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Observation of the AC Josephson effect up to THz frequencies in YBCO/PBCO/YBCO ramp-type Josephson junctions

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We present the response to 100 GHz irradiation of high-T_c Josephson junction devices for mixer/detector applications in the (sub-) mm wave range. These devices consist of a YBCO/PBCO/YBCO ramp-type junction combined with a planar logarithmic periodic antenna. The critical current and the first two Shapiro steps modulate with 100 GHz power according to the resistively shunted junction (RSJ) model. At 10 K clear Shapiro steps have been observed up to a voltage of about 7.5 mV. This corresponds to phase locking of 3.6 THz AC Josephson oscillations by the 36th harmonic of the 100 GHz signal. The number of observed steps is currently limited by the available power, but they are present up to voltages strongly exceeding the I_cR_n product of the junction at all temperatures.

1. Introduction

Josephson junctions are extremely attractive for very sensitive detection of high-frequency radiation, e.g. for radio-astronomy applications. Junctions made of high-T_c materials should enable operation in the far-infrared region at temperatures higher than 4.2 K, up to 77 K, due to their large energy-gap values and high critical temperatures. This means that the AC Josephson effect should be present at voltages of several millivolts. There are only few studies on high-T_c junctions, however, in which the high-frequency response up to such high voltages was observed, see e.g. refs. [1-3]. Since most high-T_c Josephson junctions suffer from a strong reduction of the I_cR_n product as compared to the theoretical value, the question arises whether their high-frequency response is cut off at voltages above the gap voltage, as in SIS tunnel junctions [4], or already at voltages just above the I_cR_n product.

We are developing a Josephson detector/mixer device for high-frequency applications using all high-T_c YBCO/PBCO/YBCO ramp-type junctions. In this paper we will present the response of these devices to 100 GHz irradiation. First, however, some design considerations and lay-out aspects will be briefly discussed.

2. Device description

For efficient high-frequency detector/mixer devices, with an operating temperature T_{op} between 4.2 K and 77 K, a junction is needed which fulfills many requirements:
(1) a high T_c (~85 K),
(2) a critical current I_c that exceeds the noise current at T_{op},
(3) an impedance that can be easily matched to incoming radiation and output amplifiers,
(4) a large I_cR_n, product,
(5) low noise,
(6) RSJ-like, non-hysteretic current-voltage characteristics. Furthermore, efficient broad-band coupling to (sub-) mm wave radiation is necessary, without excessive reflection and dielectric losses in the substrate [5]. YBCO/PBCO/YBCO ramp-type junctions can meet most of these requirements. In a recent paper we described the design and fabrication

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of a high-frequency device based on these junctions [6].

The fabrication process for the ramp-type junctions has been described in detail in previous papers [7,8]. They show good scaling of their parameters with the cross-section area A, as well as a clear Josephson behavior. The critical current density J_c depends exponentially on the PBCO barrier thickness L. Junctions with $L \sim 10$–15 nm show RSJ-like behavior, with $R_nA \sim 10^{-7}$–10^{-5} Ω cm^2 and $J_c \sim 10^5$–10^3 A cm^{-2}. Such parameters yield values for R_n and I_c that agree well with the requirements. In this study a barrier thickness of about 10 nm was used; the width of the junction was 5 μm. By minimizing the length of the overlap to 1–2 μm, capacitive shunting of the junctions was drastically reduced. The impedance of the junctions is therefore mainly determined by their normal-state resistance. The devices are prepared on $NdGaO_3$ substrates.

To improve the coupling of high-frequency radiation to the junction, it is placed between the terminals of a self- complementary circular toothed log-periodic antenna, which is well known from detection and mixing experiments with low-T_c Josephson junctions [5]. It is very suitable for the effective coupling to external radiation, since its beam pattern is nearly linearly polarized, with maxima in the direction perpendicular to the plane of the antenna [9]. It has a high, nearly real impedance (about 58 Ω assuming a dielectric constant of 20 for $NdGaO_3$ [10]), and it is nearly frequency independent from 0.01 THz to several THz. The antenna of the device used in this study is made of YBCO. The log-periodic structure is simply patterned into the base and counter-electrode of the junction. Figure 1 shows the complete lay-out.

