COUPLED JOSEPHSON LOCAL OSCILLATOR AND DETECTOR EXPERIMENTS IN THE TERAHERTZ REGIME

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1. Abstract

Recent coupled Josephson junction experiments in our laboratory have demonstrated that high critical current density tunnel junctions can serve as effective local oscillators at frequencies up to and in excess of the gap sum frequency of the junction, i.e. well above 1 Terahertz for a niobium or niobium compound tunnel junction. While the details of the behavior of such a THz. oscillator were found not to be in accord with the predictions of the accepted theory of the A.C. Josephson effect in the gap region significant radiation could be capacitively coupled from the oscillator junction to an adjacent junction, sufficient for SIS mixer experiments at Terahertz frequencies. Research efforts are now under way to further extend and expand these studies. A high critical current density all NbN tunnel junction system is now under development for Terahertz applications and a new set of coupled Josephson oscillator - SIS detector experiments is being initiated using NbN tunnel junctions. In this paper we will review the original coupled junction high frequency experiments and report on the recent progress of the current NbN tunnel junction experiments.

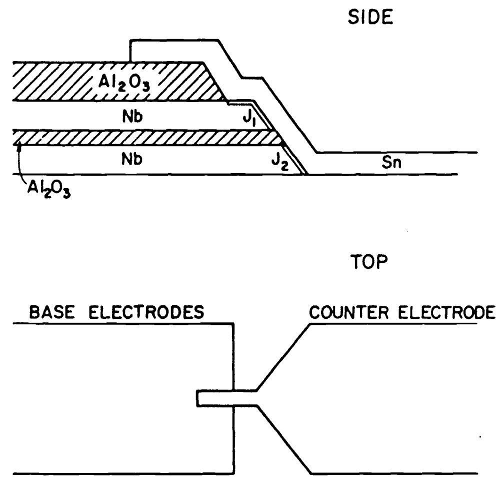


Figure 1. Double coupled tunnel junction device in cross section and from top view.

2. Introduction

The production and detection of sub-millimeter wave signals for communications systems and radio astronomy applications presents severe engineering problems for even state of the art compound semiconductor (GaAs) devices. SIS tunnel junctions used as mixers have been demonstrated to show superior performance over semiconductor (Super Schottky) mixer elements for frequencies less than 100 GHz. Theoretical predictions indicate that quantum limited detection sensitivity is possible in high quality SIS devices at these and higher frequencies. Our research program has focussed on several goals. We have investigated the high frequency *pair* current response of a Josephson tunnel junction for use as a local oscillator for heterodyne detection of THz. signals. These experiments will be described in the next section. Currently, we are also developing all refractory, high current density Josephson tunnel junctions for local oscillator experiments at higher frequencies. Refractory junctions are desirable because their durability allows them to survive post junction fabrication processing so they may be incorporated into practical, very high frequency detection circuits.

3. Previous Experiments

Our previous work involved the fabrication of a device which consisted of two high current density capacitively coupled tunnel junctions shown in figure 1. The device consists of two junctions formed on the edges of a thin film stack [1]. The capacitive coupling arises through the thin 500Å layer of Al_2O_3 separating the base Nb electrodes. Reactive ion beam oxidation was used to form the tunnel barrier, over which the counter electrode was deposited (Sn in this case). The equivalent circuit model of this device is shown in figure 2.

For a Josephson tunnel junction to serve as an effective local oscillator (LO) its capacitive shunt impedance must be higher than its normal state impedance R_n at the desired LO frequency, and its dynamic impedance at the bias point should be as low as possible for a narrow oscillator line width. This necessitates the fabrication of high current density junctions or alternatively resistively shunting the junction which reduces the LO power and leads to the requirement of fabricating junction arrays. For LO's the McCumber parameter β_c, defined by

$$\beta_c = (2e/\hbar)(I_c R_n)(R_n C) \tag{1}$$

is constrained to be less than 1. Here I_c is the critical current, and C is the junction capacitance. By biasing the the device with a constant D.C. current an average D.C. voltage V_{bias} will develop across the junction. In accord with the A.C. Josephson effect, an A.C. voltage will develop across the junction, the frequency of the oscillation being determined by the Josephson relation

