Bloch Oscillating Transistor - a new mesoscopic amplifier

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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.

Key words: 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 [1]. When the phase fluctuations are not damped by the real part of the environmental impedance Z_{env}, no true supercurrent exists in the junction ($Re\{Z_{env}\} > R_Q = \frac{h}{4e^2}$). 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 $V > (\frac{dE^{(1)}}{dQ})_{max}$, 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 $f_{Bloch} = I/2e$. 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 $V < (\frac{dE^{(2)}}{dQ})_{max}$, 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

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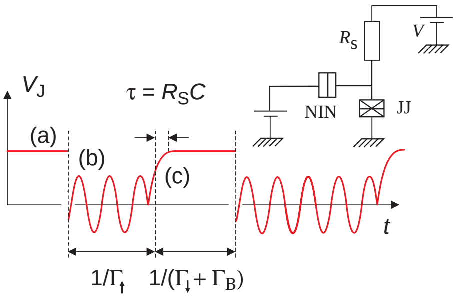

Fig. 1. Time evolution of the voltage over the Josephson junction (JJ) (a) The junction is initially on the second band in a state of Coulomb blockade. (b) A quasiparticle tunneling event brings the junction to the lowest band where it performs Bloch oscillations. (c) Zener tunneling stops the coherent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

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 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

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

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

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

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 Γ_B due to the base current to the downward transition rate. Assuming that τ can be neglected and that the base current flows only when the JJ is Coulomb blockaded, 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 β_{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. β_{max} grows strongly 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

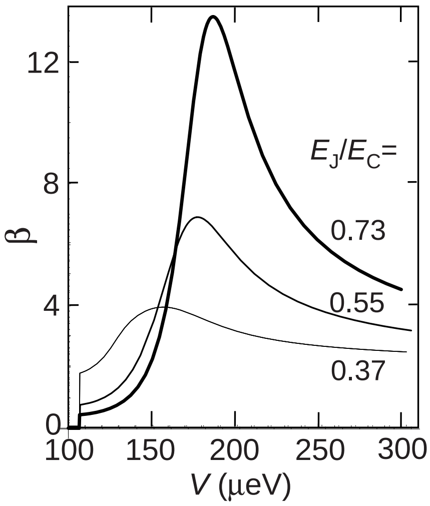

Fig. 2. Current gain β according to Eq. 3 for three ratios of E_J/E_C. The parameters employed in the calculation were $E_C = 53$ μeV ($C = 1.5$ fF), $R_S = 55$ kΩ, and $T = 80$ mK.

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.

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