Low noise Nb-based SIS mixer for sub-millimeter wave detection

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Abstract

The Nb-based SIS junction fabrication was started in 1996. The main goals of this project are to establish the capability of high quality SIS junction technology in Taiwan and to fabricate SIS mixer for sub-millimeter wave detection. In the past few years, we have integrated the fabricating facility and processing steps. The self-alignment method was used for junction definition process. The junction size is close to 1 \( \mu \text{m} \) in order to minimize its intrinsic capacitance. The critical current density is required to be \( \approx 7.5 \text{ kA/cm}^2 \) to get a reasonable \( \omega R \) product of the mixer. The high quality SIS junction was demonstrated from its I–V characteristics. We also fabricated 230 and 350 GHz SIS mixers. The performance test of the mixer shows a low noise temperature level. The details of the mixer fabrication process and performance test will be described in this paper.

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1. Introduction

The sub-millimeter array (SMA), originally proposed by the Smithsonian Astrophysical Observatory (SAO), is a radio interferometer of six 6-m antennas, which operates at sub-millimeter wave regions. The Institute of Astronomy and Astrophysics, Academia Sinica, (ASIAA) joined the SMA project in 1996 to contribute two additional antennas, and Astrophysics, Academia Sinica, (ASIAA) joined the project in 1996 to contribute two additional antennas, which will increase the detection speed of SMA by about a factor of two. An Nb/Al\textsubscript{2}O\textsubscript{3} trilayer–superconductor–insulator–superconductor (SIS) mixer is used for sub-millimeter wave detection. The designs of the first two frequency bands (176–256 and 250–350 GHz) were completed by the SAO design group \([1,2]\) and the 650 GHz mixer is now being developed.

ASIAA started the Nb/Al\textsubscript{2}O\textsubscript{3}–Al/Nb SIS mixer fabrication in 1996, in cooperation with the National Tsing-Hua University (NTHU). The fabrication process has been established at the Materials Science Center of NTHU. The designs of the lower frequency mixers are modified from the results of SAO because SiO\textsubscript{2} is used as a dielectric layer instead of SiO. The mixers of the first two bands were fabricated and tested. The detailed experimental data will be discussed below.

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2. Sample fabrication

The fused quartz wafer is used because of its low dielectric constant in the sub-millimeter wave region. The summary of the facility for the SIS junction is shown in Table 1, including the trilayer deposition system, SiO\textsubscript{2} deposition system, mask aligner and reactive-ion-etch (RIE) system. The Nb film is deposited by the DC sputtering method under conditions of low base pressure (<8 \( \times \) 10\textsuperscript{-8} torr) and high deposition rate. To avoid peel-off during the process, the Nb film is grown with weakly compressive stress. The SiO\textsubscript{2} film is deposited by RF sputtering in a 5\%O\textsubscript{2}/Ar mixture. The RF power is 300 W and the deposition rate is around 300 Å/min. The UV sources of our mask aligner are 300 nm (major) and 365 nm (minor). Vacuum contact mode is used for critical dimension patterning. The Nb is etched by an RIE system in SF\textsubscript{6} plasma, which is located on an Si plate during the etching process to increase the uniformity. The etching rate is around 300 Å/min.

The schematic diagrams of fabrication are shown in Fig. 1. Firstly, the Nb/Al\textsubscript{2}O\textsubscript{3}–Al/Nb trilayer-island is deposited and patterned by a lift-off process [Fig. 1(a)]. The junction is defined by photo-lithography and the top Nb layer is etched by the SF\textsubscript{6} plasma [Fig. 1(b)]. The insulating layer, SiO\textsubscript{2}, is deposited with the same PR pattern. The SiO\textsubscript{2} on the top of
the junction is removed by a lift-off process [Fig. 1(c)]. To improve the quality of the lift-off process, light brushing was necessary. The native oxide on the surface of Nb has to be cleaned by Ar plasma and then a thick Nb is deposited as a wiring layer. The wiring pattern is defined by photo-lithography and an Nb etching process, shown in Fig. 1(d). Finally, an additional Au/Ti film is deposited to reduce the contact resistance in the mixer block. The typical thickness of each layer in our process is summarized in Table 2. A suitable thickness of Al is quite important for high quality SIS junction fabrication. A thick Al layer will reduce the gap voltage because of the superconducting proximity effect; and a thin Al layer will introduce some pin-holes in the barrier layer which could result in a large leakage of current at the sub-gap region.

The critical current density of the SIS junction is dependent on the thickness of the Al$_2$O$_x$ layer. Several authors have reported the relationship between $J_c$ and oxygen exposure, $P_{O2} \cdot T_{exposure}$[3]. Basically $J_c$ decreases exponentially as the oxygen exposure increases. However, the temperature of the substrate is an important parameter in the oxidation process. A water-cooled sample stage and a suitable cooling time are necessary for more precise control. Fig. 2 shows the oxygen exposure dependence of critical current density. The relation between $J_c$ and oxygen exposure is consistent with other results except for the system-dependent coefficient.

The design of the 230 and 300 GHz mixers is modified from E. Tong’s fixed tune design [1,2]. The dimensions of the tuning structure for an impedance match are recalculated to fit the NTHU process. Instead of the SiO in the original design, SiO$_2$ is used as the dielectric layer for the transmission.

