enable tighter control to be achieved during InSb diode formation and should allow the potential of this material to be realized.

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A Low-Noise 47-GHz Mixer Using a Permanent Josephson Junction

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Abstract—**A new method to produce permanent Josephson junctions for millimeter-wave mixers is reported. In contrast to conventional point contacts which are mechanically unstable and require adjustments after each cooldown, these point contact junctions are set at room temperature, stay mechanically stable, and can be temperature cycled without readjustments. Using these junctions in a modified Sharpless wafer mixer mount, a single-sideband noise temperature of 71 K was measured at 47 GHz. Based on these results, system noise temperatures of less than 100 K are predicted for practical broad-band radiometers, radar, and communications receivers up to at least 100 GHz.**

I. Introduction

JOSEPHSON effect devices are known to exhibit excellent sensitivity as microwave and millimeter-wave detectors and mixers [1], [2]. However, at frequencies above a few gigahertz permanent thin-film junctions or constriction-type junctions are yielding poor conversion characteristics because of their relatively low impedance or their excessive shunt capacitance [3]. A third type of junction employs adjustable point contacts and is free of these defects; it has been used in several laboratories for mixing up to 300 GHz and it is capable of achieving a single-sideband noise temperature of less than 50 K [2], [4]. However, up to now this type could not be used in practical communications applications because of its mechanical instability and the need for a critical point adjustment after each cooldown. In this report a new type of point contact is described which is packaged in a Sharpless wafer and yields mechanically rugged and permanent Josephson devices with good mixing characteristics.

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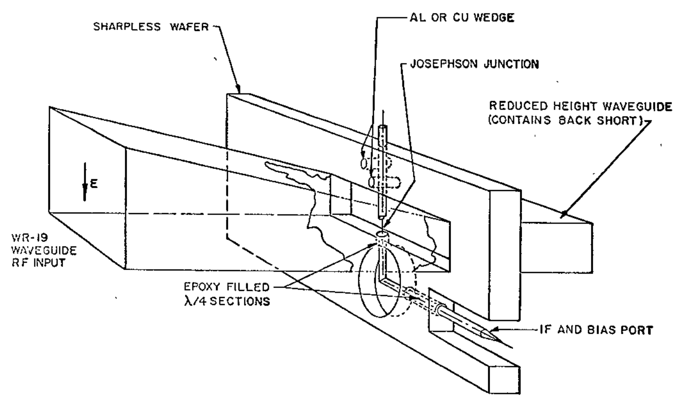

Fig. 1. Details of permanent Josephson junction in Sharpless wafer.

II. Permanent Josephson Junction in Sharpless Wafer

Fig. 1 shows the Sharpless wafer with an attached input waveguide taper and a back short. The point contact is

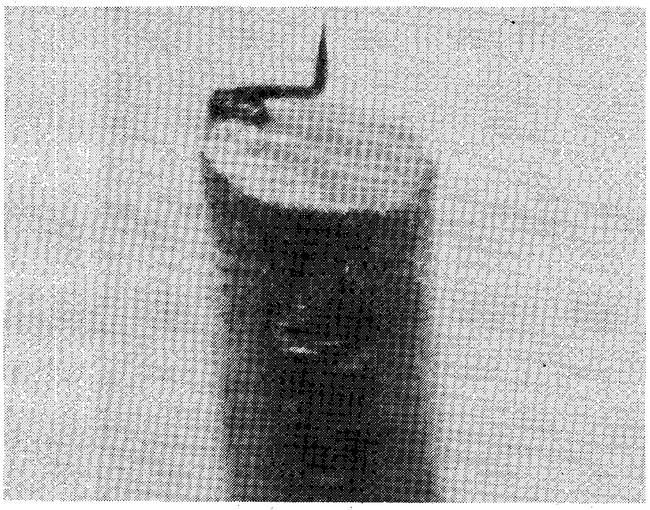

Fig. 2. Whisker post with 0.025-mm-thick chemically sharpened niobium whisker.

