Abstract

Voltage tunable Josephson junction Terahertz oscillators have been fabricated using rugged, high current density NbN\textsubscript{1-x}C\textsubscript{x} tunnel junctions with MgO barriers. The radiation emitted from such junctions is detected on chip by a second Josephson junction which is capacitively coupled to the first. For oscillator junctions with a critical current density of \( J_c \approx 3.5 \times 10^9 \text{A/cm}^2 \) we find that the junction oscillates with a voltage amplitude of \( V \approx 1.5 \text{mV} \). The detected RF voltage level remains essentially constant from 300 GHz to above 1 THz, the upper limit of the detector. From measurements of the Josephson step height in the detector IV it is determined that the oscillator junction is producing 0.5 pW of Terahertz radiation of which, due to impedance mismatch, 10 nW is coupled into the detector junction.

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. For this reason there has been much interest in the application of Josephson junctions at high frequency, voltage tunable oscillators. Although the power available from a single device is low the use of these devices in a coupled array configuration could significantly boost the available power. The focus of our research program has been the development of a device in which a high current density NbN\textsubscript{1-x}C\textsubscript{x} / MgO / NbN\textsubscript{1-x}C\textsubscript{x} tunnel junction is capacitively coupled to an SIS detector junction to measure the high frequency response of these junctions when biased to serve as local oscillators. Our results indicate that NbN\textsubscript{1-x}C\textsubscript{x} junctions can be successfully employed as local oscillators at frequencies well above 1 THz.

Device Fabrication

In figure 1 is shown a schematic representation for the integrated thin film microstructure used in this experiment. It consists of two SIS devices coupled at RF frequencies but DC isolated so that each may be individually biased. One junction is a trilayer mesa type formed with NbN\textsubscript{1-x}C\textsubscript{x} base and counter electrodes and an MgO barrier. The second junction is an edge type utilizing a Nb base electrode with a native oxide Nb\textsubscript{2}O\textsubscript{5} barrier and Sn counter electrode. In normal operation the mesa junction is biased to serve as the local oscillator and the edge junction serves as a Josephson RF detector. A Nb-Sn detector junction was used in this experiment to permit the study of the response of a Josephson junction at frequencies well in excess of the gap sum frequency.

The fabrication process starts with unoriented sapphire substrates onto which a bimetallic Nb/Au wiring is deposited using standard photolithographic lift-off techniques. Onto these substrates a NbN\textsubscript{1-x}C\textsubscript{x} / MgO / NbN\textsubscript{1-x}C\textsubscript{x} trilayer is sputtered without breaking vacuum. NbN\textsubscript{1-x}C\textsubscript{x} is reactively sputtered from a Nb target in an Ar/N\textsubscript{2}/CH\textsubscript{4} ambient with no intentional substrate heating. The films are characterized by a high transition temperature (\( T_c = 15.5 \text{ K} \)) and sharp transition width (\( \Delta T \approx 0.1 \text{ K} \)). To obtain this result we find that very close control of the sputter gas ambient pressure and composition are required. MgO barriers are RF sputtered in a 10 millitorr Ar ambient.

After the trilayer deposition the films are chemically etched to remove most of the trilayer except for areas 30 \( \mu \text{m} \) square over the active device area. The final 2 \( \mu \text{m} \times 2 \mu \text{m} \) junctions are defined by reactive ion etching of the larger 30 \( \mu \text{m} \) squares using photo resist as a mask. The etch mask serves as a lift-off stencil for the insulation of the sides and base electrode of the junction in a self aligning process very similar to the 