Current–voltage characteristics (CVC's) of the device were measured in an Oxford CF1200 continuous flow cryostat using a standard four-point technique. For this purpose four silver contacts were evaporated on the outer region of the YBCO antenna. As 100 GHz signal source an Epsilon Lambda ELMI10 Gunn diode oscillator was used. After passing the radiation through a variable attenuator and a section of stainless steel W-band waveguide, it was radiated onto the junction through the back of the substrate by a standard gain horn antenna.

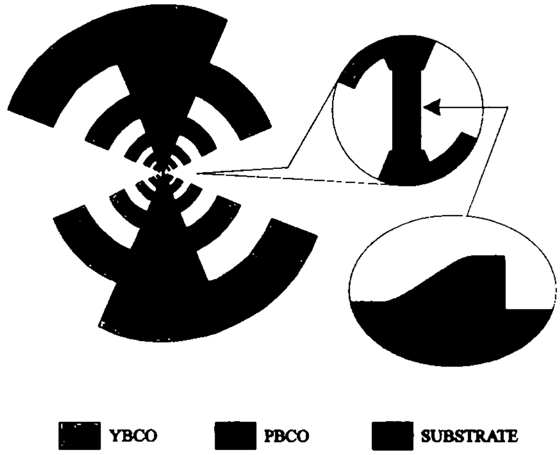

Fig. 1. Lay-out of the device. The log-periodic antenna is shown in the left part. The upper right inset shows a magnified top view of the terminal region of the antenna. A side view of the region indicated by the arrow is given in the lower right inset. It gives a schematic view of the YBCO/PBCO/YBCO ramp-type structure.

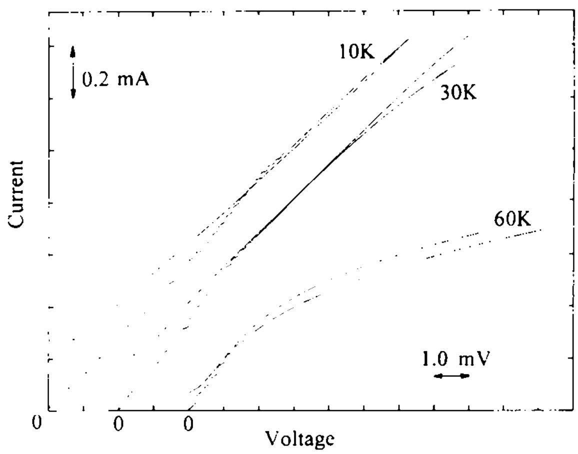

Fig. 2. Current–voltage characteristics at 10, 30 and 60 K, with and without 100 GHz irradiation. Curves with radiation are taken at the maximum power level.

3. Results.

Figure 2 shows the CVC's of the device at 10, 30 and 60 K. A critical current was observed up to $T_c = 80$ K. This junction has $I_c = 270$ μA at 10 K and $R_n = 8$ Ω, which matches reasonably well the estimated impedance of the antenna. Irradiation of the device with a coherent 100 GHz signal causes the appearance of many Shapiro steps on voltages $V_n = n\Phi_0 f$, where n is an integer, Φ_0 is the flux quantum, and $f = 100$ GHz. Non-integer steps are also frequently observed in this type of junctions. Especially at low temperatures and at low power values, strong steps at $n = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}$ and sometimes at $n = \frac{1}{3}$ and $\frac{4}{3}$ are found. At high temperatures these sub-harmonic steps gradually disappear. These observations agree with qualitative RSJ model predictions. The junction response to high-frequency irradiation is determined by the parameter $\Omega = \Phi_0^* f / I_c R_n$. At low temperatures the junction is RF current biased ($\Omega < 1$), and sub-harmonic steps may be present in the excited CVC's. At high temperatures, however, the junction is voltage biased ($\Omega > 1$), and the sub-harmonic structure is much smaller.

