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ScienceDirect
Physica C 460–462 (2007) 335–338
PHYSICA C
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Energy level quantization in a $YBa_2Cu_3O_{7-\delta}$ Josephson junction

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Available online 3 April 2007

Abstract

We have observed energy level quantization in an all high critical temperature superconductor d-wave Josephson junction. From the measurements we have also extracted the quality factor Q of the junction which is of the order of 40. These results indicate that the role of dissipation mechanisms in high temperature superconductors has to be revised, and may also have consequences for the class of solid state ''quiet'' quantum bit with longer coherence time.

1. Introduction

The microscopic origin of the ''unconventional'' properties of High critical Temperature Superconductors (HTS) still remains a big challenge in solid state physics. Despite the lack of a complete theory, however, there are a few well-established experimental facts which characterize the ground state of HTS; one of these is the unconventional d-wave symmetry of the superconducting order parameter. The two basic features of the d-wave symmetry, the ''π'' shift of the phase between orthogonal directions and the presence of nodal directions, lead to a new phenomenology which characterizes the Josephson effect. We refer to the natural existence of Josephson π junctions, to the spontaneous nucleation of half integer flux quanta (semifluxons) in frustrated loops, to the existence of an unconventional Josephson current phase relation characterized by non negligible high order harmonics. The recent advances in the nanotechnology and in the materials science applied to these materials have provided solid reliable tools to transform this huge potential into real applications. We are now at a stage we can take advantage of the new phenomenology originating from the d-wave symmetry to engineer novel quantum systems which do not have any equivalent in solid state physics [1–3]. The realization of these devices will give access to new exciting physics and applications and will provide new hints to solve the complicated puzzle of the microscopic origin of HTS superconductivity.

Among the new research topics the realization of HTS ''d-wave quiet quantum bit (qubit)'' is certainly one of most exciting. Over the past years much progress has been achieved in the field of quantum computation. A number of groups have demonstrated that it is possible to fabricate and entangle solid state qubits [4–6]. Most of these implementations have used superconducting elements; still all these structures have used Low-T_c Superconductors (LTS). At the same time several HTS based phase qubit designs have been proposed [4,5,7]. The d-wave symmetry, in fact, can be used to create a fundamental state which is naturally doubly degenerate. When compared with the low-T_c counterparts, the absence of any external bias at the operating point makes the HTS qubit protected from fluctuations of the external fields (that is why it is named ''quiet'' by inventors). Naturally double degenerate ground state offers significant advantages for quantum calculations and promises longer coherence times. However, one of the

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doi:10.1016/j.physc.2007.03.339

main arguments against HTS qubits based on systems with d-wave order parameter symmetry is the presence of low energy excitations inducing dissipation [8,9], a property which is expected to prevent the occurrence of macroscopic quantum phenomena, the key element for qubits.

In this paper, we report on our recent observation of energy level quantization in d-wave Josephson Junction (JJ), a clear signature of macroscopic quantum behavior and indicating that the dissipation in a d-wave JJ is low enough to allow the formation of the "sharp" energy levels required for a qubit.

2. Quantum dynamics of a Josephson junctions

The dynamics of a current biased JJ is well established for LTS. Within the resistively and capacitively shunted junction model [10] (Fig. 1a) the junction inductance L_J and capacitance C_J act as an anharmonic LC resonator (at zero voltage) with resonance frequency $\omega_P = (L_J C_J)^{-1/2}$. The Josephson inductance is given by $L_J = \phi_0/2\pi I_C \cos\varphi$, where I_C is the critical current, φ the phase difference across the junction and $\phi_0 = h/2e$ the superconducting flux quantum. For bias currents I close to the critical current I_C, the junction potential $U(\varphi)$ can be approximated by a cubic potential (Fig. 1b).

The phase may escape from the well either by thermal activation or by tunneling through the barrier potential, and corresponds to the junction switching from the zero voltage state to a finite voltage state. The escape is dominated by tunneling [11] at low temperature. The quantum bound states formed in the well with energy E_n are shown in Fig. 1b. Only the ground state is populated at temperatures smaller than the energy level separation. The quantum states can be observed spectroscopically by inducing a resonant transition between the ground state and excited states by applying microwaves at frequencies $\nu_{0n} = (E_n - E_0)/h$. The width of the first excited energy level is determined by the energy decay rate into the ground state,

