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Photon-assisted tunneling in double-barrier superconducting tunnel junctions

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Double-barrier Nb/Al₂O₃/Al/Al₂O₃/Nb tunnel junctions are used as mixing elements in a 345 GHz waveguide mixer. Noise temperatures (double side band) down to 720 K at 3.0 K are obtained without the need to apply a magnetic field to suppress the Josephson current. It is shown that the composite barrier acts as a single barrier for photon-assisted tunneling. Surprisingly, at these frequencies the capacitance of two stacked tunnel barriers is only determined by one barrier.

Since the original proposal by Tucker¹ and several pioneering experiments²⁻⁴ at frequencies below 100 GHz, superconductor-insulator-superconductor (SIS) mixers have become the most sensitive detection element up to frequencies of 750 GHz.⁵ The quasiparticle current as a function of voltage has a strong nonlinearity, which leads in heterodyne detection to a very efficient conversion from the signal frequency to the intermediate frequency. A potential noise source at higher frequencies is the Josephson effect. A magnetic field is commonly used to quench the dc-Josephson current. Larger magnetic fields are needed when smaller area junctions are used, required at higher frequencies. In addition, although the dc-Josephson current is zero, locally supercurrent continues to flow potentially creating excess noise. Moreover, to relieve the tight constraints on fabricating small area junctions, the use of series arrays is often considered. To suppress the Josephson effect equally effective for all members of the array becomes progressively more difficult. A possible solution is to replace the conventional SIS tunnel junction by a double-barrier tunnel structure with two tunnel barriers in series separated by a normal metal. In such a structure the supercurrent is absent while a fairly nonlinear current-voltage characteristic is maintained.

We study double-barrier tunnel junctions using two niobium superconducting electrodes separated by two Al₂O₃ barriers with 5 nm aluminum in between. A typical *I-V* curve is shown as a full line in Fig. 1. At the temperature of liquid helium (4.2 K) no supercurrent is observed because the tunnel barriers effectively suppress the proximity effect. The *I-V* curve is clearly nonlinear. It is quite different from a series *I-V* curve for NIS tunneling or the strongly nonlinear *I-V* curve known from SIS tunneling. Most prominent is the negatively shifted asymptote compared to the current carried in the normal state (current deficit).

The *I-V* curve can be understood in detail using the model studied by Heslinga and co-workers⁶⁻⁸ and independently by Zaitsev.⁹ The essential content is that when a voltage is applied the electronic states in aluminum are no longer occupied with an equilibrium distribution as is assumed for conventional tunneling configurations. Instead, the *I-V* curve is strongly influenced by a nonequilibrium distribution of electrons in the aluminum. These conditions arise only when the tunnel barriers are thin enough to provide an injection rate Γ which is much higher than the inelastic scattering rate τ_E^{-1} in the aluminum. Fortunately, for high frequency mixing high current densities are needed, resulting in high injection rates. In addition, aluminum has a very low inelastic scattering rate. In *N* a nonequilibrium distribution f_2 is found by equating the tunnel currents from *S*₁ to *N* to the tunnel currents from *N* to *S*₃ (Fig. 1, inset). Then the distribution in *N* is given by

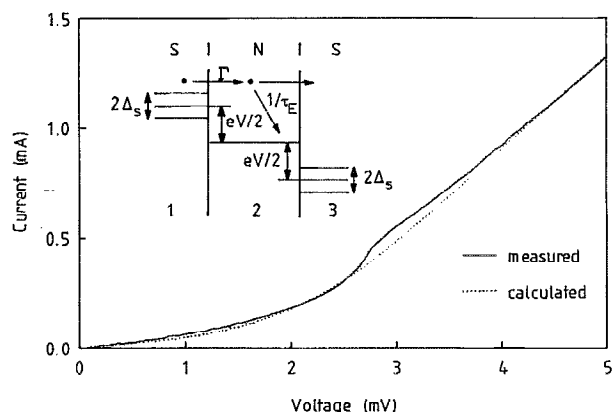


FIG. 1. Measured current-voltage characteristic (solid curve) for a double-barrier tunnel junction. Note the shifted asymptote with respect to the normal state resistance and the weak nonlinearity at $eV = 2\Delta$. The dotted curve is a theoretical curve based on Eq. (1) assuming $\Gamma \tau_E = 0.05$. The inset shows the tunnel and relaxation processes assumed in the model.

