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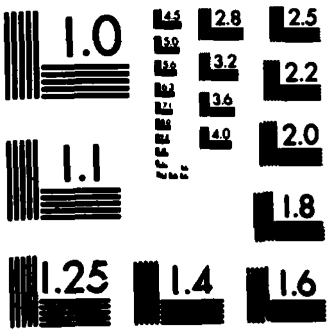

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MICROWAVE MIXING AND DIRECT DETECTION USING SIS AND SIS' QUASIPARTICLE TUNNEL JUNCTIONS

A. D. Smith, W. R. McGrath, and P. L. Richards
Department of Physics
University of California
Berkeley, California 94720

R. E. Harris and F. L. Lloyd
National Bureau of Standards
Boulder, Colorado 80302

and

. E. Prober and P. Santhanam
Yale University
New Haven, Connecticut 06520

Abstract

Quasiparticle mixers have shown strong quantum effects, conversion gain, and noise levels approaching the quantum limit, but only in tunnel junctions with very low sub-gap "leakage" conductance.[1] It has been suggested that SIS' tunnel junctions, made from two different conductors with unequal gaps, will function as high gain mixers since the dynamic conductance below the gap is negative.[2] We report results of the first SIS' mixing and direct detection experiments. At 36 GHz, a conversion efficiency of -4 dB with a noise temperature of 33 K (SSB) has been obtained. A novel gain mechanism for SIS' direct detectors is predicted. A direct detector responsivity of 250 A/W was measured. We compare our results to quantum theory models.[3] In addition, we demonstrate quasiparticle harmonic mixing of a 36 GHz signal with an 18 GHz local oscillator in tin SIS junctions. Harmonic mixers can have important advantages at high microwave frequencies where insufficient local oscillator power is available.

Fundamental Mixing

Calculations by Tucker[4] showed the surprising prediction that idealized SIS junctions could have conversion efficiencies in excess of unity (i.e. more IF power out than RF signal power in) with very low noise. To date, coupled conversion efficiencies significantly greater than unity have only been reported by McGrath, et al.[1] despite efforts by a number of workers. Two practical difficulties often limit SIS performance: RF mismatch and subgap leakage in the junction. Achieving adequate RF matching is largely a matter of minimizing and/or tuning out junction capacitance and lead inductance at the signal frequency while preventing power dissipation at harmonic frequencies. Subgap leakage is a term used to describe a variety of effects which cause more current to flow through the junction than is predicted by the ideal single particle tunneling model.

The effect of the tunnel junction I-V curve on mixer performance can be well understood in terms of a circuit model in which the pumped junction with an applied RF signal acts as an IF current generator[1,5] which is shunted by the dynamic conductance of the pumped junction (see Fig. 1). For a given local oscillator (LO) power, the IF power which can be successfully coupled to a matched load is inversely proportional to the total conductance of the pumped junction. For idealized SIS junctions at low temperatures, the subgap conductance is set by the LO-induced, photon-assisted tunneling conductance, g_{pat}. The size of g_{pat} depends both on the LO power and the source impedance[6] and may even be slightly negative.[7,8] In addition, finite lifetime effects, gap inhomogeneities, multi-particle tunneling,[9] and other current paths contribute conductance which we model as g_{leak}. A third current path is thermal quasiparticle conduction, g_{qp}. For tunnel junctions made from two superconductors with different gaps (SIS') this g_{qp} is negative in the voltage range $|\Delta_1 - \Delta_2|/e$ to $(\Delta_1 + \Delta_2)/e$. Under proper operating conditions, this negative contribution from g_{qp} can make the total conductance quite small, and make the conversion efficiency correspondingly large. Extensive computer calculations based on idealized SIS' models suggest that large mixer conversion gain is possible over a wide parameter range.

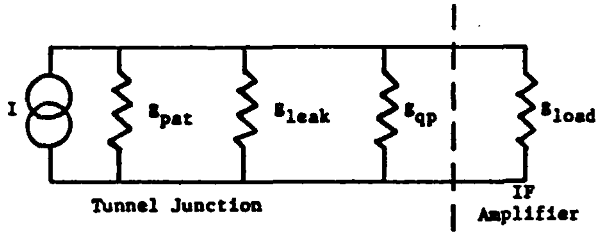

Fig. 1. Model used to predict the IF output from a quasiparticle mixer. The observed dynamic conductance of the junction is expressed as the sum of photon-assisted tunneling conductance, subgap leakage conductance (present even in the absence of applied local oscillator power) and, for SIS' junction, negative quasiparticle conductance. For optimum output coupling, the load conductance is chosen equal in magnitude to the total junction dynamic conductance.

