The Radio-Frequency Impedance of Individual Intrinsic Josephson Junctions

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We have measured the response of an array of $Bi_2Sr_2CaCu_2O_{8+\delta}$ intrinsic Josephson junctions to irradiation at 3 GHz. By measuring the dependence of the switching current upon the radio-frequency current for five of the junctions in the array we show quantitatively that the junctions have identical impedances at 3 GHz, this impedance being given by the inverse of the slope of the current-voltage characteristics.

$Bi_2Sr_2CaCu_2O_{8+\delta}$ intrinsic Josephson junctions [1] have been recently shown to be coherent tuneable terahertz sources with narrow linewidth [2,3]. Although the details of the mechanism of coherent THz emission are controversial [4,5], there is intense progress towards increasing the emitted power from intrinsic Josephson junction (IJJ) arrays to the mW level. This is required by many applications such as THz spectroscopy and imaging in the pharmaceutical and biological sciences, sensing of hazardous chemicals, detection of concealed weapons, non-invasive medical diagnostics, and high-bandwidth telecommunications [6,7]. The junction uniformity plays a crucial role in determining the number of junctions which oscillate coherently and hence the total emitted power and linewidth [2,8,9]. Many previous studies have shown that $Bi_2Sr_2CaCu_2O_{8+\delta}$ IJJs have highly uniform d.c. properties [10,11]. Here we introduce a new technique and use it to demonstrate that $Bi_2Sr_2CaCu_2O_{8+\delta}$ IJJs also have highly uniform radio-frequency (r.f.) properties – specifically the junctions have mutually identical r.f. impedances in the voltage (oscillatory) state.

Single $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) crystals were grown by using the travelling-solvent floating-zone technique [12]. The crystal was cut into platelets of approximate dimensions 3 mm x 200 µm x 20 µm (in the a-, b- and c-directions respectively), which were glued on top of an MgO substrate using polyimide. The crystal was cleaved in an argon-filled glove box in order to reduce the height in the c-direction to ~3 µm. Four silver contacts of thickness ~90 nm were evaporated through a mask onto the freshly cleaved surface. The resulting contact resistance was ~5 Ω.

The IJJ stack structure was patterned by using a 30 keV focused gallium ion beam. In order to narrow down the crystal from ~200 μm to ~1 μm in width, we oriented the c-axis parallel to the ion-beam and milled with an ion-beam current of 2 nA. This was followed by a "polishing" mill with currents down to 50 pA so as to minimize gallium implantation. The sample was then re-oriented so that the ion-beam was approximately perpendicular to the c-axis. Two slots, 1.4 μm apart, were milled into the crystal. The resulting IJJ stack was 1.4 μm x 0.85 μm in cross-section and ~300 nm in the c-direction as shown in figure 1. Since the c-axis separation of each intrinsic junction is ~1.5 nm, the array contains of order N = 200 junctions.

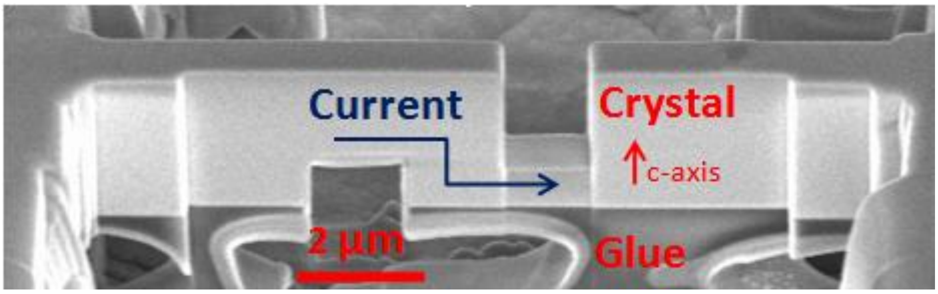

Fig. 1: Side-view scanning-electron micrograph of the IJJ stack structure in the BSCCO crystal. The intrinsic junctions are located in the region where the bias current flow is parallel to the c-axis. The glue can be seen underneath the crystal.

The sample was mounted onto the copper finger of a custom-built measurement probe. This was inserted into a He^4 storage dewar, with all measurements being carried out at 4.2 K. The IV-characteristics (IVCs) were measured by manually sweeping the bias current. The voltage across the junction was measured in a four-terminal configuration. An HP 8671B synthesized continuous-wave r.f. generator was used to irradiate the IJJ stack at a frequency of 3.0 GHz. A dipole antenna, formed by exposing the end of the inner core of a semi-rigid microwave coaxial cable, was fixed ~1 cm above the sample.