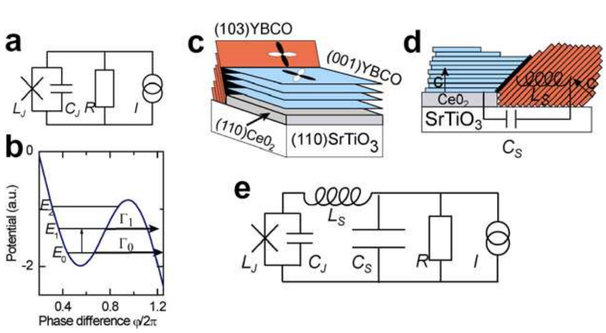

Fig. 1. (a) Circuit diagram of a current biased JJ. The damping of the JJ due to the environment and sources intrinsic to the junction is described by an ohmic resistor R. (b) Energy levels in the potential of the current biased JJ. Microwave radiation induces a transition from the ground state to the first excited state with a larger escape rate compared to the ground state. (c) Schematic of the biepitaxial JJ. (d) Cross-section of the grain boundary junction. (e) Circuit diagram of the JJ including the stray capacitance and stray inductance.

and is given by $1/\tau = \nu_{01}/Q$, where Q is the quality factor of the junction [12]. The presence of quantum bound states in low-T_c Josephson junctions has been detected in switching current experiments in the late eighties [13]. In the case of HTS d-wave Josephson systems the interest in observing energy level quantization is twofold: (1) it can give clear answers about fundamental aspects of the physics of HTS, such as dissipation mechanisms and (2) it could definitively open a new field, bringing d-wave qubits from purely theoretical designs to feasible systems.

3. Experimental results

The junctions we have used in the experiment have unique properties and have been realized by the biepitaxial technique. Fig. 1c shows a schematic representation of the grain boundary. Junctions were formed at the interface between a (1 0 3) $YBa_2Cu_3O_{7-\delta}$ (YBCO) film grown on a (1 1 0) $SrTiO_3$ (STO) substrate and a c-axis film deposited on a (1 1 0) CeO_2 seed layer. We have focused in this experiment on JJs where a lobe of the order parameter of one electrode is facing a node in the other electrode (Fig. 1c). This configuration yields a natural double degenerate ground state of interest for future qubit applications [3]. More details about the structure of the junctions and the d-wave Josephson phenomenology of the devices with this type of grain boundary are reported in [14,15]. Here we would like to point out that the biepitaxial technique allows to simultaneously controlling both the in-plane and the out-of-plane mutual orientation of the grains forming the junction. This leads, for specific configurations, to a Josephson transport with a component along the YBCO c-axis. This feature plays a crucial role: it gives highly hysteretic junctions otherwise impossible to obtain with different fabrication techniques [16].

The stray capacitance C_S of the electrodes, due to the large dielectric constant of the STO substrate at low temperature ($\varepsilon_r > 10000$), and the stray inductance L_S, due to c-axis transport in one of the electrodes (see Fig. 1d), can be taken into account by a modified RCSJ model (see Fig. 1e). Indeed the origin of a stray inductance in our system can have a twofold nature: it can be related both to the large London penetration depth λ_L in one of the electrodes due to the partial c-axis transport and to the Josephson inductance associated with the intrinsic Josephson effect in analogy with $Bi_2Sr_2CaCu_2O_{8+x}$ intrinsic junctions (Ref. [17]). The energy level separation in this simple model is given by (27) $h\nu_{01} = (h/2\pi)[(L_J + L_S)C_S]^{-1/2}$.

In our measurement scheme, by repeatedly ramping the bias current from zero at a constant rate, we have recorded the switching current probability distribution $P(I)$ which can be directly correlated to the escape rate from the minimum of the potential well $\Gamma(I)$ [18]. Microwaves at fixed frequency ν_{mw} were transmitted to the junction via a dipole antenna at a temperature below the cross-over value from the thermal to quantum regime [19]. These measurements allow us to analyze the bias current dependence of the energy level separation and determine the width of the first excited level, which gives information on the dissipation processes in the junction. When the frequency ν_{mw} of the incident radiation (or multiples of it) coincides with the bias current dependent level separation of the junction, $\nu_{01}(I) = m\nu_{mw}$, the first excited state is populated [20]. m is an integer number corresponding to a m-photon transition from the ground state to the first excited state. Fig. 2a shows the evolution of the switching current histogram as a function of the applied microwave power for the 3 photon process. At low power values (−20 dBm, measured at the room temperature termination) the occupation probability of the first excited state is negligible and the unperturbed switching histogram corresponds to the escape from the ground state. By increasing the applied power, the first excited state starts to be populated. Then the histogram becomes doubly peaked (–17 dBm and –16 dBm), corresponding to tunneling from the first excited and ground states. By further increasing the applied power the switching current distribution is again single peaked (at –14 dBm) being determined by the exponentially faster escape from the first excited level.

