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SIS QUASIPARTICLE JUNCTIONS AS MICROWAVE PHOTON DETECTORS

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Abstract

The strong nonlinearity of the quasiparticle tunneling current in superconductor-insulator-superconductor junctions near the full gap voltage  $2\Delta/e$  can be used for direct detection of microwave signals. Measurements at 36 GHz yielded a current responsivity of 3,500 A/W, which is within a factor of 2 of the quantum limited value  $e/h\omega$ . The measured NEP of  $2.6 \pm 0.8 \times 10^{-16}$  W/√Hz is the lowest value reported to date and can probably be improved significantly. The experimental results are compared with both the standard classical analysis and photon assisted tunneling theory.

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## 1. Introduction

Conventional microwave (Schottky barrier) diodes have relatively weak curvature on their  $I_0-V_0$  curve. As a consequence, direct detectors (rectifiers) which use these diodes have low responsivity and are not much used as front-ends for microwave receivers. Competitive detector sensitivities were first obtained with the super-Schottky diode which has an ideal exponential  $I_0-V_0$  curve down to helium temperatures.<sup>1</sup> The curvature parameter  $S = e/kT$  was  $11,600 \text{ V}^{-1}$  at 1 K compared with  $40 \text{ V}^{-1}$  for a room temperature diode.

Quasiparticle tunneling in superconductor-insulator-superconductor (SIS) evaporated film tunnel junctions can produce much larger effective  $S$ -values and lower diode currents than are possible with the super-Schottky device. Also, because of the absence of series resistance, it has been possible to operate the SIS quasiparticle devices at higher microwave frequencies.<sup>2,3</sup> In this paper we report operation at 36 GHz of a direct detector made from a Pb(In,Au) alloy SIS junction. The current responsivity was within a factor 2 of the quantum limited value  $e/h\omega$ . The measured  $\text{NEP} = 2.6 \pm 0.8 \times 10^{-16} \text{ W}/\sqrt{\text{Hz}}$  is the lowest value reported to date. The noise was dominated by shot noise in the diode leakage current. Since junctions with much lower leakage current have been made, significantly lower values of NEP appear possible.

II. Theory

The classical expression for the current responsivity  $R_i$  of an impedance matched microwave diode can be written in the form<sup>4,5</sup>

$$R_i^{Cl} = \frac{1}{2} \cdot \frac{d^2 I_0 / dV_0^2}{dI_0 / dV_0} = \frac{S}{2}, \quad (1)$$

where the derivatives are evaluated at the bias voltage. This expression is not valid at frequencies high enough that  $S/2 > e/\hbar\omega$ . In the high frequency limit the quantum analysis provided by Tucker and Millea<sup>5-7</sup> must be used. The quantum expression for current responsivity is

$$R_i^{QM} = \frac{e}{\hbar\omega} \left[ \frac{I_0(V_0 + \hbar\omega/e) - 2I_0(V_0) + I_0(V_0 - \hbar\omega/e)}{I_0(V_0 + \hbar\omega/e) - I_0(V_0 - \hbar\omega/e)} \right], \quad (2)$$

which approaches the quantum limited value  $e/\hbar\omega$  for a diode with a sharp knee on the  $I_0 - V_0$  curve at the bias point. In this limit one electron crosses the junction for each photon absorbed (unit quantum efficiency). If the reactive part of the diode impedance is assumed to be matched, but the RF source resistance  $R_S$  is not equal to the RF resistance of the diode, then an impedance mismatch factor

$$\xi = 4R_{RF}R_S / (R_{RF} + R_S)^2 \quad (3)$$

will reduce the measured response to the available (incident) RF power.

In the classical limit  $R_{RF} = R_D = dV_0/dI_0$ . The corresponding quantum expression is

$$R_{RF} = \frac{2\hbar\omega/e}{I_0(V_0 + \hbar\omega/e) - I_0(V_0 - \hbar\omega/e)} \quad (4)$$

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Since the bias voltage is larger than  $2kT/e$ , shot noise in the bias current will be observed in the detector,

$$\langle i_n^2 \rangle = 2eI_0(V_0)B, \quad (5)$$

where  $B$  is the post-detection bandwidth. The theoretical noise equivalent power (NEP) of the device can thus be written as

$$\text{NEP} = \langle i_n^2 \rangle^{1/2} / \epsilon R_i^{\text{QM}}. \quad (6)$$

