



ELSEVIER

Physica E 18 (2003) 15–16

---



---

**PHYSICA** E
 

---



---

www.elsevier.com/locate/physce

# Bloch oscillating transistor—a new mesoscopic amplifier

J. Delahaye<sup>a,1</sup>, J. Hassel<sup>b</sup>, R. Lindell<sup>a</sup>, M. Sillanpää<sup>a</sup>, M. Paalanen<sup>a</sup>,  
H. Seppä<sup>b</sup>, P. Hakonen<sup>a,\*</sup>

<sup>a</sup>Low Temperature Laboratory, Helsinki University of Technology, P.O. Box 2200, FIN-02150 HUT, Helsinki, Finland

<sup>b</sup>VTT Information Technology, Microsensing, P.O. Box 1207, FIN-02044 VTT, Finland

---

## Abstract

Bloch oscillating transistor (BOT) is a novel, three-terminal Josephson junction device. Its operating principle utilizes the fact that Zener tunneling up to a higher band will lead to a blockade of coherent Cooper-pair tunneling, Bloch oscillation, in a suitably biased Josephson junction. The Bloch oscillation is resumed only after the junction has relaxed to the lowest band by quasiparticle tunneling. In this paper we present a simple model for the operation of the BOT and calculate its gain in terms of the interband transition rates.

© 2003 Elsevier Science B.V. All rights reserved.

*Keywords:* Mesoscopic superconductivity; Quantum amplifier; Josephson junction; Bloch oscillation

---

Large-phase fluctuations are inherent to mesoscopic Josephson junctions owing to the conjugate nature of phase and charge (see, e.g., Ref. [1]). When the phase fluctuations are not damped by the real part of the environmental impedance  $Z_{\text{env}}$ , no true supercurrent exists in the junction ( $\text{Re}\{Z_{\text{env}}\} > R_Q = h/4e^2$ ). This Coulomb blockade of supercurrent has been observed in several experiments [2–4], in good agreement with the band model of Josephson junctions [5,6].

By taking advantage of the Coulomb blockade of the supercurrent and slow interband transition rates at low temperatures, a novel type of a quantum amplifier has been put forth [7]. This device, called the Bloch oscillating transistor (BOT), is based on controlled switching between the supercurrent (Bloch oscillating) state on the lowest band and the Coulomb-blockaded state on the second lowest band. At low  $T$  when dissipation is small, the relaxation from the upper level can be controlled by external quasiparticle current. Hence, the device is a quasiparticle to Cooper pair converter where the gain is determined by how many Cooper pairs are triggered by one quasiparticle.

The BOT circuit consists of a Josephson junction (JJ), a normal tunnel junction (NIN), and a large, small-capacitance resistance  $R_S$ , as depicted in the inset of Fig. 1. In order to have a current  $I$  flowing in the JJ, the biasing voltage has to satisfy  $V > (dE^{(1)}/dQ)_{\text{max}}$ , the maximum derivative of the lowest energy band (1) with respect to charge  $Q$ . The junction will evolve along the lowest level and the frequency of Bloch oscillations is given by  $f_{\text{Bloch}} = I/2e$ . When  $I$  increases, the probability to cross the band gap by Zener tunneling grows. By selecting the ratio of  $E_J/E_C$  and the current  $I$  suitably, one can tune the situation so that the state of the junction will tunnel into the upper band after  $\langle N \rangle$  Bloch oscillations on the average.

If  $V < (dE^{(2)}/dQ)_{\text{max}}$ , the maximum slope of the band  $n = 2$ , then the Josephson junction will become Coulomb blockaded on the upper band after Zener tunneling. In the absence of dissipation, the junction will not relax and it will stay Coulomb blockaded on the second band. Relaxation can be induced by quasiparticle tunneling, after which the junction will resume the sequence of Bloch oscillations. In this way, a small current of injected quasiparticles results into a  $2\langle N \rangle$ -fold amplified current of Cooper pairs. The principal cycle of the BOT is illustrated in Fig. 1 on the time axis.

Relaxation is also induced by charge fluctuations due to Johnson–Nyquist noise of  $R_S$ . In order to cut down the effect

---

\* Corresponding author. Fax: +358-9-4512969.

E-mail address: [pertti.hakonen@hut.fi](mailto:pertti.hakonen@hut.fi) (P. Hakonen).

<sup>1</sup> Also for correspondence.