At the maximum 100 GHz power, a large number of Shapiro steps is observed in the CVC's (see fig. 2). At 10 K 36 clear steps can be seen. This corresponds to AC Josephson oscillations in the junction at a frequency of 3.6 THz being phase locked by the 36th harmonic of the applied radiation. At higher temperatures the maximum number of observable steps gradually decreases. At 30 K 22 steps can still be seen, while at 60 K 9 distinct steps remain. In the CVC's and in dV/dI measurements structures were observed beyond these highest step numbers that indicated the presence of even higher order steps. These step-like structures, however, were broadened and shifted from the correct voltage values. This is possibly due to the transition to the voltage state of one of the electrodes of the junction, which has degraded superconducting properties. This effect also causes the strong rounding of the CVC's at higher temperatures.

These measurements show that YBCO/PBCO/YBCO ramp-type junctions have a high degree of phase locking up to voltages of at least 7.5 mV. Recently we studied the 176 GHz response of a ramp-type junction with $R_n = 2.5\ \Omega$ and $I_c = 100\ \mu A$ at 7.5 K (no antenna was used in that case) [11]. At 5 K, the 6th step at 2.2 mV was clearly present, corresponding to a Josephson oscillation above 1 THz. Only few studies on high-T_c junctions are found in the literature that demonstrate the AC Josephson effect up to such high voltages [1-3]. These studies were mainly performed with poorly reproducible devices, like point contacts [1] or thin-film bridges containing several grain-boundary junctions [2,3].

A Bessel-like oscillatory behavior of I_c and the induced steps is observed for these junctions with increasing 100 GHz power P_{RF}. Figure 3 shows the normalized values of I_c and the first two Shapiro steps at 50 K as a function of the normalized microwave amplitude I_{RF}. These data were taken on a junction with $I_c R_n = 0.35$ mV at 50 K, as determined from the CVC. The solid lines are the result of numerical simulations based on the RSJ model. The proportionality factor between I_{RF} and $(P_{RF})^{1/2}$ was used as a fitting parameter. It was determined such that the first measured zero of I_c coincides with the one of the calculated curve. The best agreement is obtained for $\Omega \approx 0.3$. This value agrees within a factor 2 with the value determined from the CVC. The measured step amplitudes are lower than the calculated ones, which is probably due to noise [12]. Nevertheless, a good fit is obtained, which shows that the high-frequency

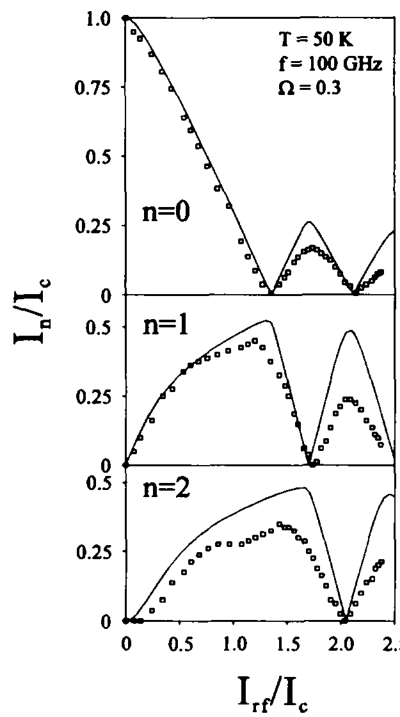

Fig. 3. Normalized amplitudes of I_c ($n = 0$) and the first and second Shapiro steps ($n = 1,2$), as a function of the normalized RF amplitude I_{RF}. The measured data are indicated by the squares. The solid lines are the result of numerical simulations based on the RSJ model with $\Omega = 0.3$.

response of this junction can well be described by the RSJ model. This result agrees with the previously measured RSJ-like response of a ramp-type junction to 10 GHz radiation [8]. In the previously mentioned study using 176 GHz, the measured amplitudes of I_c and the first two Shapiro steps could be fitted nearly perfectly with a Bessel function, as is expected for a junction with Q>1 [11].

4. Discussion

An important issue for high-T_c Josephson devices aiming at very high-frequency applications is their highest possible operation frequency. In low-T_c Josephson junctions a response to high frequency irradiation has been observed up to voltages at and even far above the gap voltage of these materials [13]. All the measurements agreed well with the predictions of the Werthamer theory [4], including the presence of the Riedel peak. In high-T_c Josephson junctions, however, a high-frequency response has been observed up to voltages of 4–10 mV [1–3], but never near or above the gap.