### III. Experimental Procedure

The Pb(In, Au) alloy SIS junctions were fabricated by conventional photoresist lift-off techniques.<sup>8</sup> They were mounted in the E-field direction across a  $TE_{10}$  mode cavity consisting of a section of waveguide, a stub, and a plunger.<sup>2</sup> Noise measurements were performed by coupling the noise power generated by the dc biased junction through a 30 - 80 MHz band pass filter, to an amplifier with a noise temperature of 50 K, and then to a commercial power meter. The output resistance  $R_D$  of the diode with dc bias was determined both by VSWR measurements and from the derivative of the  $I_0-V_0$  curve. The values obtained from the two methods agreed within 3%. A comparison of the diode noise power to that from a  $50 \Omega$  resistance at the He bath temperature gave the equivalent diode temperature  $T_D$ . The rms diode noise current in  $A/\sqrt{\text{Hz}}$  was then calculated from

$$(\langle i_n^2 \rangle / B)^{1/2} = (4kT_D / R_D)^{1/2}. \quad (7)$$

The voltage responsivity of the detector was measured at microwave modulation frequencies in the KHz range using a high impedance FET amplifier.

Values of current responsivity  $\mathcal{R}_i$  were obtained by dividing the voltage responsivity by the value of  $R_D$  measured at the bias point. Measured values of NEP were obtained by dividing the measured rms noise current by  $\mathcal{R}_i$ .

#### IV. Experimental Results

Fig. 1(a) is a typical  $I_0$ - $V_0$  curve for a Pb(In, Au) SIS junction used for direct detection. Table I presents experimental results for two different junctions measured at bath temperatures  $T_b = 4.2$  K and 1.4 K, as well as calculated results from Eqs. (1) through (6). The values of rms noise current calculated from the shot noise equation (5) are in good agreement with the measured values. Since the diode current at the optimum bias point is dominated by an essentially temperature independent excess current in our Pb(In, Au) alloy junctions, the noise is nearly independent of temperatures below 4.2 K. The measured S-values increase somewhat with decreasing temperature and approach large enough values at 1.4 K that  $S/2 \approx e/h\omega$ .

The best NEP measured at 36 GHz was  $2.6 \pm 0.8 \times 10^{-16} \text{ W}/\sqrt{\text{Hz}}$  for a junction operating at 1.4 K. This is the highest sensitivity reported to date for a microwave detector. The fit of Eq. (2) to our measured values of  $\mathcal{R}_i$  was used to obtain the estimates of the RF coupling efficiency  $\xi$  at the responsivity peak which are shown in Table I. If we correct for RF mismatch the best NEP would be as low as  $2.0 \times 10^{-16} \text{ W}/\sqrt{\text{Hz}}$ .

Figure 1(b) shows the current responsivity  $\mathcal{R}_i$  of the detector as a function of bias voltage with constant RF source impedance. The stub and plunger were adjusted for maximum peak responsivity. The theoretical curves of current responsivity computed from Eqs. (1) and (2) have been multiplied by the bias voltage dependent RF impedance mismatch factor  $\xi$ .

which is appropriate for each theory. The value of source resistance  $R_S$  was chosen in each case to minimize the rms differences between the experiment and the theoretical curves. Although the differences between the quantum and classical theories are not large for our experimental parameters, the quantum theory gives a significantly better fit--especially in the vicinity of sharp structure on the  $I_0-V_0$  curve. Because the details of the RF impedances are not known, certain arbitrary choices must be made in the analysis of the data. The procedure adapted here assumes no reactive mismatch and uses  $R_S$  as an adjustable parameter to optimize the fit of the two theoretical curves to the experiment. An alternative approach is to assume a voltage independent reactive mismatch and to adjust  $R_S$  to maximize the responsivity. This resembles in some respects the experimental procedure for adjusting the stub and plunger. The fit between the quantum theory and the experimental data obtained in this way is nearly as good as that shown in Fig. 1(b). The fit of the classical theory, however, is seriously degraded. Our conclusion that the quantum theory represents a better/fit to the data than the classical theory appears to be reasonably insensitive to the assumptions made about the unknown RF source impedance. The classical theory clearly gives the wrong prediction in the vicinity of sharp structure on the  $I_0-V_0$  curve.