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$$f_2(E) = \frac{N_1(E - eV/2)f_0(E - eV/2) + N_3(E + eV/2)f_0(E + eV/2) + N_2(E)f_0(E)/\Gamma\tau_E}{N_1(E - eV/2) + N_3(E + eV/2) + N_2(E)/\Gamma\tau_E}, \quad (1)$$

where V is the applied voltage between S_1 and S_3 , N_1 and N_3 the normalized densities of states of the two superconducting electrodes, N_2 the density of states of the normal electrode, and f_0 the equilibrium Fermi function. If Γ is small, i.e., fast relaxation, f_2 equals the equilibrium distribution in N . If relaxation is absent f_2 is fully determined by the electronic properties of the two outer electrodes ($\Gamma\tau_E \rightarrow \infty$). This condition is equivalent to the process called sequential tunneling in semiconductor double-barrier tunneling.¹⁰

If energy relaxation is fully ignored the I - V curve is given by

$$I = \frac{e}{R_N} \int \frac{N_1(E - eV/2)N_3(E + eV/2)}{N_1(E - eV/2) + N_3(E + eV/2)} \times [f_0(E - eV/2) - f_0(E + eV/2)], \quad (2)$$

where R_N is the normal state resistance. Evidently the functional form differs from the one for conventional SIS and SIN tunneling. For SIS tunneling only the product of the densities of states of the superconductors, N_1 and N_3 , and for SIN tunneling only the density of states in one of the superconductors appears. The present expression is a consequence of the conservation of energy for particles tunneling through both barriers. Equilibration occurs only in the superconducting electrodes. A typical theoretical I - V curve based on Eq. (2) is shown in Fig. 2(b). The I - V curve is sharper than for SIN tunneling but less sharp than for SIS tunneling. The current deficit arises as a result of the lack of occupancy of the states in aluminum at energies around the gap of the

niobium electrodes. In practice, a finite amount of inelastic scattering occurs. Figure 1 (dotted line) shows a calculated I - V curve using Eq. 1 for $\Gamma\tau_E = 0.05$.

The device is mounted in a two-tuner waveguide mixer operated at 345 GHz using a carcinotron as a longitudinal-optical (LO) source. The intermediate frequency at 1.5 GHz is amplified by a cooled GaAs high electron mobility transistor (HEMT) amplifier. Figure 2(a) shows a pumped I - V curve together with the derivative as a function of voltage. Clearly, photon steps are present at voltages of $2\Delta \pm \hbar\omega$. Note that these steps occur at the same voltage as one would expect for a conventional SIS tunnel device. Evaluating the (double-side band) noise temperatures of the receiver in the usual way by using a hot and a cold load we find a lowest noise temperature of 950 K at a bath temperature of 4.2 and 720 K at 3.0 K, where we find for conventional SIS-tunnel devices in the same mixer noise temperatures below 100 K.¹¹ The deterioration in noise temperature is closely connected to the nonlinearity of the I - V curve. Better results are expected when the influence of inelastic scattering is further reduced by taking thinner aluminum layers. Figure 2(b) shows the ideal case ($\Gamma\tau_E \rightarrow \infty$), whereas in Fig. 3 an example of an experimental I - V curve is shown for a thinner layer of aluminum, which is clearly much sharper than the one shown in Fig. 1. Nevertheless, we expect that application of the double-barrier technique will occur at the expense of a substantial increase of noise temperature.

A striking observation is that the photon-induced steps occur at voltages $\hbar\omega$ below or above the gap voltage. The composite barrier appears to act as a single barrier instead of producing steps at twice $\pm\hbar\omega$. In the original Tien-Gordon

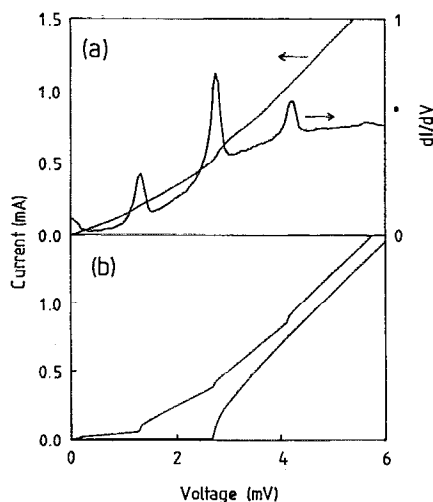


FIG. 2. (a) Measured I - V curve in the presence of a fixed power of 345 GHz radiation. The inset shows the derivative of the same curve clearly showing the photon steps around the gap nonlinearity. (b) Theoretical I - V curves for a SINIS device based on the Tien-Gordon theory for zero power and a finite power level, assuming no inelastic scattering ($\Gamma\tau_E \rightarrow \infty$).