Contrary to most low-T_c devices used to study the high-frequency response, the I_cR_n products of all types of high-T_c Josephson junctions are strongly reduced from the BCS values. In ramp-type junctions I_cR_n at 4.2 K was found to vary from 1 to 8 mV, depending on the barrier thickness [8]. In a recent paper the transport mechanism and the reduction of the I_cR_n product with increasing barrier thickness and temperature were analyzed [14]. The characteristic behavior could not be accurately described using simple SNS weak-link or SIS tunnel models. It was demonstrated that this could only be done if a SNINS model with additional pair-breaking in the PBCO barrier was used and a one-impurity tunneling process was taken into account. Other types of high-T_c junctions are also often described using localization models and additional scattering in the barrier [15].

It is not clear at this moment whether these mechanisms, that cause such a strong reduction of the I_cR_n product, will limit the presence of the AC Josephson effect to voltages of about I_cR_n, or if operation near the gap voltage remains possible. In fig. 4 we compare the voltage V_{max}, up to which clear Shapiro steps are observed in our measurements, with the I_cR_n products as determined from the CVC's. V_{max} is at least four times larger than I_cR_n over the temperature range of 10 to 70 K and is currently limited in the experiments by two obvious factors:

(1) The applied 100 GHz power is very small due to losses in the waveguide system and impedance mismatches and capacitive shunting of the junction:

(2) at higher temperatures the influence of noise limits V_{max}, especially since the step amplitude strongly decreases at higher step numbers. Taking into account such factors, fig. 4 shows that V_{max} is not limited by I_cR_n. It is not clear from these measurements if the AC Josephson effect is present in these junctions up to the gap voltage. Experiments with higher radiation frequencies and theoretical investigations should be performed to clarify this question. First results in measurements of NIST indicate that Shapiro steps in YBCO/Ag/YBCO junctions with $I_cR_n = 10$ mV at 10 K could be observed up to voltages of 15 mV [16].

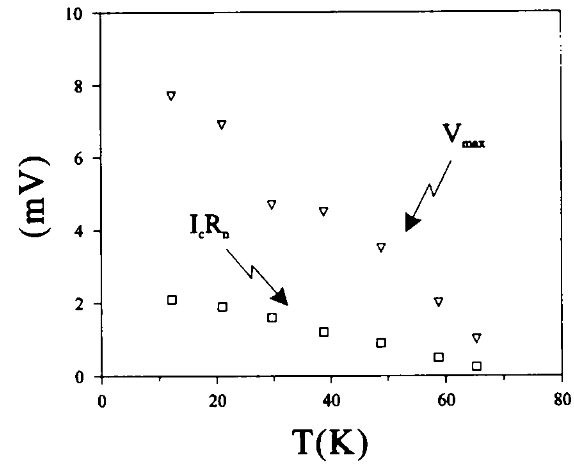

Fig. 4. The voltage V_{max}, up to which clear Shapiro steps are observable in the excited CVC's (triangles), and the I_cR_n product measured from the CVC's (squares), as a function of temperature.

Future device developments will involve the use of antennas made of gold instead of YBCO, to reduce the high-frequency conduction losses. These losses are larger in YBCO than in a noble metal for frequencies above about 200 GHz [10]. Realization of such a design, however, puts severe demands on the fabrication process. For example, the contact resistance between the leads of the junction and the gold antenna must be very small to prevent bad coupling between the junction and the antenna, while the area of the YBCO leads has to be kept small to prevent strong RF losses [6].

5. Summary

High-T_c Josephson devices, consisting of a YBCO/PBCO/YBCO ramp-type junction and a log-periodic antenna, were successfully studied using 100 GHz radiation. Clear Shapiro steps were found up to relatively high voltages. At 10 K the 36th step at about 7.5 mV was seen, corresponding to 3.6 THz AC Josephson oscillations. The amplitudes of I_c and the first two steps is well described by the RSJ model. These results imply that these devices are very suitable for use as detectors/mixers at (sub-) mm wave frequencies. It is not clear what the limiting operating frequency for such applications is. We have observed Shapiro steps up to voltages at least four times larger than the I_cR_n product of the junction at all temperatures. This means that the operation frequency is not limited by the I_cR_n product, which is strongly reduced compared to the BCS value.

Acknowledgements

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