A system for fast time-resolved measurements of c-axis quasiparticle conductivity in intrinsic Josephson junctions of $Bi_2Sr_2CaCu_2O_{8+\delta}$

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A wide-band cryogenic amplifier measurement system for time-resolved 4-point VI-characteristic measurements on $Bi_2Sr_2CaCu_2O_{8+\delta}$ mesa structures is described. We present measurements which demonstrate the importance of self-heating on $\sim$ 50 ns time scales. Such heating is likely to have been very significant in many previously published measurements, where the reported nonlinear VI characteristics have been used to derive superconducting energy gaps.

Highly anisotropic high-temperature superconductors, such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ (2212-BSCCO), can be considered as a linear array of intrinsic Josephson junctions formed by almost insulating layers between the superconducting copper-oxide planes. [1] To investigate conduction across such junctions, many groups have published measurements on mesa structures containing typically 5–20 such junctions. [2–10] The mesas are lithographically patterned [3] on the surface of almost ideally atomically flat cleaved surfaces of single crystals of 2212-BSCCO. The aim of such experiments is to investigate intrinsic conduction across the junctions and hence deduce the magnitude and temperature dependence of the assumed d-wave superconducting gap.

In practice, one observes hysteretic multi-branched characteristics, corresponding to the expected irreversible characteristics of each junction in the measured array. In all previously published measurements, marked deviations from linearity in the resistive branches have been reported, as indeed predicted by Josephson tunnelling theory. In principle, the shape of the characteristics can be used to determine the superconducting energy gap. [11] However, in many circumstances one also observes re-entrant and even S-shaped characteristics, which cannot be described by simple theory. In the past, pulsed measurements on 200–500 ns time scales have been used in an attempt to circumvent possible problems from sample heating. [6–10]

In this letter, we describe a 4-channel cryogenic amplifier with better than 50 ns resolution (shown schematically in Fig. 1), which demonstrates the importance of heating even on sub-μs time scales. We report 4-point VI measurements on a stack of intrinsic Josephson junctions in a mesa structure of 2212-BSCCO. The mesa structure is described in more detail elsewhere. [12] We show that the characteristics and voltage at which dI/dV becomes infinite are strongly dependent on the time after the application of a pulsed current, consistent with heating. This casts serious doubt on earlier deductions of energy gaps from such measurements.

Four source-follower buffer amplifiers with high input-impedance were used. These were based on the CF739 dual-gate n-channel depletion-mode FET, which has a wide bandwidth and operates successfully at cryogenic temperatures. To monitor the output signals, the
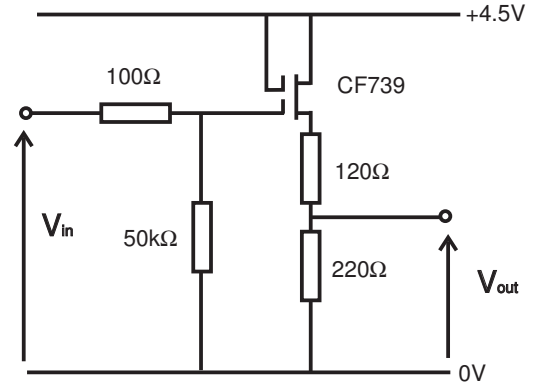

FIG. 1: Schematic of circuit for a single buffer amplifier.

amplifier-outputs were connected to a Tektronix TDS224 100 MHz 8-bit 4-channel digital storage oscilloscope via 50 Ω cryogenic coaxial lines. To retain the large-offset facility of the oscilloscope without significant loss in resolution, the amplifiers were designed to have a gain of $\sim$ 1/5. The 100 Ω resistor in series with the input eliminates high-frequency parasitic oscillations. The response of the amplifier was linear and almost temperature-independent for inputs up to 3 V. The small dc offset voltage $\sim$ 0.2 V was unimportant, since we measured differences in voltage levels before and during the application of a current pulse. The amplifiers were fabricated on two circuit boards on either side of a common earthing plate. These were situated at the low-temperature end of a continuous-flow cryostat. Short connections were made to the mesa contacts.

The inputs to the buffer amplifiers were connected to the mesa structure as illustrated schematically in the insert of Fig. 2. The voltage difference $V_4 - V_1$ across the 200 Ω series resistor monitors the current into the mesa. The voltage difference $V_2 - V_3$ corresponds to the voltage across the shaded region, which for this sample involved 30 intrinsic junctions.

