RESPONSE OF Nb-asI-Nb JUNCTIONS TO 604 GHz RADIATION

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Abstract

We have measured the response of Nb-asI-Nb junctions to 604 GHz radiation from an optically pumped far-infrared (FIR) laser source. These rugged and thermally cyclable junctions situated at the midpoint of 180 µm long dipole antennas, were fabricated on oxidized silicon wafers using the Selective Niobium Anodization Process (SNAP). Josephson current densities were -9,000 A/cm², the McElmurry parameters β, were -3.5, and the Josephson plasma frequencies ωJ-2.5x10¹⁰. On a junction with a normal state resistance of -70, we observed three Josephson steps and one photon-assisted tunneling step. The widths of the Josephson steps were studied as a function of the laser power. An RSJ model computer simulation with a nonlinear quasiparticle conductance and an rf current bias (assumed because of the low junction resistance) is able to account reasonably well for the laser-power dependence of the critical current (zeroth step) and the second step. However, the temperature dependence is more complex, and a discrepancy still exists between the RSJ model calculation and the data for the hysteretic first step.

Introduction

Superconductor-insulator-superconductor (SIS) tunnel junctions have been shown to exhibit quantum-limited noise performance when operated as quasiparticle heterodyne mixers in the millimeter wavelength region of the spectrum.1 Recently, it has been demonstrated2 that high-quality small-area (asili)²) Nb-asI-Pb tunnel junctions can be operated in the submillimeter region. When illuminated by a pumped far-infrared (FIR) laser source, these junctions exhibit both the ac Josephson effect and photon-assisted tunneling in good agreement with theory.²,³ These results indicate that small-area junctions are potentially useful as low-noise submillimeter wave heterodyne mixers.

In work reported thus far, the tunnel junctions used were fabricated from soft-metals, such as Pb and Sn, and thus were unable to cycle between room temperature and 4.2K more than a few times. Refractory metals such as Nb provide the best hops for the robust, thermally-cyclable junctions needed for practical applications such as low-noise astronomical receiving systems. In this paper we report the response to 604 GHz radiation of Nb-asI-Nb junctions, fabricated by the selective niobium anodization process (SNAP).³

Fabrication Techniques and Sample Parameters

The junctions were fabricated at Sperry Research Center using the Selective Niobium Anodization Process (SNAP). SNAP process has been described previously in detail, and we review it here briefly. A cross-sectional view of the completed device is shown in Fig. 1. The process begins with a trilayer of Nb, amorphous Si (asili), and Nb, which have been previously deposited on a 2" oxidized Si wafer. The small asili barrier was partially hydrogenated, as part of a series of experiments aimed at improving device quality.⁴ A layer of Si0₂ (not shown) is deposited and patterned by a wet chemical etch, leaving squares of material wherever junctions are desired. This serves as a mask during the anodization step, during which the Nb counter electrode is converted to Nb₂O₅ everywhere except under the Si0₂. The remainder of the Si0₂ is then etched away. While photoresist can also be used as the anodization mask, Si0₂ is preferred for small junctions, because of the absence of any measurable undercutting in perimeter effects. The anodized trilayer, which has essentially been converted to an insulated base electrode, is next patterned by plasma etching, forming half of the antenna structure. A second Si0₂ layer is then deposited, and vias are etched down to the junctions. This Si0₂ serves three functions: it insulates the edges of the patterned trilayer, it reduces the parasitic capacitance of the completed device, and it serves as an etch stop for the final Nb layer. The device is completed by depositing and patterning a Nb layer which contacts the junction and forms the other half of the antenna. A layer of gold is also deposited and patterned for ease of contacting the bonding pads, but this step is not essential.) With the sole exception of the Nb₂O₅, all layers were formed by sputter deposition and were subsequently patterned by subtractive etching through a photoresist mask. We emphasize this so as to avoid any confusion with the IBM Pb-alloy process in which most layers were evaporated through a previously patterned photoresist lift-off stencil.

Fig. 2 displays three SEM micrographs at increasing magnification of a SNAP junction at the center of a -180 µm long dipole antenna used for coupling to the FIR laser source. Fig. 2(a) shows one-half of a 2 mm x 4 mm chip upon which two devices are fabricated. The dipole antenna is the top of the "T" in the top part of Fig. 2(a). At the bottom of the figure, 100 µm x 200 µm pads can be seen, to which 25 µm diameter gold lead wires have been bonded. This sample chip is glued to a 6 mm x 6 mm Si carrier chip. Gold lead wires connect the small pads on the 2 mm x 4 mm junction chip to larger (1 mm x 1 mm) pads on the carrier. Lead wires in the dewar insert are silver painted to the pads on the carrier.