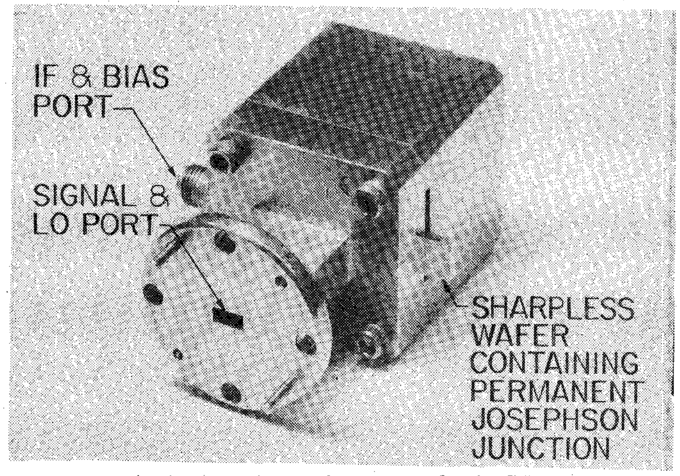

Fig. 3. Josephson mixer mount for 47 GHz.

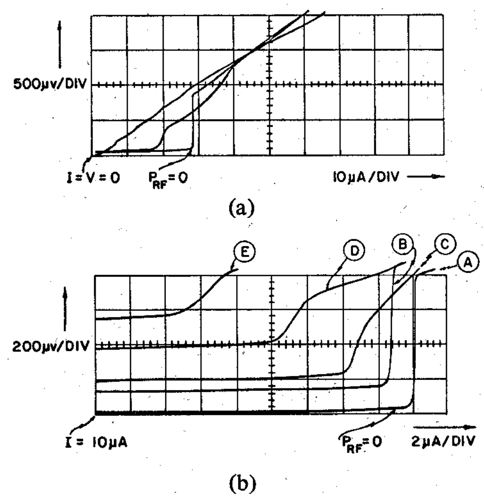

Fig. 4. I–V curves of permanent Josephson junction used for 47-GHz mixer. (a) Unexpanded. (b) Expanded.

located in a reduced-height waveguide section. A 0.025-mm-thick flexible niobium whisker is spotwelded to a 0.75-mm-thick post as shown in Fig. 2. The whisker is electrolytically sharpened to a tip width of less than 1 μm. The anvil side of the point contact consists of a polished niobium pin with a diameter of 0.75 mm. A multiple $\lambda/4$-type bypass filter connects this side with the dc bias and IF line.

A special differential whisker driver jig is used to adjust the contact at room temperature to a differential resistance R between 30 and 70 Ω. Before the contact is made, chemical cleaning with a hydrofluoric acid solution in an atmosphere of helium gas is performed. Earlier work with similar junctions [5] resulted in poor yields and mechanical instability whenever high impedance junctions were produced ($R > 15\ \Omega$). In contrast to these earlier junctions, the new ones are not epoxy sealed, use superconducting material for the whisker and the anvil only, and are set in the differential driver in a more controlled and reproducible fashion. These improvements have increased the yield to more than 90 percent.

Cooling of the wafers with liquid helium was performed employing either a special jig for accurate four-terminal measurements of the I–V curve or using the 50-GHz mixer mount shown in Fig. 3.

Fig. 4 shows an I–V curve of a typical junction with a critical current $I_c = 28\ \mu$A and a normal state resistance $R_{NS} = 33\ \Omega$; this junction is slightly hysteretic as can be seen from the almost vertical rise of the unpumped voltage ($P_{\rm RF} = 0$) at the I_c kink. Microwave-induced steps could clearly be seen up to at least the 12th harmonic of 47 GHz. The figure of merit for the mixing action of this junction, i.e., the product $I_c \times R_{NS}$ is equal to 0.92 mV. This value is about half of the theoretically possible value, given by the relation [6]

$$I_c \times R_{NS} = \frac{\pi \Delta}{2e} \qquad (1)$$

where $2\Delta/e$, the superconducting gap voltage, is 2.8 mV for niobium.

The approximate contact area A_j was obtained by measuring the flux density B of an external magnetic field that is required to suppress the supercurrent to zero, and using the relation [7]

$$A_j = \frac{\pi \hbar}{eB} \qquad (2)$$

where e and $\hbar$ are the electron charge and Planck's constant, respectively. A_j values on the order of 0.1 μm^2 were calculated for junctions with good conversion performance; this agrees fairly well with our theoretical predictions based on an R–J junction model.

Repeated temperature cycling does not affect the performance of these permanent junctions.