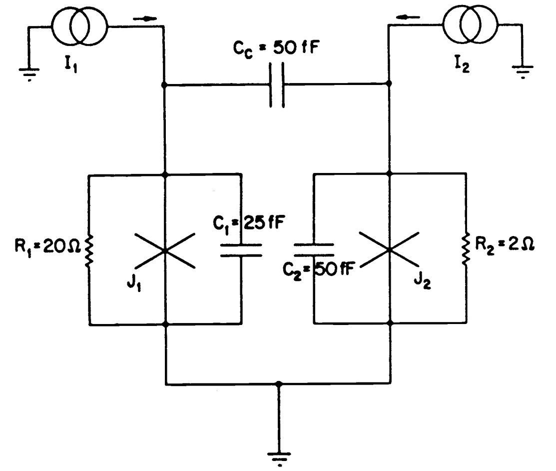


Figure 2. Equivalent circuit schematic for the double tunnel junction device.

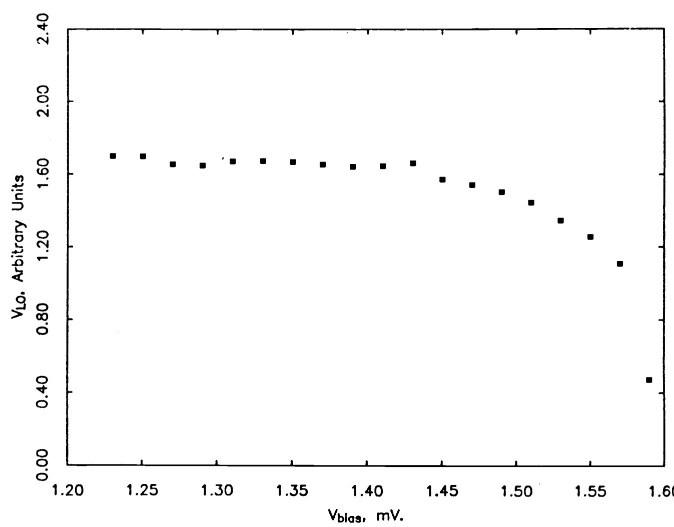


Figure 3. Measured local oscillator signal strength V_{LO} vs. V_{bias}.

$$\omega = 2eV_{bias}/\hbar. \quad (2)$$

The junction biased in this manner is a voltage controlled oscillator where the voltage to frequency conversion is $2e/h = 0.484THz./mV.$

We have measured the LO power output as a function of frequency using our double tunnel junction device. As a consequence of the A.C. Josephson effect, an A.C. signal coupled into a junction will be mixed down to D.C. and appear as a constant voltage current step in the current - voltage (IV) characteristic. The size of the step can be related to the oscillator power coupled into the device. Referring to figure 2, in our experiment J_2 was biased to serve as the LO and J_1 was used as the detector. The measured power output of J_2 as a function of frequency is shown in figure 3. For this particular set of junctions 12.5 nW was coupled into J_1 at 0.73 THz.

The theoretical frequency dependence of LO power for low β_c junctions for frequencies approaching the gap sum frequency is complex and not in agreement with our measurements for frequencies in excess of the gap sum, $V_{bias} > \Delta_1 + \Delta_2$. A more precision measurement of the frequency dependence of LO power in this region will be the focus of future experiments. However, for frequencies less than or equal to the gap sum frequency our experimental results do agree reasonably well with calculations based on the high frequency pair current theory. In this frequency regime both experiment and calculation verify that the maximum signal amplitude of the LO is well approximated by the I_cR_n product, i.e.

$$V_{LO} \sim I_cR_n \qquad (\beta_c \leq 1). \quad (3)$$

For an ideal Josephson junction this value is related to the energy gap

$$I_cR_n = \frac{\pi}{2}\frac{\Delta}{e}. \quad (4)$$

Eqn. (4) implies that LO power may be increased by using large Δ materials, in addition to raising the maximum operating frequency of the device, $\hbar\omega_{max} = 4\Delta$.