The escape rates derived from the switching probabilities are shown for various microwave powers (Fig. 2b). A pronounced bump appears by increasing the power, indicating resonant activation of the excited level. The enhancement of the escape rate can be obtained by subtracting the unperturbed rate from the escape rate in presence of microwaves (see Fig. 2c). The curve can be fitted by a Lorentzian, which indicates a resonant activation mechanism induced by level quantization. Moreover, the width of the enhancement curve is a measure of the quality factor Q. In the specific case of Fig. 2c, we get a Q value of the order of 40, which is comparable with the best results obtained in low-T_c junctions [13]. To further confirm that the enhancement we observe is due to resonant level activation (and is not be related to any spurious resonance in our measurement set up) we have recorded the dependence of the resonant bias current I_r, corresponding to the escape of the phase enhanced by microwaves, for various applied microwave frequencies. Such dependence has a very peculiar behavior and is similar to that observed in the low-T_c Josephson junction which can be well described by the standard RCSJ model [13] shown in Fig. 1a. For our junction the presence of a stray capacitance C_S and of a stray inductance (see Fig. 1e) strongly modifies the dependence of I_r on the applied microwave frequencies. In Fig. 2d we can clearly distinguish two branches, corresponding to the two ($m = 2$) and three ($m = 3$) photon transitions from the ground state to the first excited state. Fitting the dependence of the resonance frequency as a function of resonance current for $m = 3$ (see Fig. 2d) we extract the parameters $C_S = 1.6$ pF and $L_S = 1.7$ nH. Here we used the value of the Josephson inductance at zero bias $L_{J0} = \phi_0/2\pi I_C = 0.25$ nH which we determined from the unperturbed switching current distribution. More details about this analysis can be found in [21].

If we assume that the stray inductance has a kinetic origin we get that the extracted value of L_S agrees well with an estimate of the kinetic inductance $L_k = \mu_0\lambda_L^2 L/wt$ we can make from geometrical consideration, by assuming an electrode length $L = 10$ μm and a London penetration depth in the c-axis direction $\lambda_L \approx 6$ μm [22]. The width w of the junction is 4 μm and the thickness $t = 120$ nm. In order to further clarify the role of the London penetration depths in our devices, we have fabricated dc Superconductive Quantum Interference Devices (SQUIDs) with a negligible loop inductance and rather small geometrical area, of the order of 10 μm^2. In this case variations in the magnetic penetration length λ_L, and therefore in the penetration area A_p of the magnetic field, can be detected by a chance in the period of the SQUIDs response to the external magnetic field. In Fig. 3a and b (right panels) are shown two SQUIDs with identical geometry (made on the same chip) with Josephson junctions characterized by different Grain Boundary Angle (GBA) θ (which is identified as the angle