III. 47-GHz Mixer Setup

Fig. 5 shows a block diagram of the 47-GHz mixing experiment. A low-noise broad-banded multistage transistor amplifier from 1 to 2 GHz was used as IF system. Tapered,

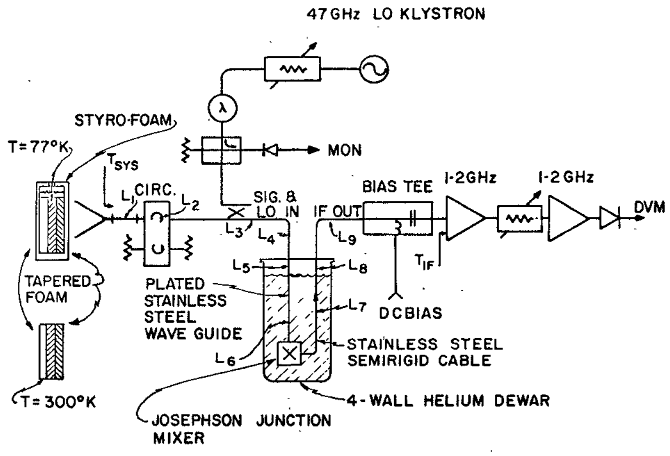

Fig. 5. 47-GHz mixer setup using permanent point contact Josephson junction.

TABLE I
SIGNIFICANT RF LOSS CONTRIBUTIONS IN FRONT OF JOSEPHSON MIXER

DEVICE DESCRIPTION	AVERAGE PHYS. TEMP.	LOSS
Waveguide Transition (2 in. lg.)	293°K	L_1 = 0.1 db
Input Circulator	293°K	L_2 = 0.7 db
LO Injection Coupler	293°K	L_3 = 0.5 db
3 in. Lg. Waveg. incl. 90° bend & Mylar window on top flange	293°K	L_4 = 0.2 db
8 in. Lg. Stainl. St., gold plated waveguide	150°K	L_5 = 0.2 db
10 in. Lg. Stainl. St., gold plated waveguide	4°K	L_6 = 0.05 db
Total RF loss in front of Josephson Mixer	4÷293°K	L_{RF} = 1.7 db

Note: Refer to Fig. 5.

TABLE II
IF CONTRIBUTIONS OF JOSEPHSON MIXER

DEVICE DESCRIPTION	AVERAGE PHYS. TEMP.	LOSS
10 in. Stainless Steel semirigid cable with plated center conductor	4°K	L_7 = 0.1 db
6.5 in. Stainless Steel semirigid cable	150°K	L_8 = 0.2 db
6 in. Stainless Steel semirigid cable	293°K	L_9 = 0.21 db
DC - TEE	293°K	L_{10} = 0.5 db
TOTAL IF LOSS	4÷293°K	L_{IF} = 1.0 db

Note: Noise temperature of two-stage IF Amplifier. T_{IF} = 300 K.

uncooled, and nitrogen-cooled foam was used for hot–cold noise measurements. More than 20-dB input isolation was provided by a broad-band circulator. The local oscillator (LO) was injected by a broad-band coupler in the input line. In order to avoid transients and discharges during the installation of the mixer, a filtered short is provided at the dc end of the bias TEE. The junction seems to be sufficiently well protected, once all connections are established, and even switching on and off the HV supply of the LO klystron cannot cause dangerous discharges in the junction.

IV. Noise Measurements and Discussion

The optimum drive point for lowest system noise was found to require LO power of approximately 3 μW; this resulted in a suppression $\Delta I_c/I_c$ of the supercurrent I_c by about 25 percent [curve D in Fig. 4(b)]. The optimum dc bias voltage V_B was measured to be 20 μV, which is fairly close to the theoretically expected bias point [2]. The relatively small ΔI_c value may partially be explained by noise and interference effects as evidenced by the rounding of the "knees" of the expanded I–V curves B through E in Fig. 4(b). The best RF performance was observed in junctions which exhibit slightly hysteretic I–V curves; this somewhat surprising result may indicate that the additional shunt capacitance of these junctions helps to reduce the detrimental rounding effects of the RF interference. Shielding of the partially transparent four-wall glass dewar should not only reduce these rounding effects, but also enable us to use our nonhysteretic junctions which should exhibit lower conversion loss.

