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# Quantum effects in small-capacitance high temperature superconducting tunneling junctions

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We investigated the effects of single electron charging energy in high temperature superconductors. Various phenomena originating from Coulomb blockade were observable in superconducting tunnel junctions. High quality tunneling junctions were fabricated from *c*-axis oriented $NdBa_2Cu_3O_{7-\delta}/PrBa_2Cu_3O_{7-\delta}/NdBa_2Cu_3O_{7-\delta}$ thin film multilayers by the pulsed laser deposition method. The current-voltage characteristics (CVCs) show a Coulomb gap for Cooper pair tunneling when the charging energy exceeds the Josephson coupling energy. We found a regime in which the CVCs exhibit sharply defined Coulomb steps due to single electron dynamics and nonlinear tunneling rates. From the obtained Coulomb staircase, the tunneling resistance shows a quantum effect: It is modulated by the tunneling current in the form $h/4e^2R_T \sim [\sin(\pi I/I_0)^2/(\pi I/I_0)]$. We suggest an interpretation involving the quantum resistance $h/e^2$ and the competition between the charging, Josephson, and thermal energies of the system. Our results give a perspective on a solid-state quantum system with considerable interest for direct application in quantum computing.
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The investigation of single electron tunneling effects (Coulomb blockade, Bloch oscillations, and Coulomb staircase[1]) and devices with a coherent control of macroscopic quantum states such as single electron and Cooper pair boxes[2] has been so far limited to low $T_C$ metal superconductors. No clear observation of these effects in high $T_C$ superconductors has yet been reported in the literature.

The effects of charging energy in small Josephson junctions have been the subject of intensive theoretical study.[3–5] Experiments on very small junctions can provide important information about the validity of quantum mechanics on the microscopic scale.[6–8]

There are two energy scales in Josephson junctions. First, the Josephson coupling energy $E_J = hI_J/4\pi e$, which is the energy associated with the macroscopic variable $\phi$, that permits the transport of Cooper pairs between the electrodes. ($\phi$ is the phase difference between the junction electrodes, $I_J$ is the Josephson current, and $h$ is Planck's constant.) Second, the charging energy $E_C = e^2/2C$, where $C$ is the junction capacitance, associated with $Q$ (the Cooper pair charge difference between the electrodes), that tends to localize the charge carriers. The behavior of the junction is determined by the ratio of these two energies. When $E_J \gg E_C$, the junction is in the conventional Josephson regime, and the phase $\phi$ is well determined. When $E_C \gg E_J$, the phase is undetermined, so the system is subject to strong quantum fluctuations and the Coulomb blockade pins the Cooper pairs to the electrodes. The single electron tunneling processes, characterized by the tunneling conductance $1/R_T$, where eV is the relevant energy scale, should not be too strong, $1/R_T \leq 4e^2/h$. The effect of strong quasiparticle tunneling between the electrodes modifies the energy levels and above a critical strength, where a phase transition occurs, makes the single electron effects almost unobservable.[5]

$NdBa_2Cu_3O_{7-\delta}$ (NBCO) thin films behave like superconducting two-dimensional (2D) systems.[9] Superconducting to single electron tunneling transitions were observed in several experiments in *c*-axis trilayer junctions fabricated from NBCO systems. The transitions occur in junctions where the charging energy $E_C$ is much larger than the thermal energy $k_BT$. They appear either as Coulomb phenomena in the current voltage characteristics or as resonances if the frequency of an external radiation matches the average tunneling frequency of the Cooper pairs.

The $NdBa_2Cu_3O_{7-\delta}/PrBa_2Cu_3O_{7-\delta}/NdBa_2Cu_3O_{7-\delta}$ (NBCO/PBCO/NBCO) trilayers used in this study were fabricated by pulsed laser deposition (PLD). Single film deposition is described elsewhere.[9,10] The crystal structure of these trilayers was analyzed by using an x-ray diffractometer (XRD) and Rutherford backscattering spectrometer (RBS). Transmission electron microscopy (TEM) show quasihomoepitaxial growth between the NBCO/PBCO/NBCO