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Integrated thin film microstructure used in the local oscillator experiments. The bimetallic layers are shown as single layers for clarity. Vertical scales are greatly exaggerated.}
\end{figure}
similar to the one developed by Shoji et. al. After reactive ion etching in a 20% O2/CF4 plasma Al2O3 is electron beam evaporated and lifted off. Al2O3 is used as an insulator because its low dielectric constant ($\varepsilon_{Al2O3} = 5$) keeps parasitic loading of the oscillator to a minimum. After insulation, lift-off stencils are applied for wiring patterns to contact the counter electrode. The counter electrode is etched with an ion mill, followed immediately by the deposition of Al (2000 Å) and Nb (400 Å). The Al provides a low strain, high thermal conductivity path away from the junction which along with the Au base electrode wiring helps to minimize self heating of the oscillator under bias, an important feature of this design in light of the requirement of high current density and the relatively low thermal conductivity of NbN1-xCx. Once the oscillator contact process is complete the Nb layer is chemically anodized to grow 350 Å of Nb2O5, ($\varepsilon_{Nb2O5} = 29$). This insulating layer forms the dielectric of the coupling capacitor. Over this 1500 Å of Nb is sputtered, followed by 2000 Å of Al2O3. This last layer forms the base electrode for the detector junction. An inert ion beam is used to etch the edge of this thin film stack, after which a counter electrode stencil is applied, through which the tunnel barrier is formed by reactive ion beam oxidation. The counter electrode is deposited and lifted off. An SEM photo of the completed device is shown in figure 2. Of course through use of NbN1-xCx for the base and counter electrodes the minimum operating temperature of the integrated oscillator-detector microstructure could be raised to 10 K. A typical current - voltage (IV) curve of a high current density generator is shown in figure 3a. The gap sum of the detector (1.8 mV) is somewhat reduced from the full theoretical value (2 mV) because of impurities in the Nb film. The generator gap sum is reduced from 5 mV to 4 mV because the NbN1-xCx is off stoichiometry. Figure 3b shows the IV characteristic of the detector junction taken with the generator junction unbiased.

**Equivalent Circuit**

The edge junction base electrode together with the common Au wiring forms a transmission line which is capacitively coupled to the generator. The typical generator operating frequency is 1 THz. At this frequency the signal wavelength is

$$\lambda = 130\mu m \text{ (correcting for the dielectric constant of Al2O3),}$$

which is much longer than the 10 μm length of line between the generator and detector. Consequently we may approximate the phase of the signal as being constant over the length of the coupling structure and use a simple AC circuit to model the device. The equivalent circuit is shown in figure 4. $C_G$ represents the coupling capacitor, $L_p$ and $C_p$ the parasitic inductance and capacitance respectively associated with the coupling structure. For the dimensions shown in figure 1 we have $C_G = 0.7 \text{ pf}$, $L_p = 24 \text{ ph}$, and $C_p = 0.05 \text{ pf}$. This means that at an oscillator frequency of 2 THz, for oscillator impedances of $\sim 1\Omega$, detector impedances of $\sim 20\Omega$ or greater, the coupling efficiency $\eta = V_d/V_o$, where $V_d$ is the amplitude of the detected signal and $V_o$ is the amplitude of the oscillator signal at the generator approaches unity. For the device whose IV characteristics are shown, taking the normal state resistances of the junctions, $R_p = 1.9\Omega$, $R_d = 110\Omega$, and $\eta \sim 1$. In this design $\eta$ remains close to unity even for frequencies down to 100 GHz, which represents a range of over a factor of 20 in frequency over which the coupling efficiency is essentially unity.

When DC biased, the generator will produce an oscillating
voltage signal $V_2$ at a frequency determined by the Josephson relation

$$f = \frac{2eV_{bias}}{\hbar}.$$  \hspace{1cm} (1)

Here $V_{bias}$ is the average voltage across the junction. $V_2$ will be determined by the total capacitive loading of the generator. When the McCumber parameter $\beta_c$ defined by

$$\beta_c = \frac{2\epsilon/h}{I_cR_n}(R_nC)$$  \hspace{1cm} (2)

is less than unity the junction is not capacitively shunted and the maximum $V_2$ obtainable is approximately $I_cR_n$, at least for $V_{bias} < 2\Delta$. At $T = 0$ the $I_cR_n$ product is related to $\Delta$ through the Ambegaokar-Baratoff relation

$$I_cR_n = \frac{\pi \Delta}{2e}.$$  \hspace{1cm} (3)

Thus larger oscillator signal amplitudes, as well as higher frequencies, are possible with higher $\Delta$ materials. This is part of the motivation in the choice of NbN$_{1-x}$C$_x$ for the generator base and counter electrodes. The capacitance in expression (2) is the total capacitance seen by the generator at the oscillation frequency which by design of the coupling structure is dominated by the junction capacitance. For a deposited MgO barrier 10 Å thick this capacitance is $C = 0.3$ pf assuming $\epsilon_{MgO} = 9.7$. This gives $\beta_c(gen) = 6$ so the generator is partially shunted and its IV characteristic is hysteretic. The degree of hysteresis shown in figure 3a is consistent with numerical estimates.

**Oscillator Performance**

When the generator is DC biased and if it emits radiation of sufficient power constant voltage steps will be induced in the IV of the detector at integral multiples of $V_{bias}$ 11. Figure 5 shows the detector characteristic with the generator biased at 1.090 mV. The $N = 1$ and $N = 2$ Josephson steps are marked, as is the supercurrent ($N = 0$).

