Physica 108B (1981) 1367-1368
North-Holland Publishing Company

NEGATIVE RESISTANCE AND CONVERSION GAIN IN SIS MIXERS

A. D. Smith, W. R. McGrath, P. L. Richards and H. van Kempen
Department of Physics, University of California, Berkeley, California
D. Prober and P. Santhanam
Becton Center, Yale University, New Haven, Connecticut

We report the observation of negative quasiparticle dynamic resistance on the DC I-V curves of superconductor-insulator-superconductor tunnel junctions. This negative resistance appears on the first few photon assisted tunneling steps below $2\Delta/e$ when our tin-tin oxide-tin tunnel junctions are pumped with a 36 GHz microwave current source. We present a simple analytical model which shows that large (and also negative) dynamic quasiparticle resistance is expected for junctions with sharp I-V curves when the microwave source impedance is high. Because the dynamic resistance can be very large, an impedance-matched quasiparticle mixer should have unlimited gain. We have observed a net mixer gain of 4.3±1 dB at 36 GHz with a mixer noise temperature $\lesssim$10K.

I. INTRODUCTION

When the theory of photon assisted tunneling was used to compute the performance of quasiparticle heterodyne mixers using superconductor-insulator-superconductor (SIS) tunnel junctions, the surprising prediction of unlimited mixer gain was obtained[1]. This prediction caused considerable interest because gain is of great practical importance in producing low noise microwave receivers. Computer calculations based on this theory show that large gain is accompanied by large and even negative values of the low frequency dynamic resistance R_D of the pumped junction[1]. In the absence of a simple physical interpretation this prediction of negative resistance was somewhat mysterious, especially since it had not been seen in the extensive previous investigations of photon assisted tunneling.

In this paper we report the experimental observation of negative quasiparticle dynamic resistance, and show by a simple analytical model that the negative resistance is expected from conventional photon assisted tunneling theory when the microwave source impedance is high, the junction leakage resistance is small, and the gap structure on the I-V curve is sharp compared with the photon voltage $\hbar\omega/e$.

II. MODEL OF NEGATIVE RESISTANCE

For a DC bias voltage V and an induced RF voltage $V_1 \cos\omega t$, the low frequency I-V curve is given by

$$I(V,P_{LO}) = \sum_{n=-\infty}^{\infty} J_n^{\,2}(\alpha)\, I_n, \qquad (1)$$

where I_n is the unpumped I-V curve evaluated at $V + n\hbar\omega/e$ and $\alpha \equiv eV_1/\hbar\omega$. We must treat the experimental case of fixed RF source resistance R_S. This can easily be done in the "3-port" approximation which ignores harmonic response so that current and voltage waveforms are sinusoidal with amplitudes I_1 and V_1. The experimental pumped I-V curve is measured with the available RF power (and therefore $I_1R_S + V_1$) held constant. Then

$$\frac{dI(V,P_{LO})}{dV} = \sum \left[J_n^{\,2}(\alpha)\frac{dI_n}{dV} + \frac{d\alpha}{dV}\,\frac{d(J_n^{\,2})}{d\alpha}\, I_n \right]. \qquad (2)$$

When R_S is small enough that the junction is RF voltage biased, the second term in the square brackets can be neglected. Since dI_n/dV is positive for quasiparticle tunneling between identical superconductors, the low frequency dynamic resistance is positive for small R_S.

To understand the more general case, the expression $d\alpha/dV$ can be replaced by $-e/\hbar\omega(dI_1/dV)R_S$. On a given step, dI_1/dV is generally positive, so the second term in the square brackets is negative. For sufficiently large source impedance, R_S, the second term in Eq. (2) can give rise to a large, or even negative, low frequency dynamic resistance. The availability of arbitrarily large R_D plays an important role in the prediction of large gain in quasiparticle mixers[1,2]. These effects can be masked by leakage resistance or insufficient gap sharpness (that is, by small dI_1/dV). Although negative resistance effects due to pair Josephson tunneling are commonplace, negative quasiparticle resistance has not been previously reported in tunneling between identical superconductors.

III. DESCRIPTION OF EXPERIMENT

The tin junctions used in our experiments are fabricated using a photoresist bridge mask. A typical junction area is $\sim 10\ \mu m^2$. Our best performance thus far has come from a junction with $R_N = 22\Omega$, which had a Josephson critical current density of $\sim 250\ Acm^{-2}$. Assuming $\varepsilon \simeq 10$ for tin oxide these parameters correspond to $\omega R_N C \simeq 7$. The shunting effect of the junction capacitance is resonated out at 36 GHz by careful adjustment of an RF matching structure consisting of a screw tuner and a backshort. The junction ca-

0378-4363/81/0000-0000/$02.50 © North-Holland Publishing Company

pacitance strongly inhibits response at harmonic frequencies, so the 3-port model is reasonably accurate.

