Properties of ferromagnetic Josephson junctions for memory applications

R. Caruso,1, 2 D. Massarotti,3 A. Miano,1, 2 V.V. Bol’ginov,4, 5 A. Ben Hamida,6, 7 L.N. Kareлина,4 G. Campagnano,1 I.V. Vernik,8 F. Tafuri,1, 2 V.V. Ryazanov,4, 9 O.A. Mukhanov,8 and G.P. Pepe1, 2

1 Dipartimento di Fisica, Università di Napoli Federico II; Monte Sant’Angelo - via Cintia; I-80126 Napoli - Italy
2 CNR-SPIN, Monte S. Angelo - Via Cintia, I-80126 Napoli - Italy
3 Dipartimento di Ingegneria Elettrica e delle Tecnologie dell’Informazione, Università di Napoli Federico II, Via Claudio, I-80125 Napoli, Italy
4 Institute of Solid State Physics (ISSP RAS), Chernogolovka, Moscow Region 142432 - Russia
5 Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia
6 National University of Science and Technology MISIS, 4 Leninsky prosp., Moscow 119049 - Russia
7 Leiden Institute of Physics, Leiden University, Niels Bohrweg 2, 2333 CA Leiden - The Netherlands
8 HYPRES, Inc. - 175 Clearbrook Road, Elmsford, NY 10523 - USA
9 Faculty of Physics, National Research University Higher School of Economics, Moscow - Russia

INTRODUCTION

The use of single flux quantum (SFQ) pulses instead of the voltage levels for superconducting digital logic was introduced in 1985 [1, 2]. In 1987-1989, the first Rapid Single Flux Quantum (RSFQ) integrated circuits were developed [3, 4]. Although RSFQ logic could operate at an extremely high clock speed with good operating margins, its energy efficiency was limited by static power dissipation due to the use of bias resistors. As a result, RSFQ circuits could hardly be scalable for large scale computing applications or very low power and ultra-low temperature applications such as required for the readout/control circuits in quantum computing or cryogenic detector arrays. In order to reduce the static power dissipation, several different approaches have been developed [5, 12]. In particular, zero-static power dissipation ERSFQ logic allows the realization of circuits of increased complexity [13] and can address the energy dissipation challenges that is now facing traditional large scale computers based on conventional complementary metal-oxide semiconductor (CMOS) circuits. However, the progress in superconducting random access memories (RAM) indispensable for large scale computing applications was significantly slower. This encouraged an active research in new memory devices for the implementation of a cryogenic, dense, energy-efficient RAM compatible to energy-efficient SFQ logics [13, 22]. A successful realization of such a RAM would require not just small and low-power memory elements, but also energy- and area-efficient addressing approaches in RAM arrays. Otherwise, the RAM power and density will be determined by the read/write addressing circuits.

Here we focus on the effect of RF pulses on switching processes of low dissipation magnetic Josephson junctions (MJJs), composed by niobium electrodes and a multilayered barrier with an Al/AIOx insulating layer, a thin niobium interlayer, and a weak ferromagnetic Pd0.99Fe0.01 layer. It has been demonstrated that in such junctions it is possible to switch between two states with significantly different critical current values using magnetic field pulses. In Fig. 1 (a) and (b) we show the two different I-V curves obtained for $H = 0.6mT$, corresponding to the blue and green $I_C(H)$ curves respectively in Fig. 1 (c). If the initial state is represented in Fig. 1 (a), the memory element can be switched into the state in Fig. 1 (b) using a positive field pulse. On the rising edge of the pulse, the critical current moves along the blue curve in Fig. 1 (c). On the falling edge of the pulse, the critical current follows the green curve, and after the end of the pulse, the junction ends up in the state in Fig. 1 (a). The hysteresis of the $I_C(H)$ curves depending on the magnetic field ramp is due to the ferromagnetic barrier [14, 15] and it can be used to calculate the $M(H)$ curve shown in Fig. 1 (d). In order to read the logic state, we use a bias current between the two critical currents: when the junction is in the ‘0’ state (high critical current state, Fig. 1 (a)), there is no voltage across the junction. On the other hand, when the junction is in the ‘1’ state (low critical current state, Fig. 1 (b)), a voltage appears across the junction.

We have demonstrated that the combined application of an RF signal together with magnetic field pulses enhances the separation between critical current levels [16]. This effect is related to the damping of the coercive field of the ferromagnetic barrier caused by the excitation of the magnetic moments due to microwave signal. In this way it is possible to select the amplitude of the writing field pulse in such a way that only the section of the memory array subject to RF field can change its digital
state. This is the first step on the path of developing alternative schemes to manipulate the memory states of cryogenic RAMs, which are crucial in order to achieve higher density and efficiency.

