth of this sample was 295 MHz and was about six times higher than expected from the RSJ model for the experimentally determined dynamic resistance R_d. Similar fixed-frequency curves are shown in figure 2 for an SNS junction at 60 K. The Josephson frequency-to-voltage relation was also fulfilled. Since R_d was constant in the sweep range of the bias current, the correct line shape of the radiation could be reproduced by a Lorentzian fit to the experimental data [6]. Any external excess noise would cause deviations from a Lorentzian fit. Hence, the data show that the spectral density of the noise was smooth and there was little disturbance from external sources.

Important for the understanding of the Josephson properties is the dependence of the linewidth of the emitted radiation on temperature and differential resistance. The theoretical linewidth is determined by R_d and the low-frequency current noise spectral density

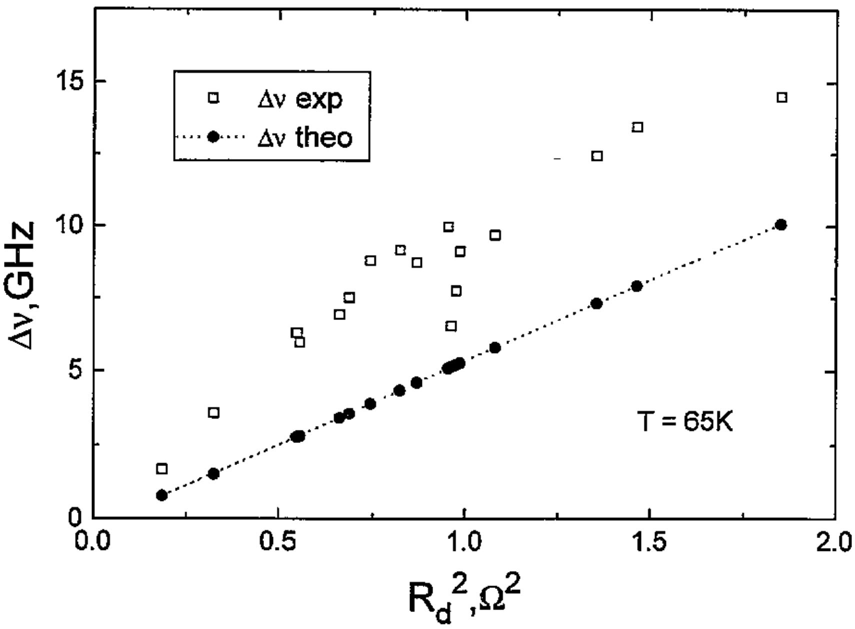

Figure 3. The linewidth versus temperature of a 16 μm wide SNS junction (□) and the linewidth calculated by the RSJ model (●).

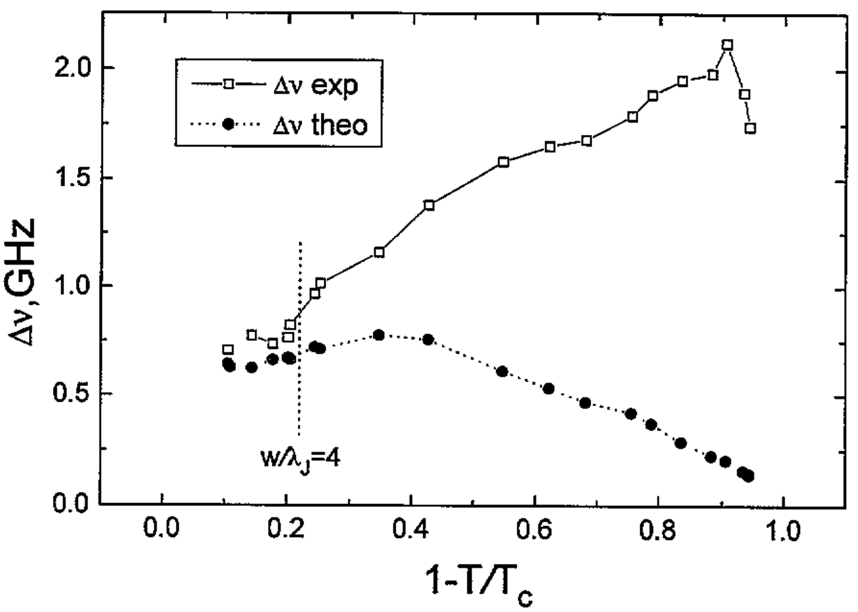

Figure 4. The dependence of the linewidth from the differential resistance at 65 K (□) and the RSJ model (●).

$S_I'(0)$ of the junction: $\Delta\nu = 1/2(2\pi/\Phi_0)^2 R_d^2 S_I'(0)$, where Φ_0 is the flux quantum [5]. For $S_I'(0)$ we assume according to the RSJ model

$$S_I'(0) = S_I(0) + \frac{1}{2}\frac{I_c^2}{I^2} S_I(w_J).$$

For $S_I(0)$ we use the Johnson noise formula

$$S_I(0) = \frac{2kT}{\pi R_N}.$$

The theoretical value of the linewidth is then calculated using the measured R_d of the junction.