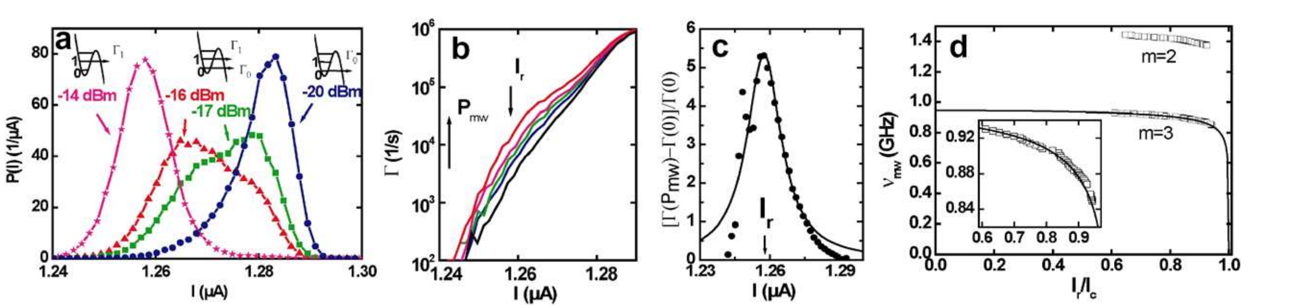

Fig. 2. Spectroscopic data. (a) Measured switching current probability $P(I)$ distribution in presence of microwaves at a frequency $\nu_{mw} = 850$ MH and $T = 15$ mK. The applied power at the room temperature termination varies from −20 to −14 dBm. (b) Escape rate extracted from the measured distributions shown in (a) for increasing microwave power from −20 to −16 dBm (see arrow). The escape rate is enhanced at the resonance current due to population of the first excited state. (c) Enhancement of the escape rate. The solid line is a fit to a Lorentzian. From the full width at half maximum we extract a width in frequency $\delta\nu = 21$ MHz, yielding a quality factor $Q = \nu_{mw}/\delta\nu \sim 40$. (d) Microwave frequency ν_{mw} versus normalized resonance current I_r/I_C. The two branches correspond to the two ($m = 2$) and three ($m = 3$) photon transitions. The solid line is a fit to the experimental data with $L_{J0} = 0.25$ nH according to the resonance condition $6\pi\nu_{mw}(I_r) = C_S^{-1/2}[L_S + \phi_0(1-(I_r/I_C)^2)^{-1/2}/2\pi I_C]^{-1/2}$. The inset shows the data for $m = 3$ and the fitting curve for a smaller range of frequencies and normalized currents.

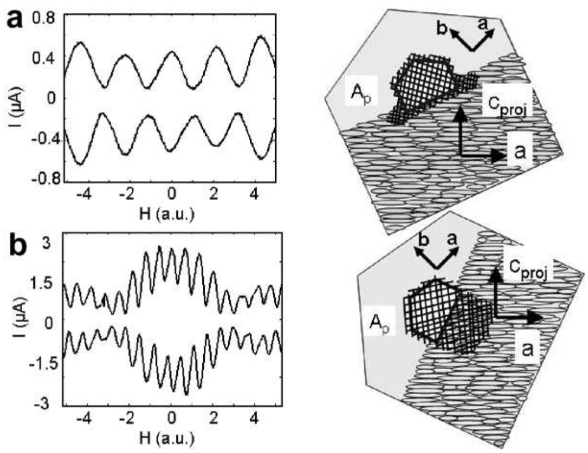

Fig. 3. (a) Right panel. Sketch of a SQUID with the two JJs characterized by a GBA of 25°. The *c*-axis YBCO electrode is gray, while the (1 0 3) electrode is represented with the usual granular structure characterized by grains elongated in the YBCO *a*-axis direction [23] (for clarity the projection of the *c*-axis in the plane of the substrate is also shown for the (1 0 3) YBCO). In the left panel it is shown the magnetic field response of the SQUID Josephson current. (b) Right panel. Sketch of a SQUID with the two JJs characterized by a GBA of 65°. Left panel: magnetic field response of the SQUID Josephson current.

between the grain boundary line and the [0 0 1] in plane direction of the substrate). The dark grid region represents the area where the magnetic field is localized. It is the sum of the geometrical area of the SQUIDs and of the area associated to the London penetration depth. In Fig. 3a (right panel) the GBA is 25°, which corresponds to a Josephson transport with a small component in the *c*-axis direction in the YBCO (1 0 3) electrode. In this case the magnetic penetration depth is almost that in *a–b* plane (of the order of 0.15 μm) and the penetration area differs only slightly from the geometrical area. In Fig. 3b (right panel) the GBA is 65° which implies a quite substantial component of the Josephson current in the *c*-axis direction of the YBCO (1 0 3) electrode.

In such a case the penetration depths is of the order of λ_L in the *c*-direction whose value can reach several microns [22]. As a direct consequence the penetration area A_p will be quite bigger than the geometrical area. These considerations are supported by the measurement of the SQUIDs critical current I_C as a function of the external applied magnetic field H. Fig. 3a and b (left panels) shows the modulation of I_C as a function of H for the two SQUIDs. The SQUIDs period ϕ_0 is proportional to $A_p * \Delta H$ (with ΔH being the variation of H in one period). We observe that ΔH is almost 3 times larger in Fig. 3a with respect to the data of Fig. 3b. As the geometry of the two SQUIDs is identical these measurements supports the idea that the different value of λ_L in the two cases have a strong influence on the magnetic penetration area A_p. This finding clearly demonstrate that the high values of λ_L in the *c*-axis direction can give rise to new features in the Josephson dynamics.

4. Conclusions

The observation of energy levels with narrow width (large Q value) is quite encouraging for the engineering of novel quantum systems based on d-wave symmetry superconductor. Our experiment has also shown that the dynamics of d-wave junctions can be strongly affected by intrinsic properties like the high values of the *c*-axis London penetration depths. This has been confirmed by studying the magnetic field response of SQUIDs with small area where the transport Josephson current has a relevant component in the *c*-axis direction.

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