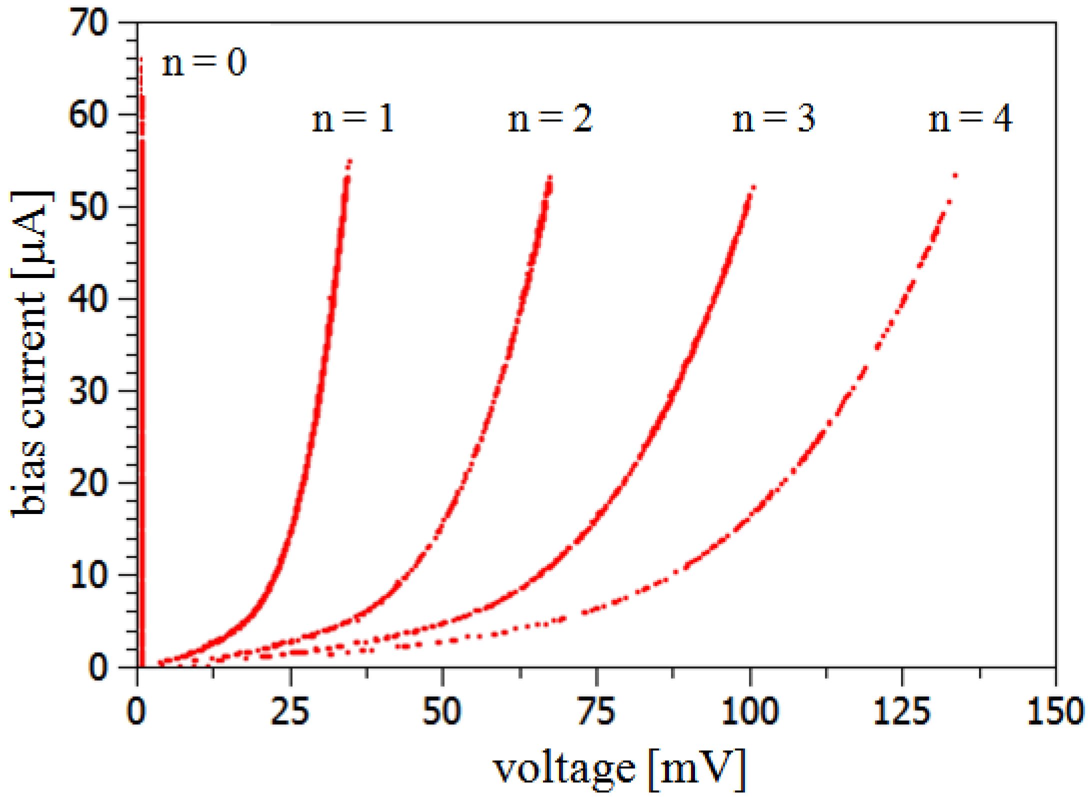

Fig. 2: IV characteristics at T = 4.2 K with no r.f. irradiation. Only the first five branches are shown.

In figure 2 the IVC with no r.f. irradiation is shown. The IVC is multi-branched and hysteric. The switching current $I_{SW}(n)$ on the n^{th} quasiparticle branch ($1 \leq n \leq 4$) is rather uniform ($I_{SW}(1) \sim 53$ µA, $I_{SW}(2) \sim 52$ µA, $I_{SW}(3) \sim 50$ µA and $I_{SW}(4) \sim 49$ µA), confirming the uniformity of the c-axis critical current in the IJJ stack. The slight suppression of the switching current as the branch number n increases is probably due to Ohmic heating. The switching current on the supercurrent branch ($n = 0$) is larger (66 µA) as is commonly observed in measurements of IJJ stacks [11,13]. From fits to switching current distributions (not shown) we find the unfluctuated critical current to be $I_C = 80$ µA, and hence the plasma frequency, $f_p = (I_C / 2\pi \Phi_0 C)^{1/2}$, is approximately 300 GHz. (Here we assume that the relative dielectric constant of the spacer layer in each IJJ is equal to 10; Φ_0 is the flux quantum.)