In this work we give an electrodynamical characterization of MJJ junctions and study the effect of RF fields on switching processes as a function of different parameters such as magnetic field pulse amplitude and pulse duration.

METHODS

The samples analyzed in this work have been realized within a collaboration between Hypres Inc. and ISSP [17]. The bottom Nb-Al/AlO_x-Nb trilayer has been fabricated by Hypres using standard process to attain 4.5 kA/cm^2 critical current density [23, 24], while the Pd_{0.99}Fe_{0.01}-Nb bilayer has been fabricated by ISSP. More details on the fabrication process can be found elsewhere [17].

The measurements have been performed using a Heliox-VL evaporation cryostat equipped with an RF antenna close to the sample stage and a NbTi superconducting coil used to apply magnetic field in the plane of the junction. The sample stage is thermally anchored to the 3He pot, while the superconducting coil is thermally anchored to the 1K-pot, in order to avoid sample heating. RC filters and copper powder filters with cutoff frequencies of 1MH z and 1GHz respectively are anchored to different thermal stages, in order to ensure optimal noise reduction [25, 26]. The junction is biased with a low frequency current ramp (approximately 11Hz) using a waveform generator in series with a shunt resistance, and the voltage across the junction is measured using a battery powered amplifier.

In Fig. 2 we show a schematic representation of the measurement setup, while in the inset we focus on the memory driving signal composed by the magnetic field pulse and the RF train. The working point is set using a dc voltage signal, which is combined with a voltage pulse generated by one of the channels of the pulse generator using an adder. The output signal of the adder is then sent to a shunt resistance, so that the coil is current biased. The second channel of the pulse generator is used to drive the RF train (see inset in Fig. 2), the length is set by the length of the driving pulse, while frequency and power level of the microwaves are controlled independently using the RF generator. We use a field pulse length of 500ms, with a rise and fall time of 1ms. The length required to induce the memory switch with our setup is quite large because of the large characteristic time of the superconducting coil, which is approximately 10ms. The microwave train is centered around the center of the magnetic field pulse. Given the high I_C*R_N product, MJJs are sought to operate at much higher speed, with much shorter pulses, when properly coupled with address and read-out circuitry.

In order to measure the current level separation we define \( \Delta I \) as

\[
\Delta I = \frac{I_{\text{high}} - I_{\text{low}}}{I_{\text{high}}}
\]

(1)

where \( I_{\text{high}} \) is the critical current corresponding to ‘0’ logic state and \( I_{\text{low}} \) is the critical current corresponding to ‘1’ logic state. Both \( I_{\text{high}} \) and \( I_{\text{low}} \) are obtained from an average of at least ten I-V curves obtained in the same conditions. To measure the enhancement in current level separation we define \( N \) as
called damping factor) and \( I_C \) is the critical current. The damping factor is defined as

\[
Q = \omega_P R C
\]

where \( \omega_P = \sqrt{\frac{2eJ_c}{hC}} \) is the plasma frequency. If \( Q \gg 1 \), then a finite capacitance is associated with the dielectric barrier. As reported elsewhere \[29\], it is possible to estimate \( Q \) from the hysteresis of the I-V curves. For tunnel junctions with small, flat subgap currents in a large voltage interval, as in the case of SIS junction in Fig. 3a, this method fails to give a reliable estimation of the damping factor \( Q \). In such conditions, the method proposed is very sensitive to small variations of the hysteresis parameter, and a small uncertainty on the retrapping current results in a large uncertainty on the quality factor.

The resistance \( R \) appearing in Eq. \( 3 \) is voltage-dependent, and takes into account the non-linear resistance in the I-V curve and the external resistors in parallel with the junction itself\[29\]. In the zero voltage state, the junction is equivalent to a phase particle oscillating in one of the minima of the washboard potential with a frequency given by \( \omega_P \). The plasma frequency is typically around a few GHz. At such frequencies, the dissipation dominates the external impedance, which is typically much smaller than the junction resistance. The total impedance due to the external circuitry is usually around 100Ω \[20\]. Moreover, it is well known that in standard tunnel Nb-Al/AlO\(_x\)-Nb junctions the specific capacitance depends on the critical current density through the empirical relation\[31\]

\[
\frac{1}{C_s} = 0.2 - 0.043 \log_{10} J_c
\]  

where \( C_s \) is expressed in \( \mu F/cm^2 \) and \( J_c \) in \( A/cm^2 \). Substituting the nominal value \[23\] \( J_c = 4.5kA/cm^2 \) we obtain \( C \approx 6pF \). Using \( R \approx 100\Omega \), we obtain \( Q \approx 230 \) for the SIS junction.

