Pulse-induced switches in a Josephson tunnel stacked device

G. P. Pepe, G. Peluso, M. Valentino, and A. Barone  
I.N.F.M.-Dipartimento Scienze Fisiche, Università di Napoli Federico II, Naples, Italy  
L. Parlato  
Facoltà di Ingegneria, Seconda Università degli Studi di Napoli, Aversa (CE), Italy  
E. Esposito, C. Granata, and M. Russo  
Istituto di Cibernetica del CNR, I-80072 Arco Felice, Naples, Italy  
C. De Leo  
Dipartimento di Energetica, Università dell’Aquila, Roio Poggio I-67040 L’Aquila, Italy  
G. Rotoli  
Dipartimento di Energetica, Università dell’Aquila, Roio Poggio I-67040 L’Aquila, Italy and I.N.F.M.-UdR, Università dell’Aquila, Italy  

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Pulse-activated transitions from the metastable to the running state and vice versa have been observed in a stacked double tunnel Nb-based Josephson system. Experimental results are compared with numerical simulations based on the Sine–Gordon model of the stacked junctions by injecting pulses with variable amplitude in one of the junctions of the stack, and observing the voltage response of the other junction. Both experimental and numerical results show the possibility to induce both direct and back-switching transitions from the metastable to the running state simply by changing the amplitude of the electronic pulses injected across the stack device. © 2001 American Institute of Physics. [DOI: 10.1063/1.1402652]

A Josephson junction biased by a fixed external current can be considered as a prototype of a macroscopic multistable system. Besides the effects due to fluctuations and the fundamental tests of quantum mechanics, the study of the escape from the zero-voltage state could deserve exciting aspects for basic physics not only in view of device applications but also for physical effects involving nonequilibrium dynamical states. Double tunnel junction configurations have been widely used both for nonequilibrium fundamental experiments and for physical effects involving nonequilibrium escape from the zero-voltage state. We have studied the passage from the Josephson mode to the dissipative state produced by injected electronic pulses, and also the possibility these devices offer of resetting under suitable conditions for injected electronic pulses. The experimental results have been checked by a numerical approach based on the perturbed Sine–Gordon equation (PSGE) for each junction in the stack. A pulsed configuration is now used in a stacked system to investigate the properties of the Josephson current and its lifetime in a current biased junction mode.

Stacked tunnel JJs have been fabricated by following a process developed for high-quality three-terminal superconducting electronics. The substrate used was a 3″ crystalline-Si wafer held at room temperature during depositions. The whole pentalayer structure, i.e., Nb–Al_{2}O_{3}–Nb/Al–Al_{2}O_{3}–Nb, was deposited by dc-magnetron sputtering in an UHV system, without breaking the vacuum, \( P < 3.0 \times 10^{-8} \) Torr. Both tunneling barriers were formed by thermal oxidation of the Al films. The final structure consisted of Nb(150 nm)–Al(10 nm)–Al_{2}O_{3}–Nb(40 nm)/Al(20 nm)–Al_{2}O_{3}–Nb(40 nm). After the pentalayer deposition, the photosresist was removed by a lift-off process, and hence, the geometry of the bottom electrode was obtained. By dry- and chemical-etching processes, the top Nb film, the thin Al_{2}O_{3} oxide and the Al film were removed in sequence from the top with the geometry of the top JJ. An anodization oxide produced the isolation of the bottom junction and also its area, with the exception of a small hole for contacting the intermediate electrode. Afterward, SiO_{2} bridges were deposited by thermal evaporation in order to have a further isolation for the Nb (350 nm) of both the intermediate and the top electrodes. Finally, the intermediate Nb film and the bottom oxide barrier outside the junction area were removed by a reactive ion etching process. The final sketch of the realized stacked junction is shown in Fig. 1.