#### V. Discussion

The SIS quasiparticle tunnel junction has been demonstrated to be the most sensitive available microwave detector. The details of the

detector response are well described by photon assisted tunneling theory. The performance of this device is analogous in many ways to that of an infrared photo-diode. Each incident photon can liberate an electron which then crosses the junction. In both types of detector noise mechanisms, which are presently unavoidable, prevent the counting of single photons. The usefulness of this detector for broad band microwave radiometry can be illustrated by calculating the receiver noise temperature  $T_R$  of a heterodyne radiometer with a practical bandwidth  $B_{\text{Het}} = 1$  GHz which would give the same performance as the above direct detector used with an input bandwidth  $B_{\text{DET}} = 10$  GHz. We obtain

$$T_R \approx \text{NEP} \sqrt{B_{\text{HET}}} / k B_{\text{DET}} = 60 \text{ K.}$$

The noise in this device is limited by the excess current near the full gap voltage which, for a given type of junction, tends to scale inversely with the impedance of the junction in the normal state. Hence, lower values of NEP were obtained by using higher impedance junctions. Other types of junctions with lower leakage current are well known. In particular, Sn or Pb junctions fabricated using thermal oxidation techniques have a very sharp corner on their  $I_0$ - $V_0$  curves and closely approach the ideal switch limit. If such junctions are used for direct detection they will exhibit strong quantum effects at 36 GHz, so that only a factor of  $\sim 2$  improvement in current responsivity is expected. However, the reduced value of excess current in such junctions could lower the NEP very significantly.

The use of series arrays of SIS junctions for heterodyne mixers is being explored in order to ease the trade-off between the conflicting requirements of impedance matching and high frequency operation.<sup>2,3,9</sup> The use of series arrays as detectors appears to be somewhat less favorable. The effective S-value for an array of N junctions in series is S/N. In the classical limit therefore, the current responsivity would

be degraded by a factor  $N$ . The responsivity for an array whose individual junctions have  $S$ -values larger than  $2e/h\omega$  is given by  $R_j = e/Nh\omega$ , so is also degraded by the factor  $N$ . A second difficulty arises from the tendency of the leakage current in a given type of junction to vary inversely with the junction resistance. A  $50 \Omega$   $N$ -junction array would therefore have  $\sqrt{N}$  more noise than a single  $50 \Omega$  junction.

#### Acknowledgments

We are grateful to Dr. John R. Tucker for his many valuable comments on this manuscript. A portion of this research was sponsored by the U. S. Office of Naval Research.

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Figure Captions

Fig. 1(a) Measured  $I_0-V_0$  curve of an  $\sim 4 \times 10^{-6} \text{ mm}^2$  Pb(In, Au) alloy SIS tunnel junction at 1.4 K.

