# $YBa_2Cu_3O_{7-x}$ /Nb Josephson Junctions for Superconducting Electronics

B. Chesca, H. J. H. Smilde, H. Hilgenkamp

*Abstract*— **Josephson junctions are excellent candidates as building blocks for both quantum computation and digital circuits using low-dissipative superconducting elements. Traditionally Josephson junctions were produced at the interface between two identical low transition temperature (low-$T_c$) superconductors, with the Nb/Al-$AlO_x$/Nb technology being the most successful so far. Recently, however, a new technology has been developed that allowed fabrication of so-called hybrid Josephson junctions formed between a low-$T_c$ superconductor (Nb with $T_c$=9.2K) and a high-$T_c$ superconductor ($YBa_2Cu_3O_{7-x}$ with $T_c$=92K). Such $YBa_2Cu_3O_{7-x}$/Nb Josephson junctions have quite unique properties when compared with the traditional ones (i.e., the Nb/Al-$AlO_x$/Nb junctions) which make them very attractive for applications. Here we report on an experimental investigation of both the *dc* and the *ac* Josephson effects in such hybrid systems.**

*Index Terms*— **Josephson junctions, superconducting digital circuits.**

## I. Introduction

The Josephson effect [1] is one of the most important effects of superconductivity. In the superconducting state, electrons form bound pairs, called Cooper pairs. The Josephson effect occurs when these pairs of electrons tunnel through a thin insulating barrier placed between two superconductors, a system called Josephson junction. If no voltage is applied to a Josephson junction, a direct current - a current of Cooper pairs $J$, - flows through the junction up to a critical value $J_c$, which depends on the geometry, temperature and magnetic field. This phenomenon is known as the *dc* Josephson effect. On the other hand , if a *dc* voltage is applied to such a Josephson junction, the Cooper pairs current crossing the junction oscillates at a frequency $f$ which depends solely on the applied voltage V and fundamental constants (the electron charge $e$ and the Planck constant, $h$): $f=2eV/h$. This phenomenon is known as the *ac* Josephson effect. On this basis Josephson junctions may be seen as natural microwave generators. Conversely, if an *ac* voltage of frequency $f_a$ is applied to the junction terminals by microwave irradiation, the current of Cooper pairs tends to synchronize with this frequency (and its harmonics) and a direct voltage appears at the junction terminals. This synchronization is revealed in the current-voltage characteristics by the appearance of voltage steps at integer multiples of the value $V = (h/2e)\, f_a$. These are called Shapiro steps. The stability and precision of the voltage-frequency relation $V = (h/2e)\, f$ and its independence from external conditions (temperature, current bias, superconducting material, or Josephson junction's properties) have been tested on many occasions with an uncertainty level of up to $10^{-16}$. A Josephson junction therefore acts as a fundamentally accurate voltage-frequency converter. This is why the Josephson effect is now used for the representation of the volt.

Traditionally Josephson junctions were produced at the interface between two identical low transition temperature (low-$T_c$) superconductors, with the Nb/Al-$AlO_x$/Nb technology being the most successful so far. Recently, however, a new technology has been developed that allowed fabrication of so called hybrid Josephson junctions formed between a low-$T_c$ superconductor (Nb with $T_c$=9.2 K) and a high-$T_c$ superconductor ($YBa_2Cu_3O_{7-x}$ with $T_c$=92 K). Such $YBa_2Cu_3O_{7-x}$/Nb Josephson junctions (see Fig.1a and 1b) have quite unique properties when compared with the traditional ones (i.e., the Nb/Al-$AlO_x$/Nb junctions) which make them very attractive for applications. Indeed, the Josephson current $J$ is highly anisotropic as we change the tunneling orientation in the *ab* plane reaching its minimum for tunneling close to [110] direction and its maximum for [100] or [010] directions. This is important as it gives us the opportunity to fabricate so-called π-interferometers, a system of two Josephson junctions connected in parallel in a superconducting loop that carries an intrinsic phase shift of π. Such π-interferometers have a highly unusual critical current $I_c$ versus magnetic field $B$ characteristic with a minimum at $B = 0$. This is in high contrast to standard interferometers which have a maximum $I_c$ at $B = 0$. π-interferometers represent a practical realization of the complementary junction technology proposed for the implementation of low-dissipative, fast, digital circuits based on superconducting devices [2, 3]. They are also excellent candidates for the implementation of superconducting qubits in quantum computation [4]. Apart from their appeal for applications investigation of basic properties in such hybrid junctions is essential in a much broader perspective in condensed matter physics as we electrically connect two completely different classes of superconductors, a low-$T_c$ metallic material with a high-$T_c$, ceramic doped Mott compound. In this paper we report on an experimental investigation of both the *dc* and the *ac* Josephson effects in $YBa_2Cu_3O_{7-x}$/Nb Josephson hybrid junctions.

