Pulse-induced switches in a Josephson tunnel stacked device

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(Received 11 May 2001; accepted for publication 24 July 2001)

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[1] and the fundamental tests of quantum mechanics,[2] 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[3] and several transistor-like superconducting devices.[4,5] They offer the possibility of changing directly the electronic distribution function of the intermediate electrode by combining the quasiparticle injection, the phonon relaxation, and the Cooper pair breaking.

In this letter, we present both experimental and numerical results concerning the behavior of a current biased Josephson Junction (JJ) under the influence of an electronic pulse injected from a second JJ forming a double tunnel junction stacked device. From a nonequilibrium point of view, one junction is used to break Cooper pairs through the injection of quasiparticles into the middle common film; the second junction, independently biased at a value lower than the critical current, senses the effects due to a change in the electron distribution function, switching thereby to the finite-voltage state. We have studied the passage from the Josephson ($V=0$) 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.[6] The substrate used was a 3″ crystalline-Si wafer held at room temperature during depositions. The whole pentalayer structure, i.e., Nb–Al_xO_y–Nb/Al–Al_xO_y–Nb, was deposited by dc-magnetron sputtering in an UHV system, without breaking the vacuum, $P<3.0\times10^{-8}$ 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_xO_y–Nb(40 nm)/Al(20 nm)–Al_xO_y–Nb(40 nm). After the pentalayer deposition, the photoresist 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_xO_y 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_x 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 ^{4}He cryostat with a local μ-metal shielding. The main results are summarized in Table I. The ratio between the static tunnel resistance at V

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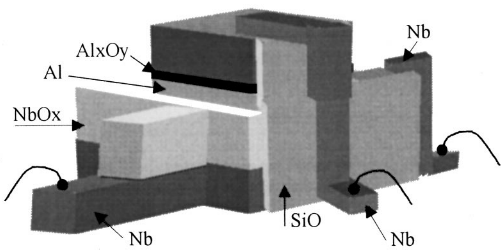

FIG. 1. Sketch of a stacked tunnel device with the indication of different layers and electrical contacts.

$=1$ mV, R_S, and the normal tunneling resistance, R_{NN}, are reported together with sum-gap voltage V_g, its width ΔV_g, the measured current jump at V_g, (see ΔI_g), and the critical current I_c. All data were recorded at $T=4.2$ K.

The Josephson penetration depth λ_J was estimated to be 70 μm, thus implying a ratio $L/\lambda_J \approx 1.4$ for a Josephson current density $J_c = 80$ A/cm^2 and $L = 100$ μm. The junction capacitance was about 1 nF.

The bottom junction was used as an injector of current pulses, whose effect was observed across the top junction (detector). The injected pulses had rise times of 2 ns, 600 μs of duration, and delay time 20 ms. They were supplied by a conventional pulse generator (EG&G 480). Each pulse was split and sent simultaneously to both the injector junction and to a digital oscilloscope (Le Croy 9361, 300 MHz) for triggering the wave form acquisition. With the detector biased at $I < I_c$, the output voltage across the detector was measured by a standard PAR 5113 preamplifier. In Fig. 2 we report the output detector voltage for different injection pulse amplitudes. Apart from some reflections in the signal due to a not completely matched injection line, a clear correlation between injected pulses and the detector voltage is present. In particular, a change of the detector voltage from the state $V=0$ to the quasiparticle branch of the $I-V$ curve, and vice versa is observed [see Figs. 2(a)–2(c)]. This behavior, observed also in single-shot measurements cannot be ascribed to the specific loading of the detector junction (the load line remains the same during the switching measurements). For larger amplitudes no back switching is observed, and the detector junction still remains on the dissipative state at any pulse across the injector.

For amplitudes within a suitable range the device has a *flip-flop* type logic characteristic, i.e., it commutes for each pulse across the injector. The possibility to control the voltage state of a JJ by pulse injection through a second junction can have many potential applications ranging from nuclear-integrated superconductive detectors[7] to several logic devices.

In order to model the double tunnel junction system, we

TABLE I. Relevant $I-V$ data.

	Top JJ	Bottom JJ
Area (μm^2)	100×100	108×125
V_g(mV)	2.54	2.70
ΔV_g(mV)	0.36	0.20
R_s(at 1 mV)/R_{NN}	20.0	36.8
ΔI_g(mA)	11.8	13
I_c(mA)	7.0	9.0