The dependence of the switching currents of each branch on the r.f. current at $f = 3$ GHz was extracted from the IVCs and is shown in figure 3 (a). Since $f << f_p$, the effect of the r.f. current is to adiabatically modulate the depth of the washboard potential well at a frequency f. This leads to an exponential increase in the escape rate from the zero-voltage state to the voltage state and hence to a decrease in I_{SW}. The degree of suppression however can be seen to be very much stronger for the supercurrent branch than for the quasiparticle branches. A qualitatively similar effect has also been observed for $Tl_2Ba_2CaCu_2O_8$ intrinsic junctions [14].

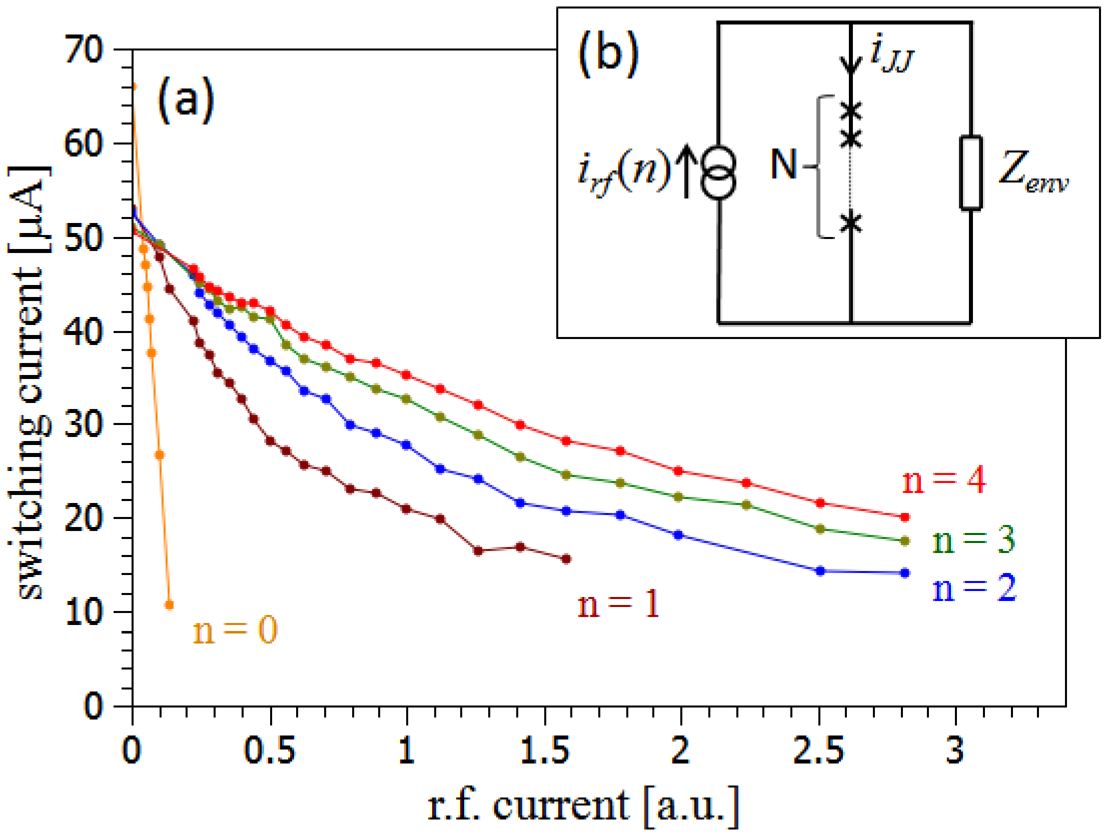

Fig. 3: (a) Switching currents I_{sw} (n) for different branches n are plotted as a function of the r.f. current in arbitrary units. The sample temperature is 4.2 K. The lines are guides to the eye. (b) R.f. current source model for a stack of N intrinsic Josephson junctions. Junctions are indicated by a cross.

It is not obvious that the very different response of the five junctions to r.f. irradiation can be reconciled with a model in which the junctions are identical. We now show quantitatively, however, that this differing r.f. response can be explained by the fact that the r.f. impedance of an array of identical junctions changes as the number of junctions in the voltage state changes. The analysis method which we introduce here is formally equivalent to the method of Klushin *et al.*[15] With our technique, however, no prior knowledge of the $I_C R_N$ product of the junctions is required. (R_N is the normal-state junction resistance.) This makes it particularly suited to analysis of IJJ arrays containing many junctions, for which the measurement of R_N may be nontrivial.