The temperature dependence of the linewidth for the sample of figure 2 is shown in figure 3. A similar result was obtained for the sample of figure 1. For high temperatures, corresponding to small critical currents, the experimental values of the linewidth agree well with the theoretical ones. The critical current I_c increases with decreasing temperatures, which results in a decrease of the Josephson penetration depth λ_J, since $\lambda_J^2 \propto 1/J_c$. According to Waldram *et al* [7], for $w/\lambda_J > 4$, Josephson vortices are generated in the junction, which means that it can no longer be treated as a short junction. The temperature corresponding to $w/\lambda_J = 4$ is marked

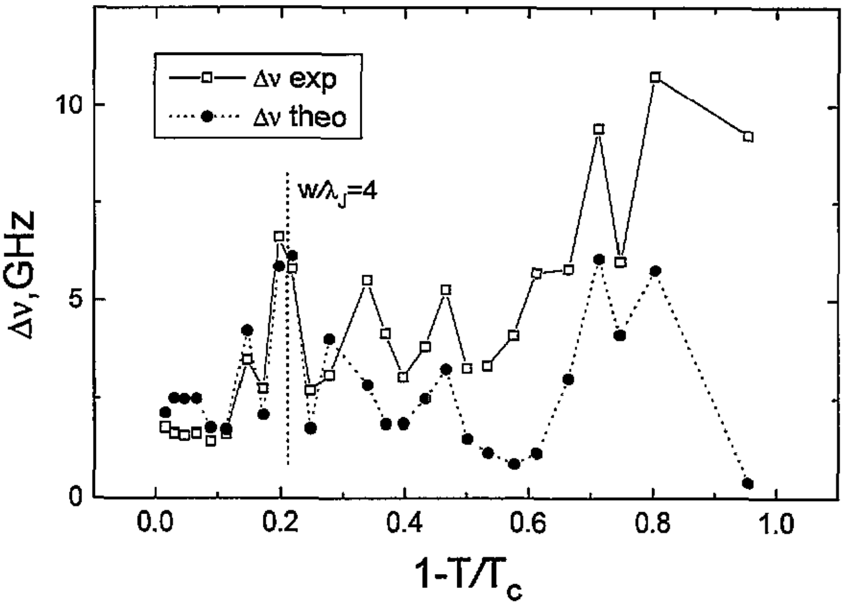

Figure 5. The temperature dependence of the linewidth for an SEJ (□) and theoretical values (●) using the RSJ model with thermal noise.

in figure 3. Above this value, the excess current and the noise of the junction increase. This increase of the experimental linewidth with w/λ_J was found to be typical for all three kinds of Josephson junction under investigation. The reason for this increase is not yet understood.

The temperature dependence of the linewidth of SEJs is more complicated than that of SNS and biepitaxial junctions. The typical dependence of the linewidth on temperature can be discussed in terms of the increase of w/λ_J as in the case of SNS junctions. In figure 4 we show $\Delta\nu$ as a function of R_d^2 for an SEJ at 65 K. The theoretically expected proportionality is fulfilled, but with a difference in the slope of the curve. This difference is determined by an additional noise source according to the formula for the linewidth in the RSJ model. This SEJ cannot be treated as a short junction because $w/\lambda_J = 5.5$. However, some SEJs exhibit a non-monotonic dependence of $\Delta\nu$ on T. An example is shown in figure 5 for a 32 μm wide SEJ. A similar non-monotonic temperature dependence of the linewidth was obtained by indirect measurements of the linewidth [8]. It is interesting to note that at certain temperatures the experimental and theoretical linewidths are close to each other. R_d again was estimated from the measured I–V curve. An analogous oscillatory, non-monotonic increase of the low-frequency voltage noise has been found for SQUIDs and SEJs [9]. This non-monotonic behaviour may be explained by a model which treats the SEJ as an interferometer consisting of a parallel array of random Josephson junctions with very small loop inductances [8]. In addition to the number of junctions connected in parallel, this oscillatory behaviour will be determined by the resulting SQUID parameter $\beta_L = 2\pi L I_c/\phi_0$ and the enclosed flux. With decreasing temperature the critical current and the SQUID screening parameter increase. This influences the differential resistance and the linewidths. In addition, the current–phase relation of the SQUID is no longer single-valued, due to multiple flux states. The switching between these metastable states is expected to cause additional noise, thereby increasing the linewidth.

References

[1] Braginski A I 1993 Thin film structures *The New Superconducting Electronics* ed H Weinstock and R W Ralston (Deventer: Kluwer) pp 89–122

[2] Herrmann K, Zhang Y, Mück H-M, Schubert J, Zander W and Braginski A I 1991 *Supercond. Sci. Technol.* 4 583

[3] Wang F, Kunkel G, Copetti C, Kohlstedt H and Wördenweber R 1993 *Eur. Conf. Appl. Supercond. (Göttingen, 1993)*

[4] DiIorio M S, Yoshizumi S, Yang K-Y, Zhang J and Mung M 1991 *Appl. Phys. Lett.* 58 2552

[5] Likharev K K 1986 *Dynamics of Josephson Junctions and Circuits* (New York: Gordon and Breach)

[6] Jain A K, Likharev K K, Lukens J E and Savaugeau J E 1984 *Phys. Rep.* **109** 309

[7] Waldram J R, Pippard A B and Clarke J 1970 *Phil. Trans. R. Soc.* A **268** 265

[8] Divin Yu Ya, Andreev A V, Fischer G M, Mygind J, Petersen N F, Herrmann K, Glyantsev V N, Siegel M and Braginski A I 1993 *Appl. Phys. Lett.* **62** 1295

[9] Glyantsev V N, Siegel M, Schubert J, Zander W, Poppe U, Soltner H, Braginski A I and Heiden C 1993 *IEEE Trans. Supercond.* **3** 2472