Square-wave current pulses were obtained from a TTi TG1304 50 Ω output-impedance function generator connected to the sample via a 50 Ω coaxial line. An initial triangular spike of duration $\sim$ 100 ns could be added at the start of the pulse to briefly exceed the critical currents
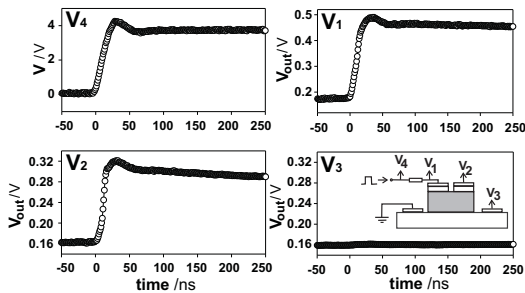
FIG. 2: Measured voltages for an applied 4 V pulse at a base temperature of 10 K. The insert shows a schematic of connections to the mesa structure, with 4-point measurements being made across the shaded region.

FIG. 3: Variation of sample current and voltage at 9 K for an applied simple square pulse of 4 V.

of the junctions in the stack so that the irreversible part of IV characteristics at low current-bias could be mapped out. However, the data we present here correspond to the characteristics above the critical currents of the individual junctions. In practice, V_4 was measured by a 10x probe at the output of the signal generator because, for large inputs, it exceeded the maximum buffer-amplifier input voltage of 3 V. This introduced a measurable time lag of 1–2 ns between V_1 and V_4, which we correct for in our analysis of data.

Measurements on short time scales can be affected by impedance mismatching, leading to unwanted reflections, as observed by Suzuki et al.. [6] We have avoided such problems by the use of a function generator matched to the input line and by terminating the coaxial output lines by 50 Ω connectors at the inputs to the oscilloscope. A particular advantage of using cryogenic amplifiers is that the wires between the sample and amplifier-inputs are short enough for time constants associated with mismatching there to have a negligible effect on measurements.

Short-time-scale measurements can also be affected by circuit/sample RC time-constants. For example, temperature-dependent sample-related rise times ∼ 300 ns are evident in several previous measurements. [9,10] We have been able to achieve circuit rise times less than ∼ 10 ns, significantly less than the rise time of the pulse generator.

Typical measured voltages are shown in Fig. 2. The finite rise time and slight overshoot in the voltage reflect the "square" pulse shape from the signal generator and are almost identical to those measured across a 50 Ω resistor connected directly to the output of the signal generator. Any changes in the initial rise time and pulse shape can therefore be associated with sample properties.

In Fig. 3, we show the current through the sample and the voltage across the sample on three different time scales after the application of a square current pulse. We note the very significant (10%) drop in voltage after only 500 ns. We identify the drop in voltage with sample heating and the associated increase in conductivity with temperature. This increase is shown in the inset of Fig. 4,
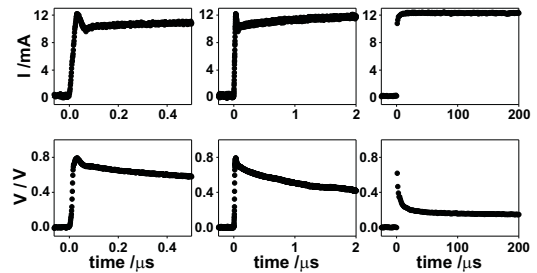
obtained from the linear term in fits to a functional form $I = AV + BV^3$ for measurements at very short times (50 ns). These measurements are in excellent agreement with earlier dc measurements of Thomas et al. [12] on the same sample, in which the mesa temperature was measured directly, allowing corrections for heating in the measured VI characteristics to be evaluated. We believe the 50 ns characteristics to be a close representation of the intrinsic sample properties.
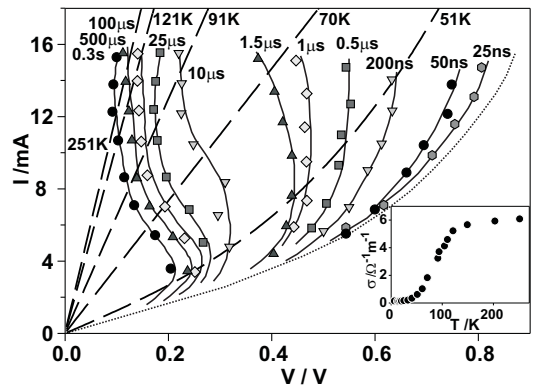

FIG. 4: Evolution of VI characteristics with time at a base temperature of 33 K. Dashed lines show fits to 50 ns VI characteristics at a number of base temperatures. Solid lines are guides to the eye. The form of the intrinsic characteristics at 33 K is suggested by the dotted line. The inset shows the temperature-variation of the low-voltage conductivity, determined by a fit of the early-time data to $I = AV + BV^3$ at each temperature.