We use an r.f. current-source model to determine the r.f. current flowing through the junction array [16,17]. The model, shown in figure 3 (b), includes the impedance of the environment, Z_{env}, at 3 GHz. Z_{env} models the combined impedance of the r.f cables, the antenna and the free space between the antenna and the junction array, as seen by the r.f. source. It is likely to be of order 100 Ω. We assume that all $N \approx 200$ junctions in the array have identical r.f. impedances, Z_{VS}, in the voltage state *and* identical r.f. impedances, Z_{ZV}, in the zero-voltage state. When n junctions are in the voltage state the r.f. current through the array is given by

$$i_{JJ} = i_{rf} \frac{Z_{env}}{Z_{env} + (N - n) Z_{ZV} + nZ_{VS}}, \tag{1}$$

where i_{rf} is the source r.f. current . We now define $\overline{i_{rf}}(n)$ as the normalized r.f. source current required to drive a fixed r.f. current, i_{JJ}, through the junction array when n junctions are in the voltage state:

$$\overline{i_{rf}}(n) \equiv \frac{i_{rf}(n)}{i_{rf}(0)} = \frac{Z_{env} + (N - n) Z_{ZV} + nZ_{VS}}{Z_{env} + NZ_{ZV}} \approx \frac{Z_{env} + NZ_{ZV} + nZ_{VS}}{Z_{env} + NZ_{ZV}}, \tag{2}$$

the approximation being valid when the number of junctions in the voltage state is much less than the total number of junctions in the array.
In the RSJ model for $f << f_p$, the impedance of a single junction in the zero-voltage state is inductive, with reactance $X_{LJJ} = f\, \Phi_0 \,(I_C{}^2 - I^2)^{-1/2}$. (Here I is the d.c. bias current.) At f = 3 GHz our junctions have $X_{LJJ} \sim 0.1\ \Omega$. In the voltage state we model the junctions as resistors with r.f. resistance $r_{JJ} = \partial V / \partial I$, this being of order 100 Ω. Hence

$$\overline{i_{rf}}(n) \approx \frac{Z_{env} + iNX_{LJJ} + nr_{JJ}}{Z_{env} + iNX_{LJJ}}. \tag{3}$$

This can be further simplified to give

$$\left|\overline{i_{rf}}(n)\right| \approx \frac{Z_{env} + nr_{JJ}}{\sqrt{Z_{env}^2 + N^2 X_{LJJ}^2}}, \tag{4}$$

provided that $Z_{env} + n\, r_{JJ} >> NX_{LJJ}$. Given the order of magnitude estimates for N, Z_{env}, r_{JJ} and X_{LJJ} in our experiment, this inequality only holds for $n \geq 1$. Plots of $\left|\overline{i_{rf}}(n)\right|$ for any fixed value of i_{JJ} should therefore be linear for $n \geq 1$.

In figure 4 (a) we show the dependence upon n of the normalised r.f. source current required to suppress the switching current, I_{SW}, to a constant value. Under the assumption that the junctions have identical values of I_C and f_p, the condition that the switching current is constant is equivalent to the r.f. current, i_{JJ}, through the junction array being constant. Hence equation (4) should hold, noting also that r_{JJ} is constant since the d.c. bias current is constant. The linearity of these plots for $n \geq 1$ therefore confirms our original assumption that the junctions have mutually identical impedances in the voltage state.