Here $\alpha = \frac{2eV_2/\hbar}{V_2/V_{bias}}$, and $J_N(x)$ is the Bessel function of the first kind of order $N$. For the steps on the detector IV in figure 5 both the generator and detector critical currents were suppressed by a magnetic field used to allow biasing the generator at this low frequency. The detected power is thus reduced. By taking the ratio of the current widths of the $N = 0$ and $N = 1$ steps and using equation (4) we may solve for $\alpha$. This is more accurate than applying equation (4) directly since flux trapping makes the precise determination of $I_c$ difficult.

Assuming a coupling efficiency of unity we find $V_2 = 1.54$ mV, 58% of the maximum value of 2.66 mV set by the $I_cR_n$ product in the low $\beta_c$ limit. While according to equation (2) to achieve the $\beta_c \sim 1$ limit a critical current density of $J_c = 3 \times 10^4$ A/cm$^2$ is required we find that with a hysteretic IV characteristic and a generator critical current density of $J_c = 3.5 \times 10^4$ A/cm$^2$ an RF power of 12 nW is being coupled into the 110$\Omega$ detector junction. This corresponds to a peak generator power of $V_{bias}^2/2R_n = 0.6$ $\mu$W which is poorly coupled into the detector because of the large impedance mismatch (50 : 1) of the detector and generator. Thus we find that single, unshunted tunnel junctions can emit a comparably high level of submillimeter wave radiation even when the critical current density $J_c \sim 10^4$ A/cm$^2$ is such that the junction is partially hysteretic and $\beta_c > 1$.

**Generator Self Heating**

In designing the biasing structure the self heating of the generator junction under bias and the local rise in temperature at the detector are important considerations. A measurement of the effectiveness of the biasing structure as a heat sink can be obtained by comparing the IV characteristic of the generator with the sample cell filled with He gas and then filled with He liquid to improve thermal contact to the bath. We have observed negligible changes in the gap sum voltage under these conditions.
two conditions and conclude that self suppression effects of the generator are small at these current densities, assuming that, as is generally the case, heat transport away from the junction is substantially increased by the presence of liquid He. Another means of examining device heating is to monitor the local temperature at the detector by measuring the Sn gap as a function of power dissipation of the generator. At a bath temperature at the detector by measuring the Sn gap as a function of power dissipation of the generator. At a bath temperature of 1.5 K, we find that biasing the generator at 24 µW will raise the temperature of the detector, which is only 12 µm from the generator, 2.2 K when only He exchange gas is present in the sample cell. With liquid He in the cell more than 5.5 times more power is required to produce the same temperature rise. When biased at the gap edge the generator dissipates 7.5 µW, so with liquid introduced into the cell adequate heat sinking should be obtainable with generator current densities well into the 10^4 A/cm^2 range. Of course it is possible that if the heating is more localized self heating of the oscillator could begin to be a problem in this higher current density range. Since our experiments demonstrate that J_s ~ 5 x 10^4 A/cm^2 is adequate for Terahertz operation this should not be a concern. Using an all NbN_x,C_y detector junction would further reduce the effects of small temperature rises on detector performance.

**High Frequency Pair Current Response**

We have measured the frequency dependence of the pair current response as the generator bias is tuned through the gap sum of the detector. At frequencies approaching and in excess of the gap sum the expression (4) is no longer valid and the full high frequency theory which takes into account the frequency dependence of the pair current must be used. With the application of the frequency dependent theory we find good general agreement with experiment up to the gap sum frequency but above this frequency the the Josephson response decays much more rapidly than is predicted by the theory. These results are consistent with previous measurements we have made on even more closely coupled tunnel junctions. Our results do indicate that the generator with its higher gap sum is functioning at frequencies at least up to 1.4 THz. Experiments with a higher gap sum detector junction are now in progress to examine this ultra high frequency limit in more detail.

**Conclusions**

In conclusion, we have designed, developed, and fabricated an integrated thin film microstructure for the study of the performance of high current density, unshunted Josephson tunnel junctions as high frequency local oscillators. The local oscillator is directly coupled to the detector by an RF capacitor, to achieve highly efficient broad band coupling. We have succeeded in coupling nearly 60% of the maximum LO voltage signal available into an SIS detector junction over a frequency range from 300 GHz to 1.0 above THz. The incorporation of an all refractory detector junction into the device would raise the minimum operating temperature to 10 K, in the range of closed cycle He refrigerators. Furthermore, there is a possibility of modifying this device for Terahertz heterodyne mixing applications.

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