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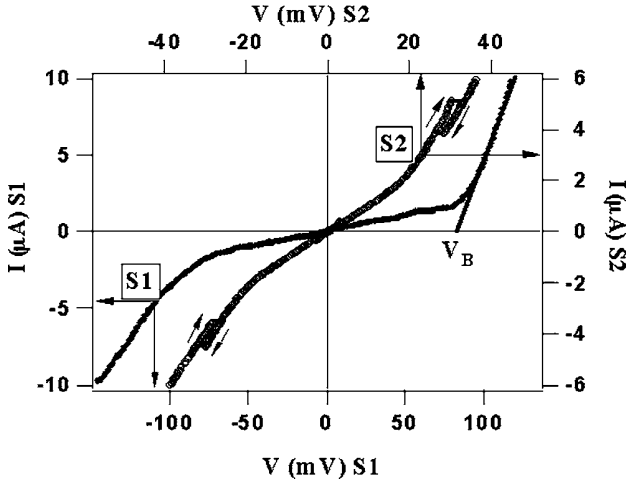


FIG. 1. *I-V* characteristics at 4.3 K for two *c*-axis NBCO/PBCO/NBCO trilayer junctions, (S1) and (S2), with different $E_C/E_J$ values of 97 and 4, correspondingly. $V_B$ is the extrapolation of the linear part of the CVC curve from voltages greater than $2\Delta/e$. The junction capacitance value is then obtained from the asymptotic voltage offset $\Delta V$, $E_C=e\Delta V/2$, and $E_C=e^2/2C$. Note the hysteretic behavior shown in S2 near 30 mV.

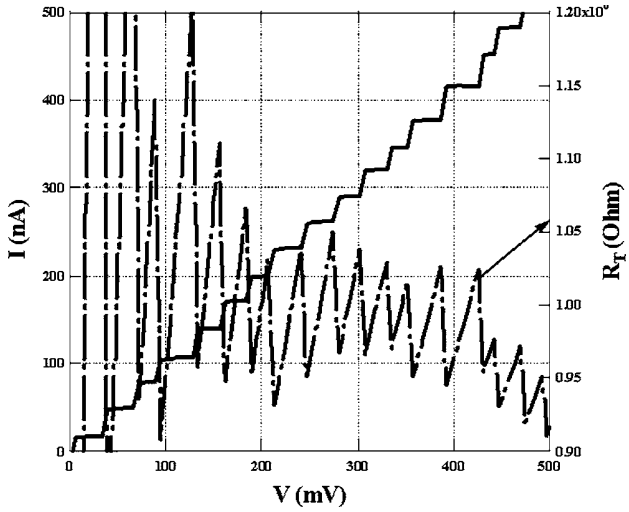


FIG. 2. Tunneling *I-V* characteristics at 4.3 K for a *c*-axis NBCO/PBCO/NBCO trilayer junction. The resistance jumps (dashed line) have a period of about 30 mV and imply a periodic Coulomb oscillation of the tunneling resistance. The tunneling resistance is represented in the right axis as shown by the arrow.

interfaces.[10] Planar tunneling junctions with widths varying from 1 to 10 $\mu$m were fabricated from these *c*-axis NBCO/PBCO/NBCO trilayers by using electron beam lithography (EBL) and standard photolithographic and ion milling techniques. We measured the current-voltage characteristics (CVCs) of NBCO/PBCO/NBCO tunnel junctions with different $E_C/E_J$ ratios. By varying $E_C/E_J$, we have swept from the conventional Josephson effect regime ($E_C \ll E_J$) well into the opposite regime, in which $E_C \gg E_J$, and the behavior is dictated by the charging energy $E_C$. This superconducting to single electron tunneling transition induced by the charging energy is shown in Fig. 1, where CVC curves are plotted for two samples with different $E_C/E_J$ ratios. The Josephson coupling energy $E_J$ is determined by the junction resistance $R_N$ and $\Delta$, the BCS gap of the superconducting electrodes: $E_J=hI_J/4\pi e=\alpha\Delta/2$,where $\alpha=R_0/R_N$ and $R_0=h/4e^2$ (where $R_0$ is the quantum resistance). For the estimation of the charging energy $E_C=e^2/2C$, we use the junction capacitance value obtained from the asymptotic voltage offset $\Delta V$, $E_C=e\Delta V/2$. $\Delta V$ was determined by careful extrapolation of the linear part of the CVC curve from voltages greater than $2\Delta/e$. The current is suppressed at voltages below the threshold value $V=e/2C$. This CVC response is suggestive of the Coulomb blockade effect, observed in tunnel junctions,[11–13] in which the charging energy is completely dominant. At low voltages, charge is trapped in the electrodes and the dynamic resistance is very large. For $V>e/2C$, however, electrons can acquire enough energy from the source to make tunneling energetically favorable. From $V_B$, we calculated the sample capacitance $C\approx 0.003$ fF.