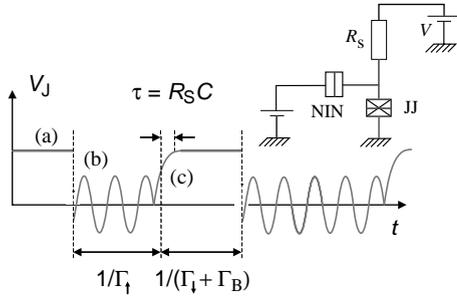


Fig. 1. Time evolution of the voltage over the JJ: (a) the junction is initially on the second band in a state of Coulomb blockade; (b) a quasiparticle tunneling event brings the junction to the lowest band where it performs Bloch oscillations; and (c) Zener tunneling stops the coherent oscillations and the junction returns to state (a). The inset displays the BOT circuit schematically.

of these fluctuations, the impedance of the environment must satisfy the condition  $R_S \gg R_Q$ . The transition rates between the two lowest levels have been calculated theoretically by Golubev and Zaikin [8]. The relaxation rate downwards can be estimated using a Gaussian distribution for the charge fluctuations, which yields

$$\Gamma_{\downarrow} = \frac{v_z}{\tau \sqrt{2\pi \langle \delta q^2 / e^2 \rangle}} \exp \left\{ -\frac{(v-1)^2}{2 \langle \delta q^2 / e^2 \rangle} \right\}, \quad (1)$$

where  $v = V/(e/C)$ ,  $\tau = R_S C$ ,  $v_z = (\pi^2/8)(E_J/E_C)^2 (R_S/R_Q)$ , and the mean-square amplitude of charge fluctuations is given by  $\langle \delta q^2 \rangle$ . The upward transition rate is given by

$$\Gamma_{\uparrow} = \frac{v}{2\tau} \exp \left\{ -\frac{v_z}{v-1} \left[ 1 + \frac{\langle \delta q^2 / e^2 \rangle}{(v-1)^2} \right] \right\}. \quad (2)$$

Eqs. (1) and (2) are based on perturbation theory and, therefore, our analysis here is valid only when  $E_J/E_C \ll 1$ .

In our model, we combine the relaxation rate  $\Gamma_B$  due to the base current to the downward transition rate. Assuming that  $\tau$  can be neglected and that the base current flows only when the JJ is Coulomb blocked, we may write for the current gain ( $V > e/C$ )

$$\beta = \frac{V}{eR_S} \frac{1}{\Gamma_{\uparrow} + \Gamma_{\downarrow}}. \quad (3)$$

Thus, the maximum gain  $\beta_{\max}$  corresponds to the minimum of  $\Gamma_{\uparrow} + \Gamma_{\downarrow}$ . The gain calculated using Eq. (3) at three different values of  $E_J/E_C$  is depicted in Fig. 2.  $\beta_{\max}$  grows strongly

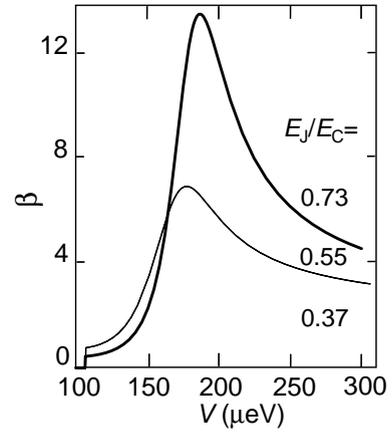


Fig. 2. Current gain  $\beta$  according to Eq. (3) for three ratios of  $E_J/E_C$ . The parameters employed in the calculation were  $E_C = 53 \mu\text{eV}$  ( $C = 1.5 \text{ fF}$ ),  $R_S = 55 \text{ k}\Omega$ , and  $T = 80 \text{ mK}$ .

with increasing  $E_J/E_C$ , together with the optimum biasing voltage. At large values of  $E_J/E_C$ , the gain will eventually go down, because the widths of the bands become small and thermal fluctuations do randomize the operation. Unfortunately, it is difficult to include this effect quantitatively into the present model.

It is a pleasure to thank Andrei Zaikin for illuminating discussions. This work was supported by the Academy of Finland and by the Large Scale Installation Program ULTI-3 of the European Union.

## References

- [1] G.L. Ingold, Yu.V. Nazarov, in: H. Grabert, M. Devoret (Eds.), *Single Charge Tunneling*, Plenum, New York, 1992, p. 21.
- [2] D.B. Haviland, L.S. Kuzmin, P. Delsing, T. Claeson, *Europhys. Lett.* 16 (1991) 103.
- [3] R. Yagi, S. Kobayashi, Y. Ootuka, *J. Phys. Soc. Jpn.* 66 (1997) 3722.
- [4] J.S. Penttilä, Ü. Parts, P.J. Hakonen, M.A. Paalanen, E.B. Sonin, *Phys. Rev. Lett.* 82 (1999) 1004.
- [5] K.K. Likharev, A.B. Zorin, *J. Low Temp. Phys.* 59 (1985) 347.
- [6] G. Schön, A.D. Zaikin, *Phys. Rep.* 198 (1990) 237.
- [7] J. Hassel, H. Seppä, *IEEE Trans. Appl. Sup. Cond.* 11 (2001) 260.
- [8] D. Golubev, A.D. Zaikin, *Phys. Lett. A* 164 (1992) 337.