4. Current Research

Our current research program in NbN films for use in high current density Josephson tunnel junctions was motivated by the desire to achieve higher operating frequencies and LO power outputs, as well by practicality. Edge junction devices with soft counter electrodes and native oxide barriers are excellent research tools but lack the ruggedness to survive post junction fabrication processing needed to incorporate the devices into useful circuits, i.e. real world electronics. Furthermore, the fabrication of Josephson junctions with high T_c electrodes ($T_c \sim 16^oK$) would allow operation at 10^oK, within the limits of closed cycle refrigerators.

Our NbN films are produced by the reactive sputtering of Nb in an atmosphere of Ar, N_2, and CH_4. The films are sputtered with no intentional substrate heating at a rate of approximately $40\AA/sec$. Films produced in this way are smooth and have high transition temperatures. Figure 4 shows a resistance v.s. temperature plot of a typical NbN film. The film has a transition temperature $T_c = 15.5K$, a transition temperature width $\Delta T_c = 0.1K$ and a residual resistance ratio $RRR = 0.96$. The narrow transition temperature width is important for the fabrication of high quality junctions with small dynamic resistance at the gap edge because a distribution in transition temperatures implies a distribution in the superconducting energy gap. If this smearing in Δ is present in the tunnel junction near the barrier the sharpness of the IV curve at the gap edge will be reduced. Since it is desirable, both for mixing and LO signal production, to keep the rise in current at the gap edge as sharp as possible highly uniform films are desirable.

In our all refractory junction process MgO is sputtered to form the artificial tunnel barrier. Our process is quite similar to others developed previously. A NbN/MgO/NbN trilayer is

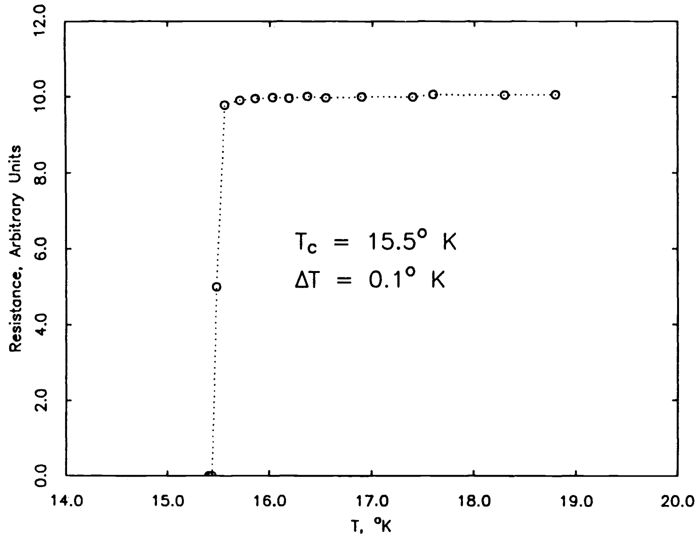


Figure 4. Resistance vs. temperature for a typical NbN film.