The I-V curves of this junction showed very sharp gap structure and little sub-gap leakage current. As a result, interesting quantum mixing effects could be seen at a frequency low enough (36 GHz) that accurate microwave measurements are relatively convenient. Figure 1 shows the portion of the I-V curve immediately below the current rise at $2\Delta/e$. Steps corresponding to tunneling with the absorption of 1, 2, and 3 photons from the 36 GHz local oscillator are visible. For the particular choice of RF source impedance chosen, the first step below $2\Delta/e$ has negative resistance, which leads to hysteretic jumps along the load line of the low frequency bias circuit as is shown by the dashed lines. With the bias scheme used it was possible to vary the DC load line, and thereby bias the junction within the negative resistance region. The junction then exhibited spontaneous oscillations at harmonics of ∿5 MHz. The frequency of these oscillations was controlled by the circuit inductance and the bias point.

Photon assisted tunneling effects have been studied extensively in the past, but the conditions for observing negative dynamic resistance have not generally been met. Most investigators have used low current density junctions which were effectively RF voltage biased by the shunt capacitance. More recent experiments with SIS quasiparticle mixers that used low RF impedance did not have sufficiently sharp junction I-V curves.

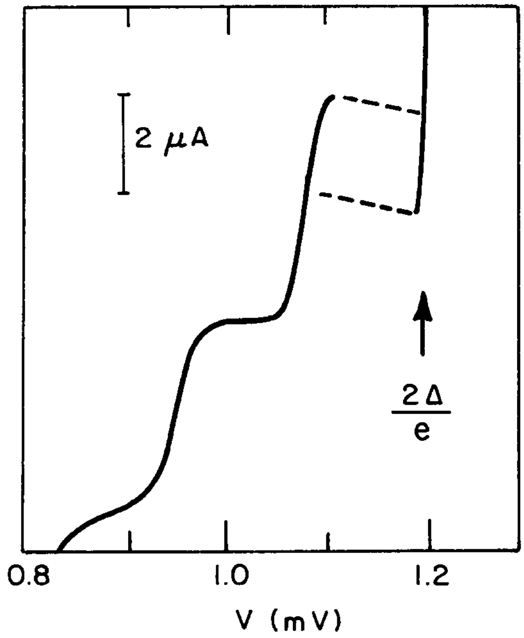

Figure 1 : Oscilloscope trace of 36 GHz photon assisted tunneling steps. On the first step below $2\Delta/e$ the dynamic resistance is negative and hysteresis is observed. On the second step the dynamic resistance approaches 800Ω which is significantly larger than the normal state resistance of 22Ω.

Series arrays of n junctions are a favorable case for observing negative resistance. In the 3-port approximation each individual junction sees an RF source resistance which contains a contribution $(n-1)V_1/I_1$ from the other junctions. If the junction critical current density is large enough to avoid capacitance shunting, each individual junction in an array with $n \gg 1$ will be RF current biased[3].

IV. MIXER EXPERIMENTS

Negative resistance is intimately related to high mixer conversion gain. Quantum effects are not important at the low intermediate frequency. Therefore (2) is valid and the available gain of an SIS quasiparticle mixer can be written[4]

$$G = \left[\frac{\partial I(V,P_{LO})}{\partial\sqrt{P_{LO}}}\right]^2 \frac{R_D}{8} \,. \qquad (3)$$

Because $\partial I/\partial\sqrt{P_{LO}}$ is only weakly dependent on the exact choice of parameters near the optimum operating point, the gain for a mixer whose IF output impedance is matched, is linearly proportional to the value of R_D.

The junction used in Fig. 1 was biased with R_S adjusted to give large (but positive) dynamic resistance on the first photon step below the gap. Both a pump power of ∿1 nW at ω = 36 GHz and a signal power of ∿1 pW at ω +50 MHz were coupled to the junction. The power at 50 MHz which was coupled into our IF amplifier increased linearly with R_D and then saturated at a value which corresponds to a power gain of 4.3±1 dB for values of $R_D \gtrsim 100\Omega$. The saturation in measured gain is clearly a result of IF mismatch. This is the first observation of power gain greater than unity in an SIS quasiparticle mixer.

REFERENCES

[1] Tucker, J. R., Predicted conversion gain in SIS quasiparticle mixers, Appl. Phys. Lett. 36 (1980) 477-479.

[2] Smith, A. D., McGrath, W. R., Richards, P. L., van Kempen, H., Prober, D. and Santhanam, P., (to be published).

[3] See also Kerr, A. R., S-Pan, Feldman, M. J. and Davidson, A. (in this issue).

[4] Torrey, H. C. and Whitmer, C. A., Crystal Rectifiers, M.I.T. Radiat. Lab. Ser. vol. 15 (McGraw-Hill, New York, 1948).

This work was supported in part by the U.S. Office of Naval Research.