Near-millimeter-wave response of high T_c ramp-type Josephson junctions

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We have studied the response of a YBCO/PBCO/YBCO ramp-type junction to coherent radiation at 176 and 270 GHz. The *I-V* characteristic of the junction closely resembles the prediction of the RSJ model. The I_cR_n product of the junction is 0.25 mV at 5 K. The millimeter-wave radiation is coupled to the junction via a quasioptical structure that focuses the radiation onto the junction through a yttrium-stabilized ZrO_2 substrate. At 176 GHz, we have observed as many as six Shapiro steps at the maximum power level of our Gunn oscillator-pumped frequency doubler. Shapiro steps are still clearly seen up to 65 K. The amplitudes of the zeroth, first, and second Shapiro steps, as functions of the square root of the radiation power, agree remarkably well with a Bessel function fit, indicating the junction is voltage-biased at the radiation frequency (rf). At 270 GHz, due to a combination of the heavy rf loss in the ZrO_2 substrate and the lack of radiation power, we have observed only the first Shapiro step.

The development of millimeter-wave detectors and heterodyne mixers using high T_c superconducting Josephson junctions has potential applications in far-infrared spectroscopy and in extensive satellite-based sky and earth surveys in which the detectors can be operated with radiative passive cooling. The reproducibility of the fabrication and the performance of such devices are crucial for success. To date, most studies on millimeter- and submillimeter-wave response of high T_c Josephson devices have involved natural grain boundary and step-edge junctions, microbridges, and weak links created by damaging the substrate.[1–4] These devices suffer from poor reproducibility and controllability, and usually have low values for the critical current and normal resistance product I_cR_n.

One of the more promising candidates for successful device applications is the ramp-type YBCO/PBCO/YBCO ($Y_1Ba_2Cu_3O_{7-\delta}/Pr_1Ba_2Cu_3O_{7-\delta}/Y_1Ba_2Cu_3O_{7-\delta}$) SNS-like (superconductor-normal-metal superconductor) junctions.[5–7] Such devices facilitate better control over junction areas and normal layer thicknesses. Furthermore, since current transport takes place in the *a-b* plane rather than along the *c*-axis, the coherence length is longer, yielding higher I_cR_n products. Ramp-type junctions with $I_cR_n \approx 1$ mV and *I-V* characteristics closely resembling the prediction of the resistively shunted junction (RSJ) model have been fabricated.[5] In this letter, we present a systematic study of the near-millimeter-wave response of a ramp-type high T_c junction.

The fabrication of our junctions, as described in Ref. 5, is reviewed here briefly. A bilayer of YBCO (100 nm) and PBCO (200 nm) is deposited by off-axis rf-magnetron sputtering with the *c*-axis normal to a 1 mm thick, yttrium-stabilized ZrO_2 (YSZ) substrate. Using photolithography, a ramp edge making an angle with the substrate of less than 30° is etched across the length of the bilayer by argon-ion beam milling. Next, a 15 nm layer of PBCO (a semiconducting perovskite used as the barrier) and a counter 100 nm YBCO layer are sputtered over the ramp edge in sequence, forming the SNS structure in the *a-b* plane. The resulting multilayer is then patterned to give the desired junction width. In the final process, the silver contacts are deposited *ex situ*.

The quasioptical system used in our measurements is similar to those reported previously.[8,9] The coherent radiation source is a tunable (75–110 GHz) Gunn oscillator-pumped frequency doubler or tripler. The maximum output power is 2 mW for the frequency doubler, and 0.5 mW for the tripler. The radiation beam of the frequency multiplier is launched into free space through a conical horn, and then focused through the window of an infrared cryostat by two TPX lenses. The radiation signal reaches the junction through the YSZ substrate, which is glued on a silicon wafer mount.

The silicon wafer mount is well heat sunk to a thermal stage connected to the liquid helium tank through a weak thermal link. With a thermometer and a heater attached to this stage, temperatures between 7.5 and 90 K are regulated by a proportional-integrator-differentiator (PID) feedback network. For measurements near 5 K, a stronger thermal link is used. Care has been taken to minimize extraneous noise signals by avoiding ground loops, using twisted pairs, and employing rf filters at the entrance of the cryostat. A four-point probe current-voltage measurement is used to avoid the effect of a large contact resistance between the silver pads and the YBCO films.