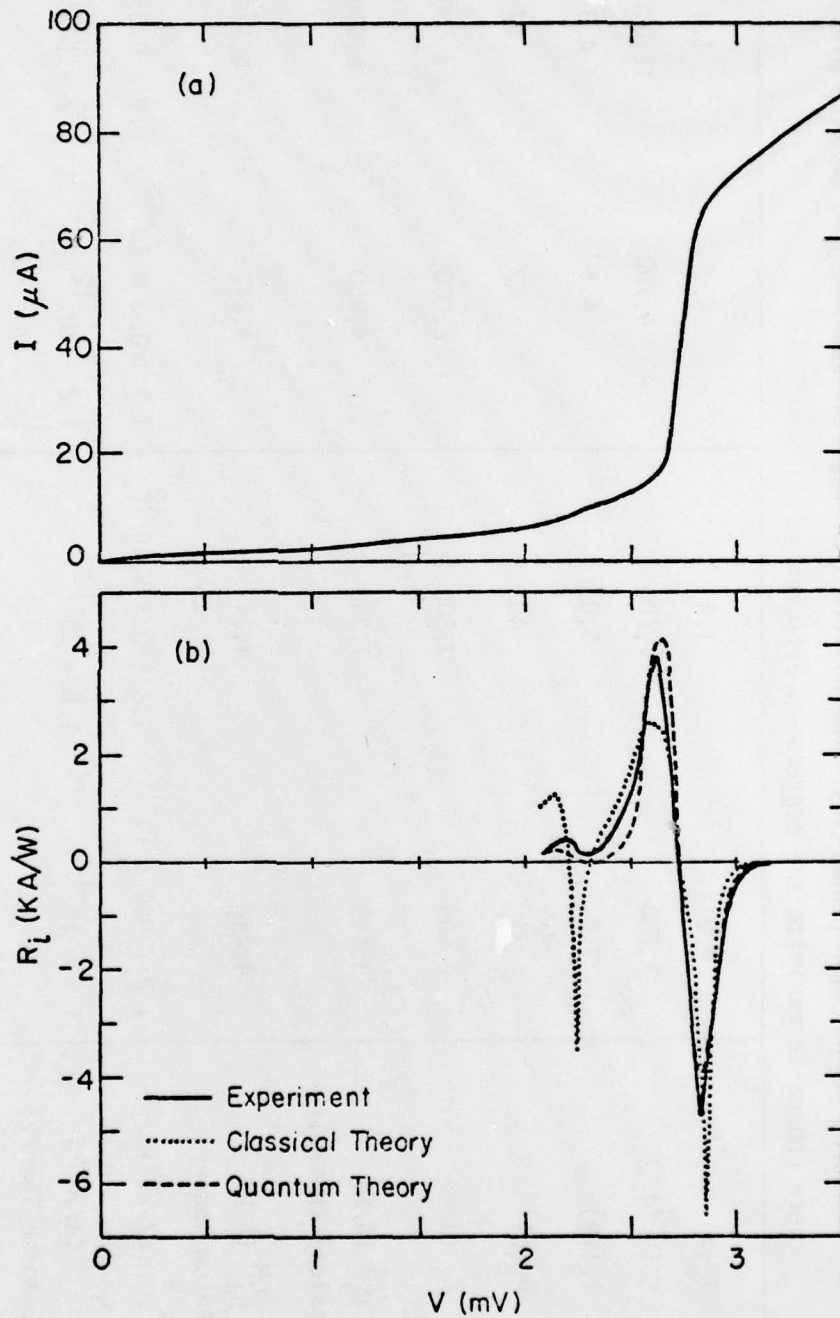
Fig. 1(b) Measured and calculated responsivities of the above junction as a function of bias voltage. The experimental curve is measured with a constant RF source resistance which is close to optimum at the peak of the responsivity curve. The theoretical curves have been computed for a constant RF source resistance, which was chosen in each case to minimize the rms deviations between the theory and the experiment. Although the differences between the classical and the quantum predictions are not generally large for our experimental parameters, the latter theory does provide a significantly better overall fit. One important aspect of the quantum theory is that it averages out the effects of features on the  $I_0-V_0$  curve which are narrow compared with  $\hbar\omega/e = 0.15 \text{ mV}$ . For example the classical theory predicts a sharp (negative) peak in responsivity at a bias of 2.25 mV which is not present in the quantum prediction and which is not observed.

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Table I. Experimental results for two different Pb(In, Au) SIS junctions measured at bath temperatures  $T_b = 4.2$  K and  $1.4$  K compared with calculations from the classical and quantum theories using measured DC junction properties. The positions of the stub and plunger, and the bias voltage were chosen to maximize the conversion efficiency.

$T_b$ (K)	4.2	1.4	4.2	1.4
$S$ ( $V^{-1}$ )	7,200	14,700	9,700	12,000
$I_b$ ( $\mu A$ )	9.5	8.0	4.5	4.3
$R_D$ ( $\Omega$ )	31	40	52	47
$\alpha_i$ (A/W)	2,600	3,200	2,000	3,500
$\alpha_i^{Cl}$ (A/W) (Classical Theory)	3,600	7,350	4,850	6,000
$\alpha_i^{QM}$ (A/W) (Quantum Theory)	4,242	4,242	4,242	4,516
$\langle i_n^2 \rangle$ ( $A/\sqrt{Hz}^2$ )	$1.8 \pm 0.4 \times 10^{-12}$	$1.6 \pm 0.3 \times 10^{-12}$	$1.1 \pm 0.3 \times 10^{-12}$	$0.9 \pm 0.3 \times 10^{-12}$
$\langle i_n^2 \rangle$ ( $A/\sqrt{Hz}^2$ ) (Shot Noise Theory)	$1.7 \times 10^{-12}$	$1.6 \times 10^{-12}$	$1.2 \times 10^{-12}$	$1.2 \times 10^{-12}$
NEP ( $W/\sqrt{Hz}^2$ )	$7.0 \pm 1.5 \times 10^{-16}$	$5 \pm 1 \times 10^{-16}$	$5.5 \pm 1.7 \times 10^{-16}$	$2.6 \pm 0.8 \times 10^{-16}$
$\xi = \alpha_i / \alpha_i^{QM}$	0.61	0.75	0.47	0.78



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Figure 1