Figure 4 illustrates a series of VI measurements at a sample base-temperature of 33 K, taken at various times after the switching-on of square current pulses of different amplitudes. At short times, the VI characteristics show little curvature but become increasingly nonlinear at higher bias. At the highest bias levels currently achievable, the slope approaches infinity only 200 ns after the start of the pulse and significant backbending is observed 1.5 μs after the start of the pulse. S-shaped VI characteristics are observed 25 μs after the start of the pulse, and the 0.3 s characteristics are indistinguishable from dc measurements. The strong time-dependence of the shape of the characteristics makes it clear that the infinite slope

and onset of the backbending feature is not an intrinsic feature associated with the gap voltage at 33 K.

We deduce the temperature at points on the heated curves by comparison with the 50 ns quasi-intrinsic characteristics at higher base temperatures. For example, for a current of 15 mA, the sample temperature rises from 33 K to above T_c in around 10 μs, and to above room temperature in about 500 μs.

Note also that the backbending feature does not correspond to the sample being heated through T_c. Neither does it correspond to any feature that might be associated with the gap at the higher temperature to which the mesa is heated. This is illustrated by the onset of infinite slope at around 0.5 V in the 500 ns data, intersecting with the relatively featureless quasi-intrinsic 51 K characteristics. At this temperature, any marked feature associated with the gap parameter clearly lies at larger voltages and larger current bias than those currently available in our measurements. Other than immediately following the application of a pulse, any identification of the energy gap with the voltage at which dI/dV becomes infinite is therefore very unsafe; such values will seriously underestimate the true gap when heating is significant.

Backbending is a consequence of significant heating and the steep increase in electrical conductivity with temperature. The S-shaped curves arise because, once the mesa is heated to a high temperature, any further rise in temperature with increasing current has only a small influence on the electrical conductivity (see inset, Fig. 4).

The problem of self-heating in the steady state in such measurements has been modelled by Krasnov et al.. [13] Indeed, when a temperature-independent thermal diffusivity D is assumed and dissipation in the contacts is neglected, it is straightforward to show that, for a mesa structure of area L^2 containing N intrinsic junctions, the temperature of the mesa will rise above the base temperature by an amount $\propto$ NL for a given voltage across individual junctions in the stack. Heating can be significantly reduced by using thinner mesa structures containing a smaller number of junctions, though potential problems of heating from contact resistances remain. For our sample, the contact resistance is comparable to that of the mesa stack.

Smaller-area junctions can also be used to reduce heating. However, the initial rate of rise in temperature is essentially a 1–D problem, since the volume of the crystal initially heated by the mesa is $\sim L^2\sqrt{Dt}$. This gives a temperature rise which is proportional to $t^{1/2}$ and to the input power density, but which is *independent* of the mesa area for a given voltage across individual junctions. Therefore, on time scales $t \ll L^2/D$, self-heating is not reduced by using smaller-area mesas. Using published data for the thermal conductivity and heat capacity, we estimate that at 4 K, $L^2/D \sim 1$ μs, while at 40 K, $L^2/D \sim 500$ μs. [14,15]

Our measurements on $(30~\mu m)^2$ devices already demonstrate the need to make measurements on < 100 ns time scales, if one wishes to measure the intrinsic characteristics at higher bias levels. It is interesting to note that, in Ref. [6], Suzuki et al. made their measurements on similar-size samples to our own. They derived characteristics from measurements made 500 ns after the application of a current pulse, using electronics with a settling time of ~ 300 ns. However, if they had derived characteristics from measurements at 800 ns (see Fig. 5 in Ref. [6]), a backbending feature at around 0.5 V would have been observed. This suggests that heating may well also have been significant in their 500 ns measurements. [16]

In summary, a system has been developed to allow measurements to be made on BSCCO multi-junction array mesa structures within 50 ns of the start of the current pulse. This enables us to monitor and largely circumvent problems of self-heating, and thereby to estimate the intrinsic superconducting tunnelling properties between the atomic planes, even when dc measurements would heat the sample to temperatures well above T_c. Our measurements demonstrate that backbending and S-shaped features can be explained by heating without invoking nonequilibrium effects. [17,18] We suggest that, in most previously reported measurements, the voltage at which backbending was first observed was almost certainly associated with self-heating and not the gap voltage.

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