A close-up of the 10 µm line-width antenna is shown in Fig. 2(b). In this micrograph the antenna axis is vertical. The horizontal bars on the left are...
The capacitance of the junction itself was estimated to be 0.08 pF, based upon estimates of the area and specific capacitance of the junction. The junction area could not be accurately measured from the micrograph, because the junction is covered by a layer of SiO which tends to shift the apparent edge of the junction inward by an unknown distance, as indicated in Fig. 1. Its area was therefore computed by dividing its measured critical current by the critical current density, which was estimated to be 9000 A/cm² from measurements with larger junctions. The specific capacitance was measured to be 0.035 pF/vm² (215%) from resonance in SQUIDs prepared on the same wafer, though the uncertainty in the total SQUID inductance and the junctions studied in the FIR are listed in Table 1. This ratio is smaller than that in Sn-Pb junctions studied previously and is also smaller than that in lower current density aSi SNAP junctions, which had R/L/RL=10 for plain Si barriers or as high as 18 for composite Si/Si:H/Si barriers.7

As the laser power illuminating the junction is increased from zero, Josephson steps appear at discrete voltages Vn=n(-EuL/2e) where n is an integer; simultaneously photon-assisted tunneling steps appear at ±Vg+k(Δφ/2e) where k is also an integer. At maximum FIR laser power, we observe that the critical current, i.e., the zeroth Josephson step, is depressed to about 35% of its zero-laser-power value. The n=1 and 2 Josephson steps are easily seen in the figure, while the n=3 step is barely visible. A small photon-assisted tunneling step is observed at Vg+ effic of 5.4 mV. This step may be so small because the large leakage

![I-V curve taken with zero laser power applied to the junction. The bottom part of the figure displays an I-V curve taken at the maximum laser power.](image)

FIG. 3 I-V curves of the SNAP junction in Fig. 2 irradiated with zero and maximum power 604 GHz (λ = 496 nm) laser radiation. We observe Josephson steps at Vg+n(Δφ/2e) where n=1, 2, and 3, and a single photon-assisted tunneling step at Vg+ effic of 5.4 mV.

With zero laser power, we observe that the gap structure of niobium is at Vg=2πΔφ/2e = 2.8 mV. The ratio of the leakage resistance below the gap, RL, to the junction normal state resistance Rn is R/L/Rn=2.6. This ratio is smaller than that in Sn-Pb junctions studied previously which had R/L/Rn=10. It is also smaller than that in lower current density aSi SNAP junctions, which had RL/Rn=10 for plain Si barriers or as high as 18 for composite Si/Si:H/Si barriers.7

Table I. Junction Parameters. IC, Ec, and ωj values are for 1.4K. Area is computed from IC, taking IC=9000A/cm². C is estimated from areas and measured specific capacitance values (see text.)

<table>
<thead>
<tr>
<th>Sample</th>
<th>IC (µA)</th>
<th>Rn (Ω)</th>
<th>A (µm²)</th>
<th>C (pF)</th>
<th>ωj/2π (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRL-7-1.5</td>
<td>2.4</td>
<td>0.11</td>
<td>3.7</td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>SRL-7-2.5</td>
<td>3.2</td>
<td>0.22</td>
<td>3.3</td>
<td>410</td>
<td></td>
</tr>
</tbody>
</table>

Results and Discussion

The junction shown in Fig. 2 has a normal resistance of 7.2Ω, and a critical current, IC, of 215 µA at 1.4K. I-V curves of this junction are displayed in Fig. 3. The top portion of the figure shows an
current seen in this junction reduces the current discontinuity at the gap, upon which the photon-assisted tunneling structure depends.

The variation of the step widths with laser power has been measured for this junction, and the results are plotted vs. the square root of laser power in arbitrary units. Because the junction resistance is small compared with typical antenna impedances, we presume that the approximation of ac current bias is more appropriate for interpreting our data than that of voltage bias. In this case, the laser-induced current $I_L$ in the junction is proportional to the square root of the incident laser power. Accordingly, we have labeled the horizontal axis in terms of $I_L/I_c$ with a scale factor chosen by fitting the reduction of the zero-voltage step width to a computer simulation. This simulation includes the nonlinear quasiparticle resistance, and assumes both dc and ac current bias. Noise currents were not included because of the low resistance and hence large current levels of the devices. A detailed discussion of this simulation scheme has been published in previous work on Sn-Pb junctions and will not be repeated here.