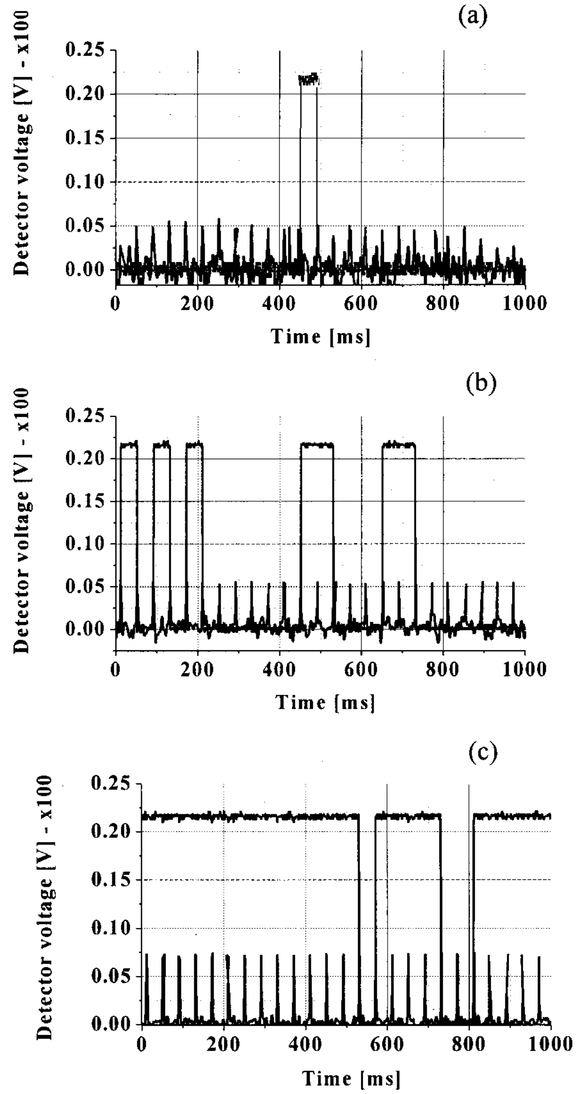

FIG. 2. Detector voltage as a function of injected electronic pulses across the coupled junction. The scale is referred to the detector voltage, while pulses are reported in arbitrary units.

describe it as a stack of two long junctions using the theory developed in recent years for stacked junctions.[8–10] 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 ψ and detector φ are

$$\epsilon\partial_{xx}\varphi - \partial_{xx}\psi + \partial_{tt}\psi + \alpha\partial_t\psi + \sin\psi + \gamma_P(x,t) + \gamma_N(x,t) = 0,$$

$$\epsilon\partial_{xx}\psi - \partial_{xx}\varphi + \partial_{tt}\varphi + \alpha\partial_t\varphi + \sin\varphi + \gamma_B + \gamma_N(x,t) = 0,$$

where ϵ is the stack coupling, α the loss parameter, and γ_B 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.,

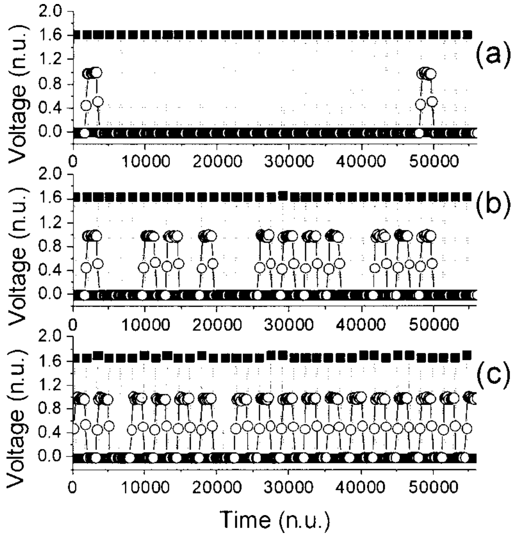

FIG. 3. Simulated flip-flop transition of two junction stacks vs the pulse amplitude: (a) $\Gamma=20.4$; (b) $\Gamma=20.6$; and (c) $\Gamma=21.0$. The dotted curves with black squares refer to the injector junction and the full curves with empty circles to the detector junction. Time and voltage are normalized to $1/\omega_J$ and $\omega_J\Phi_0$, respectively.

$$\gamma_P(x,t)=\begin{cases} 2\Gamma\left(\frac{x}{l}\right)\left(\frac{t}{T}\right) & \text{for } 0\leqslant t\leqslant \frac{T}{2} \\ 2\Gamma\left(\frac{x}{l}\right)\left(1-\frac{t}{T}\right) & \text{for } \frac{T}{2}\leqslant t\leqslant T \\ 0 & \text{for } T\leqslant t\leqslant T_p, \end{cases}$$

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 Γ 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 $\gamma_N(x,t)$ 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 Γ 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 ϵ even if at different pulse amplitudes and/or pulse spatial dependence (e.g., using a quadratic rather than linear pulse, has no qualitative effect). Changes of the pulse length have no effect since the detector junction always responds on the pulse trailing edge.

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.[11,12] 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[13] 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.

The authors are grateful to G. Filatrella for useful discussions on the effects of thermal noise. This work is supported by the I-MURST in the framework of the COFIN2000 Program ''Dynamics and Thermodynamics of Vortex Structures in Superconducting Tunneling.''

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