For our experiments, Indium/Indium Oxide/Lead-Bismuth junctions were prepared at NBS Boulder on silicon substrates using an RF sputter oxidation technique. Junction diameters were 2 to 3 microns. The junction under test was placed in the E-field direction across a Ka-band waveguide and submersed in liquid helium. The apparatus and the measurement procedures are described in full detail in an earlier publication.[1] The I-V characteristic of the SIS' tunnel junction is shown as the dashed curve of Fig. 2a. A negative conductance region from $(\Delta_{PbBi} - \Delta_{In})/e$ = 1.1mV to 1.3 mV appears as a gap in the I-V curve. Subgap leakage is sufficiently large from 1.3 mV to the rise at $(\Delta_{PbBi} + \Delta_{In})/e$ = 2.2 mV to overwhelm the negative g_{qp} conductance. Application of LO power produces photon-assisted tunneling steps, which are evident both in the I-V curve of Fig. 2a and the derivative curve plotted in Fig. 2b. Mixer IF output for fixed RF signal input power is shown in Fig. 2c. The maximum observed conversion efficiency was -4± 1 dB, with single sideband mixer noise of T_M = 33± 12 K (SSB). This performance is superior to conventional Schottky diodes in the same frequency range, but is less good than has been achieved for SIS quasiparticle mixers with lower values of g_{leak}. We believe that the conversion efficiency of

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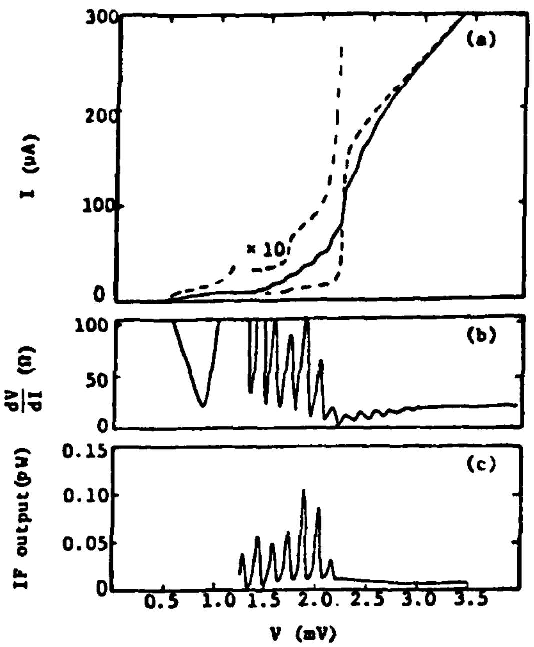

Fig. 2. Operating curves for an SIS' mixer.

this mixer is somewhat better than would have been achieved in an SIS junction with similar values of g_{leak}. The measured conversion efficiency is limited somewhat by a larger junction capacitance than can be tuned out.

Direct Detection

When no local oscillator power is applied, tunnel junctions can be used as direct RF detectors (also known as video detectors). Classical detector theory predicts a maximum RF-power-to-DC-current responsivity of $\mathcal{R} = (\partial^2 I/\partial V^2)/2\ (\partial I/\partial V)$. Quantum Theory (Tucker, 1979) corrects the current responsivity to

$$\mathcal{R} = \eta \frac{e}{\hbar\omega} \frac{I_1 - 2I_0 + I_{-1}}{I_1 - I_{-1}} \qquad (1)$$

where η is the RF coupling efficiency and $I_n = I_{dc}(V_{dc} + n\,\hbar\omega/e)$. For SIS junctions biased at voltages slightly less than the gap ($2\Delta/e$), where $I_1 \gg I_0$ and $I_1 \gg I_{-1}$, $\mathcal{R} = \eta \frac{e}{\hbar\omega}$. This corresponds to one tunneling electron per absorbed photon. At our experiment frequency of 36 GHz, $e/\hbar\omega$ equals 6700 A/W.