![Diagram showing step half-widths as a function of normalized laser-induced current ($I_L/I_c$, assumed proportional to $P_L^{1/2}$) for the Josephson steps of Fig. 3 at two temperatures $T=1.4K$ (crosses) and $T=4.2K$ (solid circles). Open circles denote step half-widths calculated from the BJJ model computer simulation described in the text, and the dashed curve shows the Bessel function dependence appropriate to the voltage bias case assuming $V_L=V_L^*$.](image)

Simulations at several different values of the Stewart-McCumber parameter $\beta$ were performed to test the sensitivity of the results to the junction capacitance. Normalized step half-widths from the simulation for $\beta = 3.4$, $R_L/\pi \phi_0 = 1.5$, $R_L/\beta = 2.6$ are shown in Fig. 4 as a function of the normalized laser-induced current $I_L/I_c$. The simulated step widths are denoted by open circles, while the measured step widths are shown at two temperatures, $T = 1.4K$ and $4.2K$, by crosses and solid circles, respectively. We observe that there is very good agreement between the simulation and the data for the zeroth step and second step at $4.2K$, although there appear to be substantial differences between the simulation and the data for the second step at low values of $I_L/I_c$ and at $1.4K$. The agreement between simulation and data on the hysteretic first step is much less good.

Roughly comparable agreement between simulation and the data is obtained with $\beta = 3.0$, instead of $3.4$. If $\beta > 4.4$ then the simulations produce step half-widths which look much like the step widths of the voltage-bias calculations in Fig. 4, whereas if $\beta < 2.0$, then non-integer value Josephson steps appear on the simulated I-V curves. These simulation results support the estimated value of the capacitance of the junction and hence $\beta$, and indicate that a -140% excursion from this value would give data with a much different character.

Among the issues remaining open to further clarification, we mention the temperature dependence of the step widths. Although the depression of the critical current (zeroth step) by laser power appears quite similar at 1.4K and 4.2K, the first and second steps come in more strongly at the higher temperatures. This might be attributed to "tuning" the gap down toward the condition $\Delta \omega / \omega_0 = \frac{1}{2}$, at which the frequency-dependent pair response ("Peierls peak") is at a maximum. However, this explanation seems unlikely because a similar temperature dependence was observed at 245 GHz, which is far below the gap frequency. A more likely explanation is suggested by the fact that, in work now in progress, a chaotic type of response is observed if the drive frequency is lowered from 604 GHz to 419 GHz, which is very near $\omega/2\pi$. More extensive simulations, motivated by these observations, have shown that period-doubling and other complex non-sinusoidal waveforms occur, and also that step widths found in simulations are very sensitive to small changes in parameter values and computational techniques because of instabilities and metastabilities of steps. Thus, it appears that the close proximity to a chaotic regime distorts the 604 GHz data, even if no chaos or intermittency is apparent in the data at that frequency. The first step is in a particularly pathological region, as evidenced by the simulated point at $I_L/I_c = 1.25$, which is a factor of 3 below nearby simulated points (and near the data). The strong temperature dependence of the data may reflect the great sensitivity of the behavior to $\beta$ and $\omega_0$, which change with $I_L(I_c)$. Simulations show that the -15% change in $I_c$ between 1.4K and 4.2K is sufficient to cause marked changes in the I-V curves.

These measurements illuminate the important consequences of current- vs. voltage-bias. With sinusoidal plus dc voltage bias, $\delta = 2eV(t)/h$, and hence $\psi(t)$, are completely determined, simple functions, which lead to the familiar Bessel function dependence of the step widths: $I_L/I_c = J_0(2\alpha)$, where $\alpha = V_L/\pi \phi_0$. The complications of period doubling, intermittency and chaos can then not arise. Our earlier work on Sn-Pb junctions was extremely consistent with the simple predictions of the voltage-bias theory. This is understandable because in that case, $\beta$ was not small compared with the antenna impedance, and also because shunting of the (nonlinear) Josephson element by (linear) capacitance was sufficient to yield an effective voltage bias in any case. To illustrate the relative failure of the voltage-bias approximation in the present case, we have plotted its predicted $J_0(2\alpha)$ dependence in Fig. 4, with a single scaling factor between $\alpha$ and $I_L/I_c$ chosen to fit the reduction...
of the critical current. Clearly the quality of fit is much poorer than with the current-bias simulation, as expected for the reasons outlined above.

We conclude by noting that we have coupled 604 GHz laser radiation into a SNAP junction, and that we have observed up to three Josephson steps and one photon-assisted tunneling step. Josephson step widths calculated from an RSJ model current-bias computer simulation agree reasonably well with the data for the zeroth and second Josephson steps. However, the calculated step widths for the first Josephson step, which is on the hysteretic part of the I-V curve where the simulations are very sensitive to instabilities, are about a factor of two to five larger than the data. More power could be coupled into smaller area junctions of higher resistance, if they can be fabricated, which would decrease the impedance mismatch between the junction and the antenna. This would enable more Josephson steps and photon-assisted tunneling steps to be observed, and also tend to suppress incipient chaos effects by a closer approach to voltage-bias, allowing a more detailed investigation of the FIR response of these junctions.

Acknowledgments

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References