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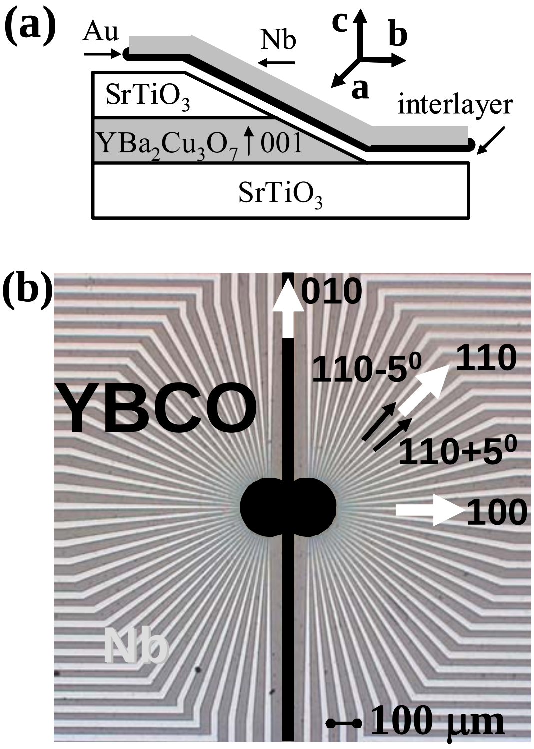


Fig. 1: Untwinned $YBa_2Cu_3O_{7-x}$/Au/Nb ramp-type junction layout. a) Schematic sideview; b) Topview photograph in the *ab* plane. The YBCO base electrode (in black) is contacted by a Au barrier (not shown) and a Nb counterelectrode (light-gray). 72 Josephson junctions 4 μm wide are patterned this way so that tunneling is tested in all 72 different directions in the *ab* plane. The arrows indicate some of those tunneling directions.

The physics of $YBa_2Cu_3O_{7-x}$/Nb Josephson junctions, is not fully understood at present. Thus, a key element, namely the knowledge of the current-phase relation (CPR) of the Josephson current remains unsettled [5]. It has been predicted [6-10] that a significant second harmonic Josephson current $J_2$ in the CPR should be observed in such junctions. $J_2$ is an important parameter, as a superconducting qubit based on $J_2$ will have an operating point intrinsically stable and protected against the environmental noise, which will reduce decoherence [11]. In this paper (a more detailed description is published elsewhere [12]) we report on an extensive experimental investigation of $J_2$. $J_2$ is expected [4-8] to be highly anisotropic as we change the tunneling orientation in the *ab* plane reaching its maximum for tunneling close to [110] direction and its minimum for [100] or [010] directions. As mentioned already, $J_1$ is known to be highly anisotropic as well, as we change the tunneling orientation in the *ab* plane. However, in sharp contrast to $J_2$, $J_1$ vanishes for tunneling close to [110] direction and reaches its maximum for [100] or [010] directions.

$J_2$ is expected [6-10] to produce a significant deviation from the standard sinusoidal CPR of the Josephson current density $J$:

$$J(\varphi)= J_1 + J_2 = Jc_1 \sin(\varphi) + Jc_2 \sin(2\varphi) \qquad (1).$$

Here $\varphi$ is the phase difference across the junction. For a purely *d*-wave order parameter as we increase θ (the angle in the *ab* plane between the normal to the junction interface and the [100] crystal axis) starting from 0, $J_2$ is expected [12] to increase monotonically up to $\theta = 45^o$ which corresponds to tunneling into the [110] direction. It then should decrease monotonically as we further increase θ from 45° to 90°, corresponding to tunneling into the [010] direction. In particular, for tunneling close to the [110] direction, where $J_1$ vanishes due to the unconventional nature of superconductivity in this material, $J_2$ will dominate the CPR.

## II. Josephson junction's response to Microwave radiation

We prepared thin film ramp-edge junctions between 170-nm untwinned $YBa_2Cu_3O_{7-x}$ and 150-nm Nb using a 30-nm Au barrier on a $SrTiO_3$ substrate (see Fig. 1a). The use of untwinned $YBa_2Cu_3O_{7-x}$ thin films is especially important because otherwise $J_2$ may be strongly suppressed due to excessive diffusive scattering [11] at the crystallographic twin boundaries. Also, $J_2$ may be averaged out for a badly defined nodal orientation in a twinned film. The junctions are fabricated on the same chip, and the angle θ with the $YBa_2Cu_3O_{7-x}$ crystal *b*-axis is varied in units of 5 degrees, so that tunneling can be probed in 360°/5° = 72 different directions in the *ab* plane (see Fig. 1b). The growth of untwinned $YBa_2Cu_3O_{7-x}$ films [13], as well as detailed order parameter studies [14], and quasiparticle tunneling [15] in these particular junctions are reported elsewhere. All 72 junctions are 4 μm wide.