For an SIS' junction biased at a point of positive dynamic resistance slightly below the cusp in the I-V curve at $|\Delta_1 - \Delta_2|/e$, values of $I_1 - I_{-1}$ can be much smaller than $I_1 - 2I_0 + I_{-1}$. Consequently we predict that responsivities in excess of $e/\hbar\omega$ are possible with SIS' junctions. The responsivity obtained depends strongly on the actual cusp shape. Gain mechanisms are well known in devices biased in regions of negative conductance, or near enough that the negative conductance is sampled during the RF cycle. While negative conductance is required for our proposed gain mechanism, neither criterion is satisfied in the limit of small RF power. Our gain mechanism is thus a quantum effect not predicted by classical theory.

Figure 3 shows direct detection results for 36 GHz radiation on an In/InO/PbBi junction at 2.3K. A screw tuner and backshort were adjusted for maximum responsivity at V_{dc} = 1.0 mV. This maximum responsivity was measured as 250 A/w. Qualitative features are well described by the quantum model. The sharply negative $\mathcal{R}$ near $(\Delta_{PbBi} - \Delta_{In})/e$ = 1.1 mV is dramatic evidence in favor of the quantum formulation of the responsivity. The quantum prediction based on the dc I-V curve and scaled by a coupling factor of η = .025 is plotted as the solid line in Fig. 2b. We attribute the implied low coupling efficiency to untuned junction capacitance. The fitted value of η = .025 implies that ωRC = 12.

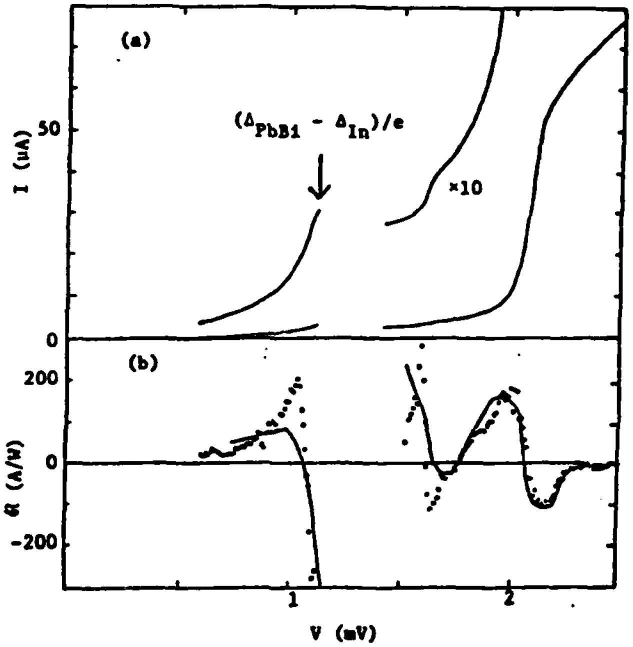

Fig. 3. (a) DC I-V for SIS' junction showing cusp singularity. (b) Direct detector responsivity experiment (points) and theoretical prediction (line).

The scaled quantum theory correctly predicts the shape of the observed responsivity for $V_{DC} \gtrsim$ 1.75 mV, where the junction RF conductance (and hence η) is expected to be constant. For voltages below 1.75 mV, where the RF conductance is voltage dependent, this oversimplified analysis with a fixed value for η still gives a qualitatively correct prediction for $\mathcal{R}$, despite the existence of two-particle tunneling[9] leakage in the form of a hump at ~ 1.6 mV. Within 0.149 mV of the negative resistance region, extrapolation of $I_{\pm 1}$ values leads to uncertainty in the theoretical curve.

Harmonic Mixing

Harmonic mixers, in which the LO is near some submultiple of the signal frequency, can be of practical importance in cases where higher frequency LO power is not readily available. We report here the first measurement of a quasiparticle harmonic mixer.

The smallness of $\hbar\omega_{LO}/e$ which equals 0.075 mV at 18 GHz meant that in order to observe quantum effects junctions with very sharp gap structures were required. We used tin SIS junctions made by thermal oxidation using photoresist masks made at Yale. For purposes of comparison, both fundamental (36 GHz LO) and harmonic (18 GHz LO) mixer performances were measured.

The fundamental mixer results are described in detail in a previous publication,[1] and are summarized here for ease of comparison to harmonic mixer results. Application of ~ 1 nW of 36 GHz LO power induces discernible photon-assisted tunneling steps on the I-V curve, as is shown in Fig. 4a. The steps, at voltage intervals of $\hbar\omega_{LO}/e$ = 0.15 mV are especially evident in plots of dV/dI. The third row of Fig. 4a shows the 50 MHz IF output power for fixed 36.05 GHz input signal power. The best experimental value of the coupled mixer gain for the fundamental mixer was +4.3 ± 1 dB.