The *I-V* characteristics of the junction closely resemble the prediction from the RSJ model. Figure 1 shows several *I-V* curves taken at different temperatures. The junction becomes normal at temperatures above 75 K. The measured critical current as a function of temperature is shown in the inset to Fig. 1. The junction capacitance is estimated to be about 1.5 fF for a specific capacitance

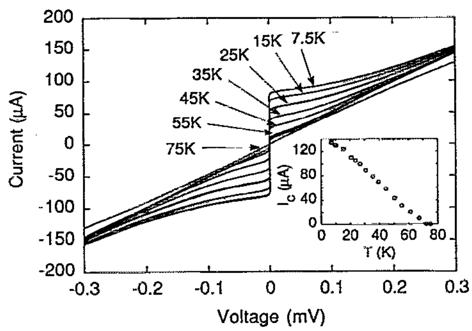

FIG. 1. dc *I-V* curves of a ramp-type YBCO/PBCO/YBCO junction taken at different temperatures. The value of the I_cR_n product is about 0.25 mV at 7.5 K. The *I-V* curves closely resemble the predictions of the RSJ model. The inset is the measured critical current as a function of temperature.

$C/A \approx 0.5$ fF/μm^2,[5] and an effective junction area of 15×0.2 μm^2. The critical current I_c is 100 μA at 7.5 K, yielding the Josephson plasma frequency $\omega_p/2\pi = (2eI_c/\hbar C)^{1/2}/2\pi \approx 2.3$ THz and the Stewart–McCumber parameter $\beta_c = (\omega_p R_n C)^2 \approx 3 \times 10^{-3}$, where the junction resistance R_n is 2.5 Ω. Thus, the junction is extremely overdamped and no hysteresis is observed in the *I-V* curves.

Under coherent radiation at 176 GHz, many integer Shapiro steps appear on the *I-V* curves of the RSJ-like junction. Figure 2 shows a set of such *I-V* curves taken at different temperatures. The level of the pump power is chosen to maximize the amplitude of the second step at 7.5 K, so the first few Shapiro steps can be observed up to 65 K. As the temperature increases from 7.5 K, the amplitudes of the Shapiro steps decrease, partially because of the decrease of the Josephson critical current and partially because of the noise rounding at higher temperatures.[10,11] For temperatures at and above 75 K, the *I-V* curve exhibits the characteristic of a flux-flow dominated transport and displays no Shapiro steps.

In order to minimize the noise effects and to compare the results with the predictions from a noiseless RSJ model, we focused our further studies at temperatures below 8 K, where thermal noise is insignificant compared to the Josephson coupling energy. At the maximum power level of the frequency doubler, we have observed as many as six Shapiro steps. In Fig. 3, we plot the normalized amplitudes of the zeroth, first, and second Shapiro steps relative to the square root of the power P_{rf}, where P_{rf} is monitored independently by a pyroelectric detector using a lock-in technique. In great contrast to most of the millimeter-wave measurement results published in literature, our measured amplitude of the *n*th step as a function of $P_{rf}^{1/2}$ can be fitted extremely well with the *n*th Bessel function $J_n(2\alpha)$, shown as the solid curves in Fig. 3. The proportionality factor between $P_{rf}^{1/2}$(measured in arbitrary units) and 2α is the sole fitting parameter used. The best overall fit results by choosing this proportionality factor so that the first zero of $J_1(2\alpha)$ matches that of the amplitude of the first step. Once chosen, is used this proportionality factor for the other steps. Because of their small amplitudes, the higher steps ($n \geqslant 3$) are affected more strongly by noise and do not change smoothly with $P_{rf}^{1/2}$. As a result, the quality of the Bessel function fitting is poor.

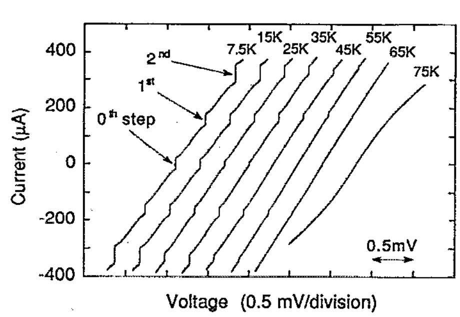

FIG. 2. *I-V* curves of the junction irradiated by coherent radiation at 176 GHz and taken at different temperatures. Shapiro steps are still visible at 65 K.

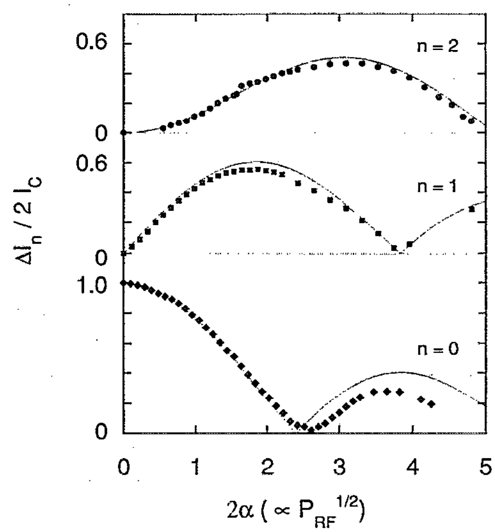

FIG. 3. Measured amplitudes (normalized by the critical current in the absence of radiation) of the zeroth, first, and second Shapiro steps as functions of 2α and relative to the square root of radiation power ($P_{rf}^{1/2}$) at 176 GHz near 5 K. The solid lines are Bessel functions. The proportionality between 2α and $P_{rf}^{1/2}$ is chosen so that the minimum of the first step and the corresponding Bessel fit coincide.