The presence of a metallic PdFe barrier in the MJJ leads to a different behavior of the subgap current: at 1 mV, we observe \( I = 8\mu A \) for the SIS junction and \( I = 39\mu A \) for the MJJ. These values, together with the overall trend of the subgap current, indicate a higher dissipation in MJJ junctions when compared with standard SIS junctions, still preserving an underdamped behavior with a large quality factor. The larger dissipation and the subsequent different trend of the subgap current in MJJ allows us to use the hysteresis of the I-V curve to estimate the quality factor of the junction. This estimation gives \( Q \approx 40 \). The method we used to estimate the capacitance in SIS using Eq. \[5\] cannot be used for MJJ, due to the presence of the ferromagnetic layer and of the additional superconducting interlayer, which change the overall capacitance of the junction. We can estimate the capacitance from the damping factor \( Q \), taking into account that, due to the multilayered structure of the
where voltage is then given by the Planck constant. The ratio between frequency and normal state resistance, Eq. 4 is no longer the lead impedance but the junction barrier with a metallic layer, the resistance appearing in using 7 as a function of frequency. Green diamonds are measured values, dark red line represents the expected values calculated using 7.

In Fig. 3b we show the characteristic in presence of an external RF field is a well known Ambegaokar-Baratoff formula, while the experimental data for MJJ are in agreement with the model for SIS junctions in literature, with a tunnel-like behavior at low temperature and a pronounced proximity effect tail at higher temperatures.

**Shapiro steps**

The appearance of current steps in the I-V characteristic in presence of an external RF field is a well known consequence of the second Josephson equation. The voltage steps appear at

$$V_n = \frac{nh}{2e}$$

where $n$ is an integer, $e$ is the electron charge and $h$ is the Planck constant. The ratio between frequency and voltage is then given by

$$\frac{\nu}{V} = 483 \text{ MHz/} \mu \text{V}$$

We measured such steps for different frequencies of applied microwaves, for a MJJ with 18nm thick PdFe at 4.2K. In Fig. 4 we show I-V curves for the same two thick PdFe at 3.88GHz, as shown in Fig. 5 (c). It has been shown that this behavior can be explained considering the magnetization curve of the ferromagnetic barrier, obtained using Josephson magnetometry in Fig. 5 (a). For small field pulse amplitudes $M(H)$ curve is almost linear, and so there is no difference between high and low critical current levels within the error bars, and the application of an external RF field does not change it significantly. At large pulse amplitudes, the ferromagnet is close to its saturation, and so the influence of external RF fields is negligible. Intermediate fields correspond to an intermediate region of $M(H)$ curve, and so here the effect of microwaves is most significant. This results in an optimal working point to observe the microwave effect on MJJs, depending on the $M(H)$ curve of the sample. For the measurement presented in Fig. 5 and 6 the optimal field amplitude is 3.9G.
different time duration: 50ms, 150ms and 400ms. As reported in section II, the length of the field pulses is set by our measurement setup rather than the intrinsic switching time of the MJJ. In Fig. 6 (b) we report the current levels obtained for different power level values with a time duration of the RF pulse set to 250ms. This supports our previous conclusions[16] on the dependence of the RF effect from the energy transferred to the junction.

In particular, we identified the optimal working point to be used to test alternative addressing schemes for magnetic memories based on Josephson junctions using more appropriate circuits, such as coplanar waveguides.

CONCLUSION

We characterized for the first time magnetic Josephson junctions down to 0.3K, and determined the electrodynamical parameters of the junction, which is an important step towards the integration of these devices in complex circuits. We report measurements of ac Josephson effect in presence of microwaves that allow us to identify the optimal microwave frequencies to observe the current level separation enhancement in our setup. We also present measurements supporting our previous conclusions on the effect of RF fields on memory switching processes. We have also shown that the perturbative effect of microwaves becomes important for large $M$, and thus it is observed in particular on the low critical current states of MJJs. These results play an important role for future implementation of RF-based addressing schemes for MJJs and potentially lead to higher hardware-, area-, and energy-efficient cryogenic memory solutions.

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