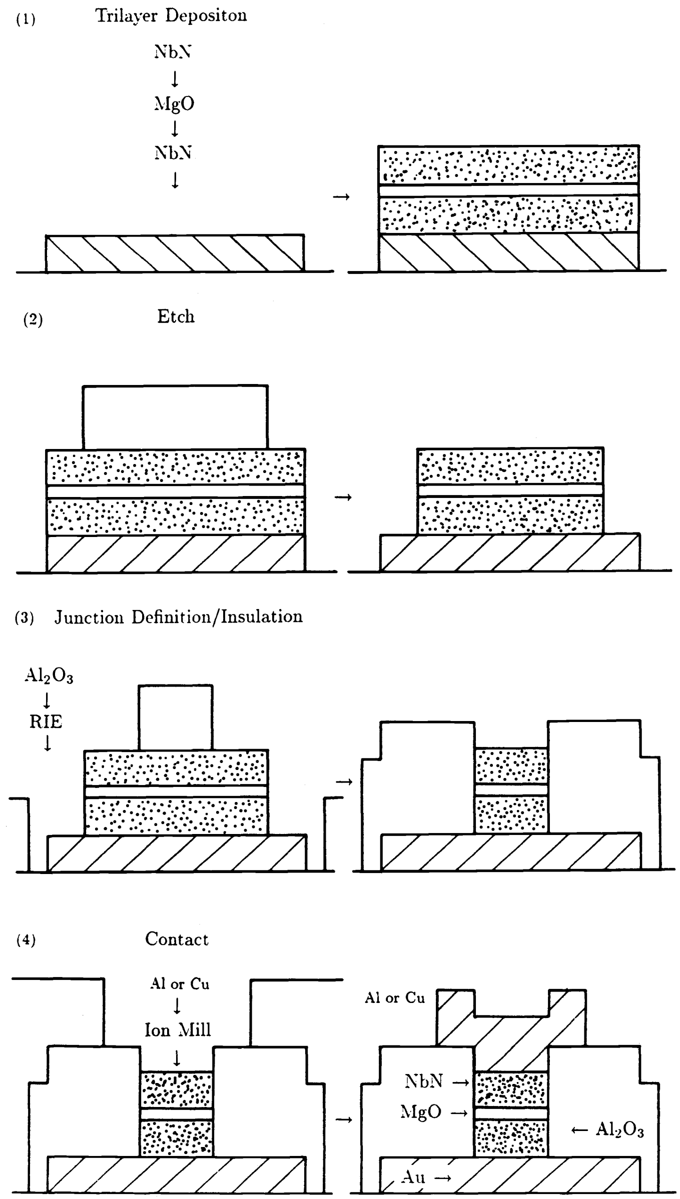


Figure 5. Fabrication process for all refractory NbN/MgO/NbN Josephson tunnel junctions.

sputtered, without breaking vacuum over a sapphire wafer with Au contact pads previously deposited. The trilayer is etched, first with a wet etch and then with RIE to define the $2\mu \times 2\mu$ junctions. Al_2O_3 is used to insulate the junction sides and base electrode wiring. Further photolithography defines the counter electrode wiring, which is typically Cu or Al to aid in the removal of heat from the junction while the junction is biased. The entire process is shown schematically in figure 5.

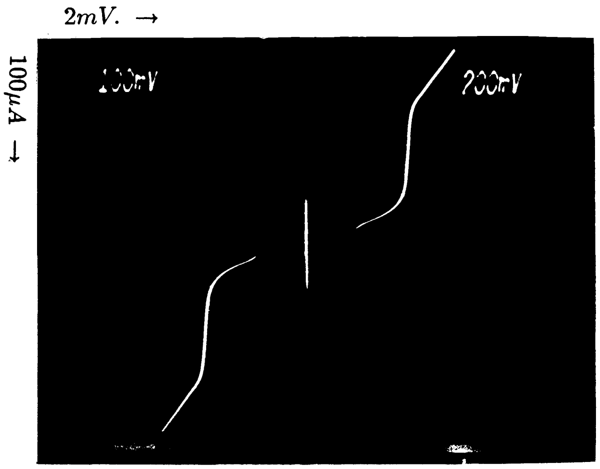
Some typical junction characteristics are shown in figure 6. Figure 6a shows the IV characteristic of a junction with a critical current density $J_c = 5 \times 10^3 A/cm^2$, $V_m = 12mV.$, and $2\Delta = 4.1mV$. Figure 6b shows the IV of a higher current density junction, $J_c = 4 \times 10^4 A/cm^2$, $V_m = 4mV.$, and $2\Delta = 4mV$. Future process work will concentrate on raising 2Δ, V_m, and J_c. We have subjected these devices to post junction fabrication photolithographic processing as well as thermal cycling between 300 K and 4.2 K, and have found them to be quite durable.