The remarkable Bessel-like behavior of the zeroth, first, and second step amplitudes indicates that the junction is voltage-biased at the radiation frequency.[12] The operating regime in which the junction is current- or voltage-biased depends on the dimensionless parameter $\Omega = \omega L_J / R_n$, where $L_J = \hbar/2eI_c$ is the Josephson inductance at zero current.[13] Ω is the ratio of the impedance of the nonlinear Josephson inductance over the linear normal resistance. For $\Omega < 1$, the linear resistance is greater so the junction is rf current biased, and the junction is rf voltage biased for the opposite case $\Omega > 1$. For our junction, $L_J \approx 3$ pH for $I_c = 100$ μA. Thus at 176 GHz, $\omega L_J \approx 3.3$ Ω and $\Omega \approx 1.3$, and the junction becomes voltage biased. Most of the measurements published in literature were carried out at frequencies lower than 100 GHz, at which $\omega L_J < R_n$. In this range, the measured step amplitudes versus $P_{rf}^{1/2}$ follow the predictions from the rf current-biased RSJ model.[2,5] It should be noted that the dimensionless parameter Ω is proportional to the radiation frequency. Thus, rf voltage-biased behaviors should be expected from RSJ-like junctions (with $I_cR_n \approx 1$ mV) irradiated at near-millimeter- and submillimeter-wave frequencies.

The implication of the Bessel-like behavior of the step amplitudes on detector application is quite interesting. The detector response can then be predicted analytically. For simplicity, we discuss the case for direct detectors, which are operated in the small-signal limit where $\alpha \ll 1$ and the dc bias current $I_{dc} \approx I_c$. The current responsivity η_I is defined as the ratio of the radiation-induced dc current ΔI_{dc} over the rf power P_{rf} dissipated in the junction. In our case, $\Delta I_{dc} = I_c[1 - J_0(2\alpha)] \approx 2I_c\alpha^2$, and $P_{rf} = V_{rf}^2/2R_n = (\alpha\hbar\omega/e)^2/2R_n$, where V_{rf} is the rf voltage seen by the junction. Thus, $\eta_I \approx 4I_cR_n/(\hbar\omega/e)^2$, which is proportional to the device parameter I_cR_n. For our device at 176 GHz, $\eta_I \approx 2\times10^3$ A/W, and is comparable to the quantum efficiency $e/\hbar\omega \approx 1.4\times10^3$ A/W. At quantum efficiency, exactly one transport electron is created per absorbed photon. However, we should note that as the current responsivity of a RSJ-like Josephson detector decreases as ω^{-2}, the quantum efficiency decreases as ω^{-1}.

We have also studied the response of this junction to coherent radiation at 270 GHz provided by the frequency tripler. We observed only the first Shapiro step even at the maximum radiation power level. Figure 4 shows a set of *I-V* curves taken at different temperatures. We believe that this poor rf coupling is due to a combination of heavy rf loss of the YSZ substrate at this high frequency[14] and a relatively weak radiation power from the source, instead of an intrinsic rolloff of the Josephson oscillation at high frequencies. This belief is supported by the evidence that we have observed up to the sixth Shapiro step at 176 GHz, which corresponds to a Josephson oscillation at 1 THz. In a separate measurement on a similar junction irradiated at 100 GHz, at least sixteen Shapiro steps appeared, implying a Josephson oscillation up to 1.6 THz.[15]

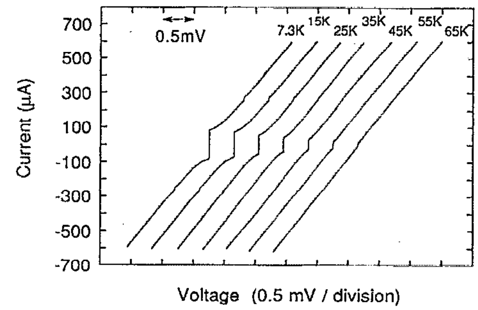

FIG. 4. *I-V* curves of the junction pumped at 270 GHz and taken at different temperatures.

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