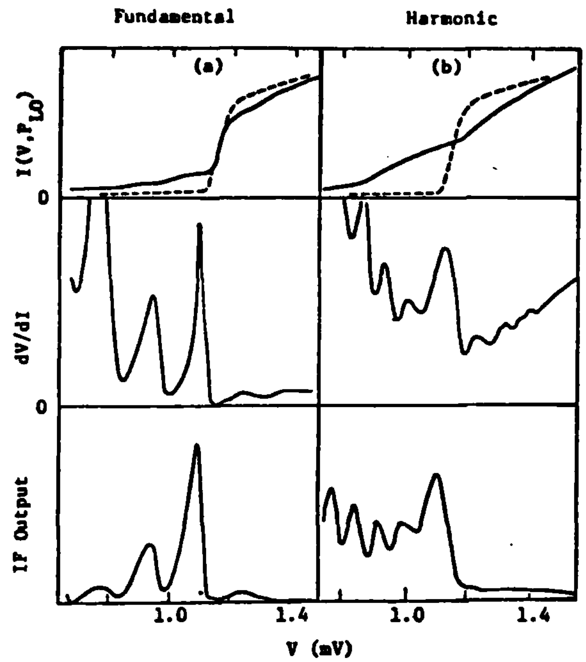

Fig. 4. Operating curves showing mixer performance near 2Δ/e. The left column (a) shows operation with a 36 GHz local oscillator, while the right column (b) describes harmonic mixing with an 18 GHz local oscillator. Different vertical scales have been employed between the two columns except for the I-V curves on the top row.

For our harmonic mixer experiments, LO drive was coupled to the junction through the IF line. A low pass stub structure was used to prevent the 18 GHz LO power from propagating in the direction of the IF amplifiers. No attempt was made to match the LO drive to the junction efficiently.

The photon-assisted tunneling step width ($\hbar\omega_{LO}/e$) of 0.075 mV was nearly equal to the width of the tin gap rise. As a result, quantum effects were not strong and the data in some ways resemble those for the In/InO/PbBi SIS' experiment discussed above. The step structure shown in Fig. 4b is not readily perceivable in the DC I-V curve, but is clearly seen in the plot of dV/dI. The IF output power curve can be described by a broad overall classical structure superimposed on a somewhat smaller amplitude quantum response with 0.075 mV period. The height of the individual quantum peaks varied with local oscillator power, although the voltages at which the peaks appeared were constant. The Bessel function-like dependence of the quantum peak amplitudes on local oscillator power is a well-known characteristic of quantum SIS mixers.

The best experimental values of the coupled conversion efficiency for the harmonic mixer were -3.2 ± 1 dB for one sideband, and -5.6 ± 1 dB for the other. While these values are significantly lower than corresponding fundamental mixer results, they are comparable to the best possible for a classical fundamental resistive mixer. Gain is theoretically expected in harmonic mixing experiments where the quantum effects are strong at the LO frequency.

The local oscillator coupling scheme used for harmonic mixing made measurement of the LO power available at the junction difficult. On the basis of the shape of the pumped I-V curve, the amount of coupled LO power can be estimated to be 5-10 nW. This is orders of magnitude smaller than the power requirements for typical Schottky diode mixers, but is somewhat larger than the 1 nW used in the fundamental mixer experiments. If the harmonic mixer is more strongly in the quantum regime at higher frequencies, it is expected that less local oscillator power will be necessary for optimum conversion efficiency.

Quantum three port mixer theory[3] has been extended to examine harmonic response.[10,11] We have performed extensive computer calculations based on these theories in an effort to model the mixer operation. Uncertainties in the values of the experimental embedding admittance near ω_{LO}, and ω_{RF} corresponded to large variations in calculated mixer performance. A meaningful comparison of data to theory was therefore not possible without more accurate information about these admittances.

Summary

The first SIS' mixer and direct detector experiment results show strong quantum structures but only moderately good coupled gain and responsivity. We expect that SIS' junctions with lower leakage and lower capacitance will display large conversion efficiencies. We calculate a novel gain mechanism for SIS' direct detectors allowing responsivities in excess of $e/\hbar\omega$. Harmonic mixing in SIS junctions appears promising for applications where convenient fundamental LO power sources are not readily available.

Acknowledgements

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