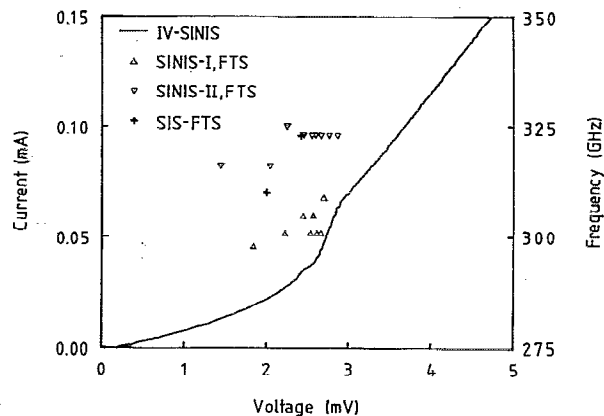


FIG. 3. Measured current-voltage characteristic for a SINIS device with an integrated tuning element and a thin aluminum layer. The markers indicate the resonant frequencies as determined with a Fourier transform spectrometer. The triangles and inverted triangles represent two different double-barrier junctions at different bias voltages. The plus signs are for a single barrier junction.

theory¹² of photon-assisted tunneling it is assumed that one side of the junction is grounded and that a time-dependent voltage is applied across the junction in addition to the dc bias: $V(t) = V_0 + V_\omega \cos \omega t$. It is assumed that this applied voltage modulates adiabatically the potential energy for each quasiparticle level on the ungrounded side of the barrier. This modifies the time dependence of the wave function for every one-electron state in such a way that for each quasiparticle a finite probability $J_n^2(eV_\omega/\hbar\omega)$ exists to be displaced in energy by an amount $n\hbar\omega$, with J_n the n th order Besselfunction and V_ω the amplitude and ω the frequency of the microwave signal. The resulting tunnel current is found by multiplying the density of states in the expression for the tunnel current with these probability amplitudes. To interpret the experimental results we will use the same approach and apply it to double-barrier tunneling. As above, we assume that the energy is conserved in the tunnel process through the two barriers. Then the probability of a quasiparticle energy in S_1 to be displaced by an amount $\hbar\omega$ will be maintained unaffected in the tunnel process through the double-barrier structure. We replace N_1 in Eq. (2) by the virtual energy levels with probabilities $J_n^2(eV_\omega/\hbar\omega)$. The result of such a calculation is shown in Fig. 2(b) for one power level. For comparison the curve for $V_\omega=0$ is also shown. Note the sharpness of the I - V curve, due to the absence of inelastic scattering. Clearly the pumped curve reproduces the qualitative aspects of the experimental results very nicely.

Since optimum heterodyne mixing requires a well-tuned system, we have also evaluated double-barrier tunnel structures with an integrated tuning element (open-ended stub). A Fourier transform spectrometer is used to determine the resonant frequencies. The absorption is measured as a function of frequency for different dc bias voltages. The open-ended stub acts together with the geometrical capacitance as an inductance-capacitance (LC) resonator. The inductance can be determined from the stub length, which was kept constant for different samples. In Fig. 3 the results, obtained at different dc bias voltages, are shown for two different double-barrier devices (triangles and inverted triangles) and for a single-barrier device (plus signs). Surprisingly, the resonant frequencies are all comparable and there is no difference between the single-barrier device and the double-barrier devices. The resonant frequencies are all between 300 and 325 GHz and not shifted by a factor $\sqrt{2}$ to about 400 GHz as one would expect for two tunnel barriers in series forming two capacitors in series. Apparently, the usual rule for adding capacitances in series no longer holds at these frequencies and only one barrier plays a role as a high frequency capacitor. We assume that this observation is tied to our analysis of

photon-assisted tunneling in double-barrier devices. If the energy levels in one electrode are adiabatically modulated by the ac voltage of the microwave field the states in N follow these modulations also adiabatically if energy relaxation is absent between the barriers. Then the ac voltage representing the potential energy of the quasiparticle levels is effectively only present across one barrier. Clearly, the frequency should be sufficiently high to prevent equilibration of the energy levels.

In summary, we have demonstrated that double-barrier tunnel junctions can be used as mixer elements without the need to apply a magnetic field to suppress the Josephson currents, although at the expense of a higher noise temperature. In addition, we find that the double barrier acts as one composite barrier for photon assisted tunneling. Finally, we find that at least at frequencies around 345 GHz two capacitances in series no longer divide in the conventional way to one half. We believe that the latter results are also important in understanding the dynamic response of semiconductor double-barrier tunneling devices.

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