Our ultimate goal is to produce high quality junctions with a critical current density of $5 \times 10^5 A/cm^2$ so $\beta_c \leq 1$. Of course in such high current density junctions non-equilibrium and local heating problems will likely be a serious concern. But previous experiments in our laboratory with small area, high current density tunnel junctions have shown that such effects can be alleviated through the use of efficient fan-out geometries that permit the rapid diffusion of non-equilibrium quasiparticles from the active junction area.

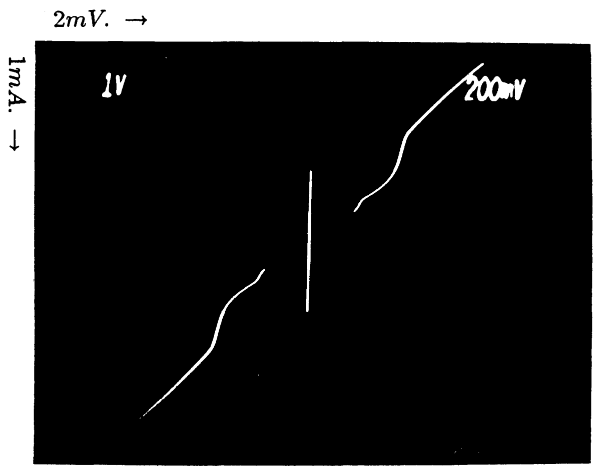
Our initial experimental goal is to use these high current density junctions to make more precise and unambiguous measurements of the pair current response of a Josephson tunnel junction at frequencies close to and greater than the gap sum. We propose to establish the suitability of such junctions for use as LO's for heterodyne mixing of THz. signals. The line width of a Josephson junction oscillator biased at a D.C. voltage V_0 has the theoretical form [2]:

$$\Delta\omega = \left(\frac{2e}{\hbar}\right)^2 R_d^2 \Big[2eI_{Pair}(V_0)coth(\beta eV_0) + eI_{Qp}(V_0)coth(\beta eV_0/2) + 2eI_{Qp-Pair}(V_0)coth(\beta eV_o) \Big] \quad (5)$$

Here I_{Pair}, I_{Qp}, and $I_{Qp-Pair}$ are the pair, quasiparticle and quasiparticle - pair interference currents at a voltage V_0 respectively. R_d is the dynamic resistance of the device at the bias point V_0 and $\beta = 1/k_bT$. Since the linewidth is proportional to the square of the dynamic resistance it is clear that the most favorable operating point for a junction biased to serve as a local oscillator is at the gap edge where R_d is smallest. Using device parameters that we have achieved for NbN/MgO/NbN



(a)



(b)

Figure 6. IV characteristics of several junctions; (a) $J_c = 5 \times 10^3 A/cm^2$ (b) $J_c = 4 \times 10^4 A/cm^2$.

tunnel junctions biased at the gap edge, $R_d = 2\Omega$, T = 10 K and $I_c = 200\mu A$ we find that

$$\left.\frac{\Delta\omega}{\omega}\right|_{\omega=2.3THz.} = 4 \times 10^{-5} \qquad (6)$$

which should be suitable for mixing down to an IF frequency of 100 GHz. With a factor of 10 reduction of R_d at the gap edge, which is not an unreasonable goal the line width would be further reduced by a factor of 100. Such a reduction in R_d could probably be achieved through the fabrication of junctions with improved characteristics, or through the use of a stripline resonator or junction arrays.

In conclusion, we have investigated the feasibility of using high current density Josephson tunnel junctions as very high frequency local oscillators. Experiments with capacitively coupled junctions demonstrate that sufficient power can be coupled out of the junctions at frequencies in excess of 1 THz. We have developed an all refractory NbN/MgO/NbN tunnel junction process to raise both the LO power output and frequency, as well as the operating temperature of the device to the 10 K range. Future work will include raising the current density of these junctions as well as capacitively coupling them to a second junction to extend our measurements of LO power output to frequencies above 2 THz.

5. Acknowledgements

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6. References

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2. D. Rogovin and D. J. Scalapino, "Fluctuation Phenomena in Tunnel Junctions", Ann. Phys., vol. 86, 1, 1974.