For high temperature operation, the Coulomb energy $E_C$ should be much larger than the thermal energy $k_BT$. The quantum-mechanical behavior of the junction became more noticeable by increasing the $E_C/E_J$ ratio, and steplike features were induced in the *I-V* curves. These discrete steps or the "Coulomb staircase" represent single electron transfer events occurring at the high temperature superconductor (HTS) electrodes. This is one of the most important phenomena arising from Coulomb blockade. This Coulomb staircase arises from the incremental increase in the current at voltages where it is energetically favorable for an electron to be located in the electrodes. Figure 2 shows the CVCs with the Coulomb staircase. The peak spacing corresponding to the step width of the Coulomb staircase is between 15–30 mV. The step heights show some variation but were typically 30 nA. The conductance oscillations shown in Fig. 2 with periodicity of about 30 mV imply a periodic Coulomb oscillation of the tunneling resistance. The lower peaks of the conductance oscillation correspond to the flat regions of the current of the Coulomb staircase. The tunneling conductance is modulated by the tunneling current in the form $h/4e^2R_T \sim[\sin(\pi I/I_0)^2/(\pi I/I_0)]$, where $R_T$ is the tunneling resistance, $I$ is the tunneling current, and $I_0$ is the maximum amplitude of the tunneling current.[14]

The general shape of the staircase was reproducible, although the coupling between charge transport and the configuration of the system leads to the hysteresis effect in the CVC as shown in Fig. 3. The arrow lines refer to increasing and decreasing voltages, correspondingly. Hysteresis is generally an effect of bistability.[15] It occurs because the criterion for switching between two stable configurations depends on from which configuration the system starts. However, the source of this bistability will not be discussed in the scope of this paper.

The observed superconducting to single electron tunneling transitions were induced by localization of charge carriers and the corresponding enhancement of quantum-mechanical phase fluctuations of the superconducting order parameter. A quantitative comparison is, however, hindered at this stage by the absence of quantitative theoretical predictions for high $T_C$ superconductors, by a significant uncertainty in important parameters, and by experimental restrictions in order to measure relevant parameters of the system independently.

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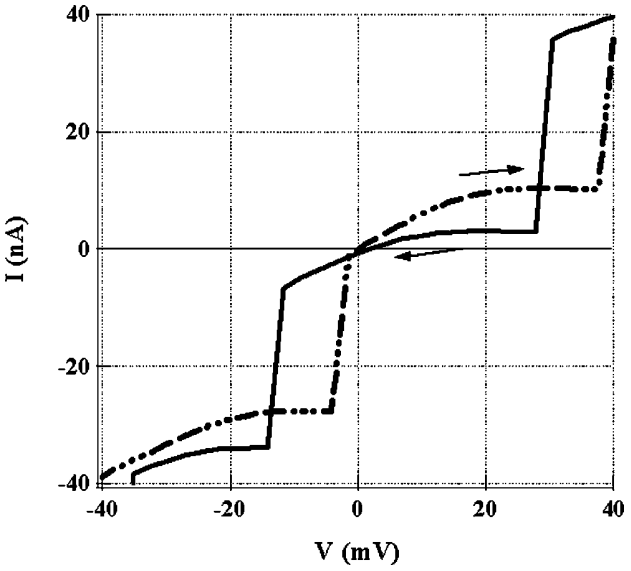


FIG. 3. Experimental bistability in the tunneling *I-V* characteristics at 4.3 K for a *c*-axis NBCO/PBCO/NBCO trilayer junction. The dashed line displays the current as the voltage is increased and the solid line displays the current as the voltage is decreased.