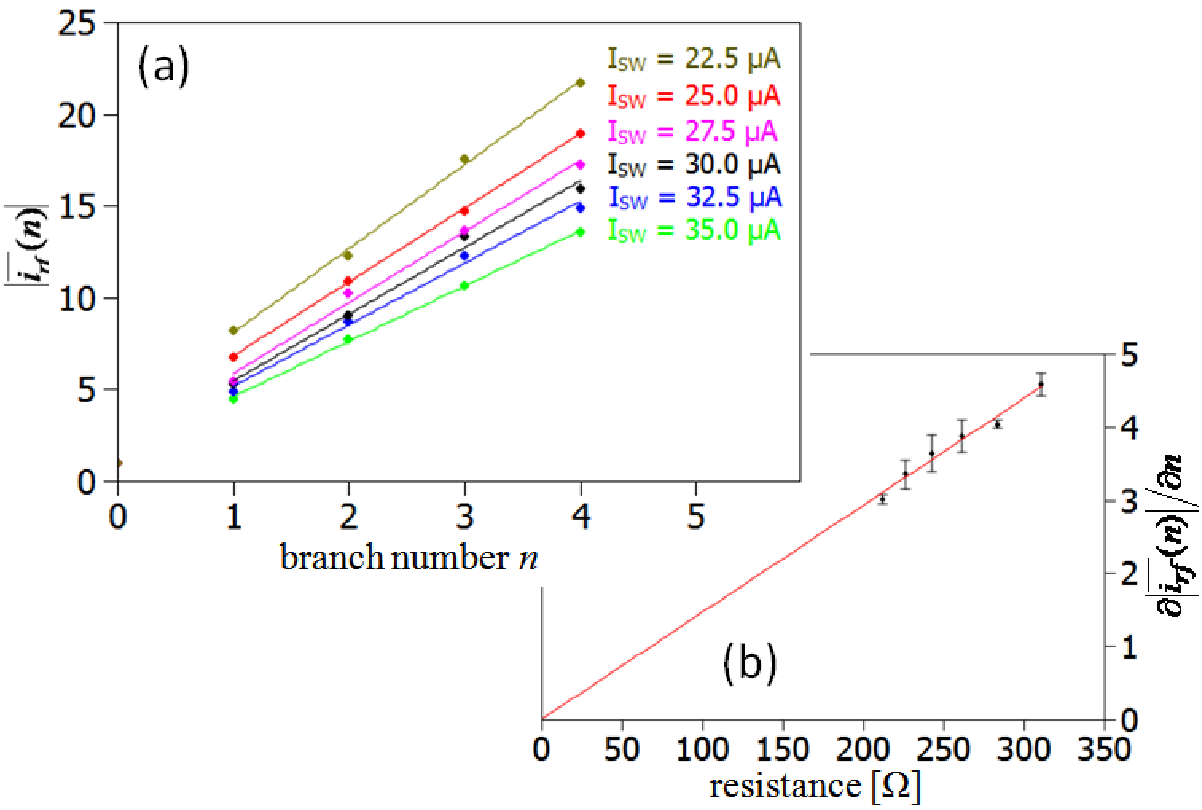

Fig. 4: (a) Branch dependence of the magnitude of the normalised r.f. source current $\left|\overline{i_{rf}}(n)\right|$ required to suppress the switching current I_{SW} to a fixed value as indicated. The lines are linear fits to the experimental data in the range n = 1 to n = 4. (b) The slope $\partial\left|\overline{i_{rf}}(n)\right|/\partial n$ of the linear fits to the plots in (a) as a function of the junction slope resistance $r_{JJ} = \partial V / \partial I$. The line shows the best linear fit being forced to pass through the origin to the data, from which Z_{env} = 65 ± 7 Ω can be extracted.

In figure 4 (b) we plot the slope, $\partial\left|\overline{i_{rf}}(n)\right|/\partial n$ of the plots in figure 4 (a) as a function of the slope resistance $r_{JJ} = \partial V / \partial I$ obtained numerically from the IVCs. As can be seen from equation (4), this plot should extrapolate through the origin and have slope equal to $(Z_{env}^2 + N^2 X_{LJJ}^2)^{-1/2}$. From figure 4 (b) we extract Z_{env} = 65 ± 7 Ω, consistent with typical r.f. line impedances.

In conclusion we have shown that, in spite of each junction in a $Bi_2Sr_2CaCu_2O_{8+\delta}$ intrinsic Josephson junction array having a different response to r.f. irradiation, the junctions have identical r.f. impedances when in the voltage state. This impedance is given by the inverse of the slope of the d.c. current-voltage characteristics. Our measurements were performed at 3 GHz but can in principle be extended into the technologically-important THz regime, this currently being limited only by experimental design. Equation (4) indicates that our technique is least susceptible to error when the junction impedance is of the same order as Z_{env}. If the junction impedance is significantly smaller than Z_{env} (as is the case for the large area intrinsic junctions which have been used in THz emission experiments [2,3]) then it may be necessary to extend the measurements to higher branch numbers and/or bias at a lower current so that the dependence of the normalised r.f. current $\overline{i_{rf}}(n)$ upon junction number *n* is measurable.

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