The double-sideband noise temperature of the 47-GHz mixer system shown schematically in Fig. 5 was measured to be

$$T_{SYS} = 5600 \text{ K}.$$

Subtracting the contributions of the input RF and output IF components (Tables I and II) yields a single-sideband noise temperature for the Josephson mixer mount

$$T_{MIX} = 71 \text{ K}.$$

Assuming pure Johnson noise for the Josephson mixer results in a single-sideband conversion loss

$$L_C = \frac{T_{MIX}}{T_A} + 2 = 17.1 \mathrel{\hat{=}} 12.3 \text{ dB} \qquad (3)$$

where T_A = 4 K is the temperature of the liquid helium bath. It should be noted that the RF back short was set at room temperature and could not be readjusted at low temperature; also, the match at the IF port was fixed-tuned and probably not optimized. It is therefore likely that the aforementioned L_C value contains a substantial amount of RF and IF mismatch loss. This may also explain why at 300 GHz the same conversion loss (L_C = 12 dB) was measured for a similar, but adjustable, and well-matched Josephson mixer [4].

In order to utilize the low-noise characteristics of this Josephson mixer in a practical radiometer, radar, or communications receiver, one would use a low-noise IF amplifier such as a state-of-the-art maser or cooled paramp with a maximum noise temperature of 8 K. Assuming that a cooled input LO coupler and an existing cooled circulator were installed in the input line, one could expect for the total single-sideband noise temperature the fairly attractive value of 100 K. Millimeter maser and cooled paramp systems can achieve comparable noise performance; however, the Josephson mixer system can provide a much wider instantaneous bandwidth and tuning range, and also has a much better potential for frequencies above 100 GHz [4].

ACKNOWLEDGMENT

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The Challenge of Astronomy to Millimeter-Wave Technology

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Invited Paper

***Abstract*—The inseparability of pure and applied science, or the synergy between scientific discovery and technological advance, has already been well illustrated in the field of radio astronomy. Recent astronomical discoveries in the millimeter range, and what can be expected to emerge from the far-infrared region, make further technological developments in these relatively unexploited areas of great interest to astronomy as well as technologically challenging. The nature of problems and the goals of astronomy in this area are discussed with particular reference to technological needs and developments.**

RADIO ASTRONOMY has benefited enormously from the steady advance of microwave technology; at the same time it has stimulated many of these advances. This important realm of astronomy originated in Jansky's engineering investigations of the early 1930's, grew rapidly with the help of wartime microwave technology, and recently has become all the more active following the discovery of complex molecules in interstellar clouds. So far, 38 species of molecules, some having as many as eight atoms, have been found in the large and relatively dense clouds of dust and gas within our galaxy, and a few species have been detected in external galaxies. The absorption or emission of molecular lines are associated primarily with their rotational motions; these resonance lines occur commonly in the centimeter region but are even more abundant and intense in the millimeter range. This adds great importance to the development of millimeter-wave technology. In addition, there are many molecular resonances at still shorter wavelengths in the submillimeter range. This latter region, which is presently almost completely unexploited, needs imaginative invention for its development as well as airborne or spaceborne platforms for any extensive astronomical use.

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The relatively simple spectra of linear molecules are characterized by a series of almost harmonically related frequencies given to good accuracy by $\nu = (Jh/4\pi^2 I)$, where J is an integer, h is Planck's constant, and I is the molecular moment of inertia. For example, CO has lines at wavelengths 2.6 mm, 1.3 mm, and various other fractions of the fundamental wavelength 2.6 mm. Thus the lightest and simplest molecules have spectra only in the millimeter range or at still higher frequencies. More complex molecules, having three different moments of inertia and possibly internal rotational motions as well, have a more complicated spectrum which can give a variety of frequencies at both long and short microwave wavelengths. Generally, the shorter wavelength resonances, at least down to about 1 mm, are the more intense. In addition to rotational motions, there are some exceptional cases where molecular vibrations such as the inversion spectrum of ammonia, or even atomic hyperfine structure such as the 21-cm hydrogen line, fall in the microwave region. Molecules which have been found in interstellar clouds by their microwave spectra include many of the simplest, such as diatomic oxides and hydrides, but also a surprising number of organic molecules such as formaldehyde, dimethyl ether, various amines and acetylenes, and even ethyl alcohol.

Gas clouds containing molecules are interesting for a variety of reasons besides the existence of molecules there. They contain considerable solid materials in the form of dust