The samples were characterized in a ¹²⁷He cryostat with a local \( \mu \)-metal shielding. The main results are summarized in Table I. The ratio between the static tunnel resistance at V...
In order to model the double tunnel junction system, we describe it as a stack of two long junctions using the theory developed in recent years for stacked junctions. Coupling between stacked junctions depends on the second spatial derivative of the phase. In the following, we model the junctions in the stack as long junctions. This allows spatial variation of the phases, and so of magnetic fields and currents. For the sake of simplicity, we assume that injection and bias currents have an equal well-defined direction so the spatial variations take place only in one of the spatial dimensions of the junction, avoiding the use of a more complex two-dimensional description. In normalized units the PSGEs for injector \( \psi \) and detector \( \varphi \) are

\[
\epsilon \partial_{xx} \varphi - \partial_{xx} \psi + \partial_x \psi + \alpha \partial_x \psi + \sin \psi + \gamma_p(x,t) + \gamma_N(x,t) = 0,
\]

\[
\epsilon \partial_{xx} \varphi - \partial_{xx} \varphi + \partial_x \varphi + \alpha \partial_x \varphi + \sin \varphi + \gamma_p + \gamma_N(x,t) = 0,
\]

where \( \epsilon \) is the stack coupling, \( \alpha \) the loss parameter, and \( \gamma_N \) the constant detector bias. We note that the injector junction is not biased, but the function \( \gamma_p(x,t) \) represents the effect of pulses. The function \( \gamma_p(x,t) \) is chosen linear in space and in the form of a triangular pulse train in time, i.e.,
The simulations show that a moderate increase in temperature has the effect of smearing the set on of the flip-flop state in amplitude. Moreover, the same transition from no switches to the fully developed flip-flop state is obtained also sweeping the bias current at a fixed pulse amplitude. These properties are very reminiscent of thermal escape from Josephson current in small or long junctions. So, an interesting hypothesis can be stated in the case of direct switches from Josephson to resistive state: pulses induce in the detector junction a pulse-assisted escape from the washboard potential. Pulses increase the energy of the Josephson oscillations causing escape toward the resistive state. As in the normal thermal escape, the transition is smeared by noise. The same idea can be applied also to the back-switching transition. We think that the return current phenomenon is important in order to determine the reset to the zero-voltage state, but the influence of heating and self-induced fields make the analysis much more difficult.

In conclusion, we presented measurements of pulse-activated transitions from the metastable to the running state and vice versa in a stacked double tunnel Nb-based Josephson system. The results have been compared with numerical simulations of the PSGE model applied to a stacked system in which the pulse pumping has been modeled as an extra current source with suitable time characteristics. Besides the interesting physical aspects concerning the study of both direct and back-switching pulse-activated transitions, the device has great potentialities for the development of flip-flop-type logic devices, and front-end electronics for nuclear-integrated Josephson detectors.

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\[ \gamma_p(x,t) = \begin{cases} 2\Gamma \left( \frac{x}{l} \right) \left( \frac{t}{T} \right) & \text{for } 0 \leq t \leq \frac{T}{2} \\ 2\Gamma \left( \frac{x}{l} \right) \left( 1 - \frac{t}{T} \right) & \text{for } \frac{T}{2} \leq t \leq T \\ 0 & \text{for } T \leq t \leq T_p, \end{cases} \]

where \( T \) is the pulse length, \( l \) the normalized junction length, and \( T_p \) the time interval between pulses. This choice implies that the pulse is localized mainly on one side of the stack. The peak value \( \Gamma \) is the maximum value of current pulse in the injector junction, its average value being \( 1/4 \) of this. We choose \( l = 1 \) and \( \alpha = 0.15 \) for both junctions (no variation of losses was introduced). The term \( \gamma_p(x,t) \) is a Gaussian noise at 4.2 K, modeled as in Ref. 11. We take \( \epsilon = -0.85 \) for the stack coupling; the detector is biased at \( \gamma = 0.2 \), which is sufficient to exclude any effect of thermal return current.

The results are reported in Fig. 3. From (a) to (c) the plots show the spatial average voltages in both junctions. A train of pulses of normalized time length \( T \) equal to 100 was applied in the injector junction with peak amplitudes slightly increasing from \( \Gamma \) equal to 20.4 (a) to 21.0 (c). The voltage pulse response of the injector junction is shown as a full square line in Fig. 3. The pulse response of the detector junction is shown with empty circles. The flip-flop state progressively sets on with the increase of the pulse amplitude, in agreement with the experiments. Similar results can be obtained indifferently also with different values of the stack coupling \( \epsilon \) even if at different pulse amplitudes and/or pulse spatial dependence (e.g., using a quadratic rather than linear pulse, no qualitative effect). Changes of the pulse length have no effect since the detector junction always responds on the pulse trailing edge.

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