It is conceivable that the low junction capacitance in our tunneling junctions is due to the proximity of the PBCO layer to the NBCO base and counter electrodes. The charges are distributed inhomogeneously in the electrodes accumulating in that thin layer next to the PBCO barrier. Since the charge density is the result of a displacement of the electronic charge with respect to the ionic background, the integrated density can take any continuous value. Only the charges next to the barrier interact. Their interaction can be described by the capacitance $C$ between the NBCO electrodes. By making the assumption that the NBCO/PBCO interface layer is embedded in a "uniform" PBCO dielectric medium with the dielectric constant $\varepsilon$ ($\sim$80), this implies that the voltage spacing $\Delta V = e/2C$, where $C$ can be approximated by $C \approx 2\pi\varepsilon_0\varepsilon d$, and $d$ is the PBCO thickness. Since the uniform PBCO dielectric medium in which the NBCO/PBCO interface is embedded has a constant $\varepsilon \approx 80$, then $C$ will be consistent with the values we obtained from our experimental data.

Finally, these high $E_C/E_J$ ratio junctions prominently exhibit charging effects and quantum coherence. We consider this as the clearest observation so far of macroscopic quantum coherent effects for tunneling junctions in high $T_C$ superconductors. These results confirm the existence of Coulomb blockade phenomena in HTS. These tunneling devices allow us to study a variety of phenomena related to the quantum mechanics of mesoscopic systems and give a perspective on a solid-state quantum system with considerable interest for direct application in quantum computing.

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[1] R. Wilkins, E. Ben-Jacob, and R. C. Jaklevic, Phys. Rev. Lett. **63**, 801 (1989); E. Lebanon, A. Schiller, and F. B. Anders, Phys. Rev. B **68**, 041311 (2003), and references therein.
[2] A. Guillaume, J. F. Schneiderman, P. Delsing, H. M. Bozler, and P. M. Echternach, Phys. Rev. B **69**, 132504 (2004), and references therein.
[3] K. K. Likharev and A. B. Zorin, J. Low Temp. Phys. **59**, 347 (1985).
[4] F. Guinea and G. Schön, J. Low Temp. Phys. **69**, 219 (1987); A. Furusaki and M. Ueda, Phys. Rev. B **45**, 10576 (1992).
[5] U. Geigenmüller and G. Schön, Physica B **152**, 186 (1988).
[6] A. I. Larkin, K. K. Likharev, and Yu. N. Ovchinnikov, Physica B & C **126**, 414 (1984).
[7] H. S. J. van der Zant, W. J. Elion, L. J. Geerligs, and J. E. Mooij, Phys. Rev. B **54**, 10081 (1996), and references therein.
[8] P. Delsing, C. D. Chen, D. B. Haviland, Y. Harada, and T. Claeson, Phys. Rev. B **50**, 3959 (1994), and references therein.
[9] G. A. Alvarez, K. Hayashi, and Y. Enomoto, *Advances in Superconductivity VIII*, Proceedings of the Eighth International Symposium on Superconductivity (ISS '95), Hamamatsu, Japan, 30 October–2 November 1995 (Springer-Verlag, Tokyo, 1996), p. 1055.
[10] G. A. Alvarez, J. Wen, F. Wang, and Y. Enomoto, Jpn. J. Appl. Phys., Part 2 **35**, L1050 (1996).
[11] D. V. Averin and K. K. Likharev, J. Low Temp. Phys. **62**, 345 (1986).
[12] K. Mullen, E. Ben-Jacob, and Z. Schuss, Phys. Rev. Lett. **60**, 1097 (1988).
[13] L. J. Geerligs, V. F. Anderegg, J. Romijn, and J. E. Mooij, Phys. Rev. Lett. **65**, 377 (1990).
[14] G. A. Alvarez, I. Iguchi, X. L. Wang (unpublished).
[15] P. D. Dresselhaus, L. Ji, S. Han, J. E. Lukens, and K. K. Likharev, Phys. Rev. Lett. **72**, 3226 (1994).

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