To identify $J_2$ we searched for half-integer Shapiro steps. It is well known that if the CPR is pure sinusoidal ($Jc_2 = 0$ in Eq. (1)) microwave radiation of frequency $f$ will induce Shapiro steps at *integer n* multiples of the voltage $V_0$, satisfying the Josephson voltage-frequency relation $f/V_0$=0.486 GHz/μV. If $Jc_2$ is finite also *half-integer* Shapiro steps should appear at multiples of $V_0/2$ [16-18]. If half-integer Shapiro steps are not observed then the presence of a significant $J_2$ in the CPR can be ruled out. We performed a very detailed search in the entire frequency range where integer Shapiro steps could be observed, carefully examining every 10 MHz frequency interval within the 1-20 GHz region. We repeated this approach for all junctions investigated. Typical sets of current-voltage characteristics are shown in Figs.2a-2c for three junctions: [100], [110] and [110]-5°. Well-defined integer Shapiro steps in accordance with the theoretical expectations are clearly visible. We detected pronounced integer Shapiro steps up to n=21 (as in Fig.2(a)) or even higher in some cases. We also measured the amplitude of the integer Shapiro steps as a function of the microwave current amplitude. Some typical examples are shown in Figs.2(d)-2(f) for three junctions: [110], [110]±5°. We found no trace of half-integer Shapiro steps in any of the junctions, although we paid particular attention to those microwave amplitudes where the integer Shapiro steps or the $I_c$ vanishes and consequently the half-integer Shapiro steps are expected to be most pronounced. In particular, as can be inferred from Figs.2d-2f, increasing the microwave power first fully suppresses $I_c$ and thereafter the first integer Shapiro step. However, no signature of the first half-integer Shapiro step is observed. Moreover, the fact that $I_c$ is fully suppressed by microwaves (see Figs.2(d)-2(f))) is a further confirmation that $J_2$ is insignificantly small as non-zero minima are expected for $I_c$ in case $J_2$ has considerable amplitude [16-18]. Taking into account our finite resolution in detecting the Shapiro steps an upper bound on $J_2$ of about 1% from $J_1$ is found, where both $J_1$ and $J_2$ are being measured for the same crystal orientation.

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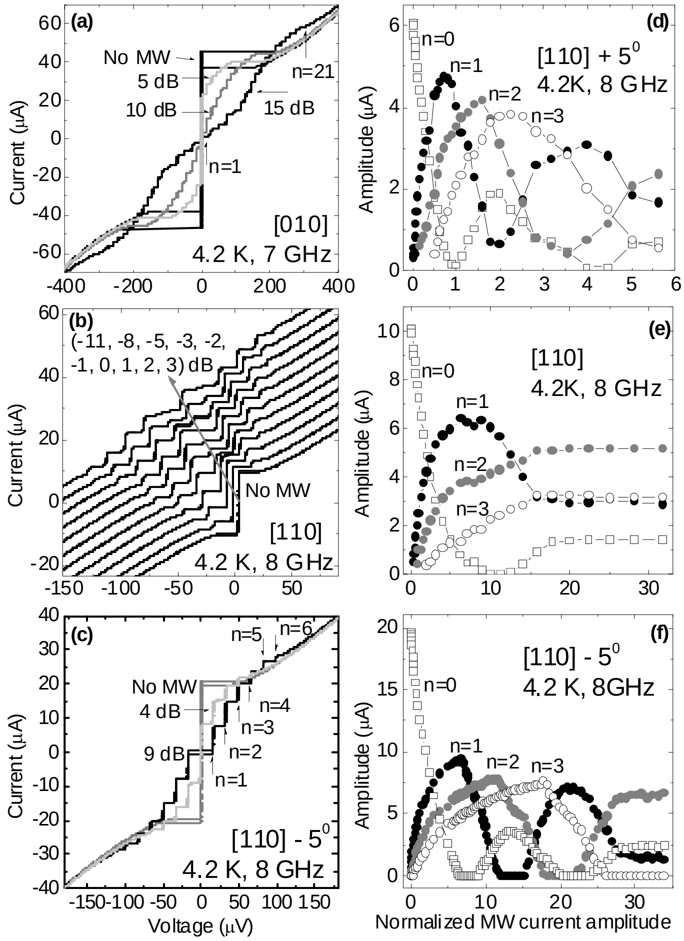


Fig.2*:* (a-c) Integer Shapiro steps (indicated by vertical arrows) at 4.2 K of [010], [110], and [110]–5°-oriented junctions at different microwave amplitudes. For clarity, the current-voltage characteristics in (b) are shifted in diagonal direction shown by the gray line. (d-f) Amplitude of the first three integer Shapiro steps and of the critical current versus the normalized microwave-current amplitude for a [110], [110]–5°, and [110]+5° junction.

## III. CONCLUSION

In summary, the microwave response in the 1-20 GHz range of $YBa_2Cu_3O_{7-x}$/Nb Josephson junctions reveals no trace of half-integer Shapiro steps on the current-voltage characteristics. That strongly suggests that the second harmonic Josephson current $J_2$ is negligible small in comparison to the first harmonic $J_1$. Consequently, $YBa_2Cu_3O_{7-x}$/Nb junctions have a purely sinusoidal current-phase relation which is essential to take into consideration for their implementation as qubits [4, 11] or π-phase shifts in digital circuits [2, 3].

## REFERENCES

[1] B. D. Josephson, *Phys. Lett.,* vol. 1, 1962, pp 251-253.

[2] T. Ortlepp, Ariando, O. Mielke, C. J. M. Verwijs, K. F. K., Foo, H. Rogalla, F. H. Uhlmann, and H. Hilgenkamp, *Science,* vol. 312, 2006, pp. 1495-1497.

[3] E. Terzioglu and M. R. Beasley, *IEEE Trans. Appl. Supercond.*, vol. 8, 1998, pp. 48.

[4] L.B. Ioffe, V. B. Geshkenbein, M. V. Feigel'man, A. L. Fauchere, and G. Blatter, *Nature*, vol. 398, 1999, pp.679-681.

[5] A. A. Golubov , M. Yu. Kupriyanov, and E. Il'ichev, *Rev. Mod. Phys.* vol. 76, 2004, pp.411-469.

[6] Y. Tanaka and S. Kashiwaya *Phys. Rev. B*, vol. 53, 1996, pp. R11957-R11960.

[7] Yu., S. Barash, S.H. Burkhardt, and D. Rainer, *Phys. Rev. Lett.*, vol. 77, 1996, pp. 4070-4073.

[8] S. Samanta and S. Datta, *Phys. Rev. B*, vol. 55, 1997, pp. R8689-R8692.

[9] Y. Tanaka and S. Kashiwaya, *Phys. Rev. B*, vol. 56, 1997, pp. 892-912.

[10] R. A. Riedel and P. F. Bagwell, *Phys. Rev. B*, vol. 57, 1998, pp. 6084-6089.

[11] M. H. S. Amin, A. Yu. Smirnov, A. M. Zagoskin, T. Lindström, S. A. Charlebois, T. Claeson, and A. Ya. Tzalenchuk, *Phys. Rev. B*, vol. 71, 2005, pp. 064516.

[12] B. Chesca, H. J. H. Smilde**,** H. Hilgenkamp, *Phys. Rev. B*, vol. 77, 2008, pp. 184510.

[13] J. M. Dekkers, G. Rijnders, S. Harkema, H. J. H. Smilde, H. Hilgenkamp, H. Rogalla, and D. H. A. Blank, *Appl. Phys. Lett.*, vol. 83, 2003, pp. 5199-5201.

[14] H. J. H. Smilde, A. A. Golubov, Ariando, G. Rijnders, J. M. Dekkers, S. Harkema, D. H. Blank, H. Rogalla, and H. Hilgenkamp, *Phys. Rev. Lett.*, vol. 95, 2005, pp. 257001.

[15] B. Chesca, D. Dönitz, T. Dahm, R. Huebener, D. Koelle, R. Kleiner, Ariando, and H. Hilgenkamp, *Phys. Rev. B*, vol. 73, 2006, pp.014529.

[16] L. E. Hasselberg, M. T. Levinsen, and M. R. Samuelsen, *J. Low Temp.Phys.*, vol. 21, 1975, pp. 567-587;

[17] K. H. Gundlach and J. Kadlec J, *Phys.Lett.*, vol. 63A, 1997, pp. 149-150;

[18] R. Kleiner, A. S. Katz, A. G. Sun, R. Summer, D. A. Gajewski, S. H. Han, S. I. Woods, E. Dantsker, B. Chen, K. Char, M. B. Maple, R. C. Dynes, and J. Clarke, *Phys.Rev.Lett.*, vol. 76, 1996, pp. 2161-2164.

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