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**Table 1**
Facilities for Nb/Al$_2$O$_x$–Al/Nb SIS junction fabrication, the important parameters are shown in the right-hand column

<table>
<thead>
<tr>
<th>System</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb/Al–Al$_2$O$_x$/Nb trilayer deposition system</td>
<td>Base pressure $&lt;8 \times 10^{-3}$ torr</td>
</tr>
<tr>
<td></td>
<td>Nb deposition rate = 22 Å/sec</td>
</tr>
<tr>
<td></td>
<td>Al deposition rate = 2 Å/sec</td>
</tr>
<tr>
<td></td>
<td>Pure O$_2$ exposure for oxidation process</td>
</tr>
<tr>
<td>SiO$_2$ deposition system</td>
<td>Home made system</td>
</tr>
<tr>
<td></td>
<td>Base pressure $&lt;2 \times 10^{-3}$ torr</td>
</tr>
<tr>
<td></td>
<td>SiO$_2$ deposition rate $\sim$300 Å/sec</td>
</tr>
<tr>
<td>Mask aligner</td>
<td>Karl Suss MJB3</td>
</tr>
<tr>
<td></td>
<td>300 nm/365 nm UV source</td>
</tr>
<tr>
<td></td>
<td>Vacuum contact mode</td>
</tr>
<tr>
<td>RIE system</td>
<td>Nb etching rate $\sim$300 Å/min with Si plate in SF$_6$ plasma</td>
</tr>
<tr>
<td></td>
<td>SiO$_2$ etching rate $\sim$250 Å/min in O$_2$/CHF$_3$ plasma</td>
</tr>
</tbody>
</table>

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Fig. 1. The schematic diagrams of the SIS junction fabrication process. (a) Trilayer island deposition by DC sputtering; (b) junction definition by RIE; (c) SiO$_2$ deposition and lift-off by RF sputtering and brushing; (d) the wiring Nb deposition and patterning.
sion line, because it has a lower dielectric constant. In
general, a small junction and high $J_c$ is necessary to get a
reasonable wide-band response.

3. Result and discussion

The schematic diagram of the noise measurement setup is
shown in Fig. 3. The local oscillator (LO) consists of a
GUNN oscillator and multiplier. The LO and signal from
the black body emitter inject into the corrugated horn
through the mylar window and IR filter. The mixer block
is mounted on the liquid He cooled copper plate. And the
DC bias is applied to the mixer through an isolator. The IF
signal was amplified by a low noise HEMT amplifier
mounted on 4.2 K plate. After passing the room temperature
post amplifier, the IF signal is measured by power meter.

A typical $I$–$V$ curve and IF output of SIS mixer is shown
in Fig. 4. The dashed line is the regular $I$–$V$ curve without
LO pumping and the thick solid line is the LO pumped $I$–$V$
curve at a frequency of 270 GHz. The step of the LO
pumped $I$–$V$ curve at below and above gap voltage is the
evidence of the mixing effect. The hot load source is from a
black body emitter at room temperature, 295 K, and the cold

Fig. 2. The oxygen exposure dependence of superconducting critical
current density, $J_c$. The oxygen exposure is defined by the product of
oxygen partial pressure, in mtorr, and exposure time, in minutes.
The exponential relationship is consistent with other results.

Fig. 3. The schematic diagram of the receiver noise temperature measurement setup. $T_{rx}$ is calculated by the $Y$-factor method. The signal is from
the thermal radiation of a block body emitter at 77 K or room temperature (295 K).

Table 2

<table>
<thead>
<tr>
<th>Process</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb/AlO$_x$–Al/Nb trilayer</td>
<td>Base Nb 2000 Å</td>
</tr>
<tr>
<td></td>
<td>Al–AlO$_x$ 70 + $x$ Å</td>
</tr>
<tr>
<td></td>
<td>Top Nb 1000 Å</td>
</tr>
<tr>
<td>Insulator SiO$_2$</td>
<td>1500 Å/3000 Å (200 GHz mixer)</td>
</tr>
<tr>
<td></td>
<td>3000 Å (300 GHz mixer)</td>
</tr>
<tr>
<td>Wiring layer Nb</td>
<td>4500 Å</td>
</tr>
<tr>
<td>Contact pad Au/Ti</td>
<td>2000 Å/100 Å</td>
</tr>
</tbody>
</table>
load is from a 77 K source. The $Y$-factor can be calculated from the ratio of the IF output power at hot/cold load (~2.13).

Fig. 4. The DC and IF responses of the 300 GHz mixer at 270 GHz. The LO pumped I-V curve has a clear step near the gap voltage. The $Y$-factor can be calculated from the ratio of the IF output between the hot and cold loads.

$$T_{\text{rx}} = (T_h \times Y \times T_c)/(Y - 1).$$

where $T_h/T_c$ is the hot/cold load temperature. The receiver noise temperature at 270 GHz is around 100 K for 295 K/77 K hot/cold load temperatures.

The RF testing result of 230 and 300 GHz mixers is shown in Fig. 5. The receiver noise temperature is below 100 K from 180 GHz to 330 GHz. The solid line shows the noise temperature of $6\ h/\kappa$, where $h$ is the Plank constant, $k$ is the Boltzmann constant and $f$ is frequency. The noise temperature of these two mixers are about twice the best
result, \( T_{\text{inp}} \approx 3 \frac{h}{k} [1,2] \). It can be attributed to two causes, the offset of device parameters and the loss from the optical absorption of aperture. For the 200 GHz mixer, both junction size and micro strip-line dimension are smaller than the design value. For the 300 GHz mixer, junction size is too large and critical current density is too low. Parameter deviations will result in bad RF impedance matching and increase in the total receiver noise temperature. The optical absorption of window or lens also gives some extra noise to the system. According to noise theory [4], the effective noise temperature generated by lossy aperture is given by \( T_e = (L - 1)T \), where \( L \) is loss factor and \( T \) is the thermal equilibrium temperature of aperture. For instance, a 2% absorption aperture at 300 K will contribute about 6 K extra noise temperature to the whole system.

To understand the sources of our SIS receiver, the total receiver temperature can be broken into three parts: (1) input noise, \( T_{\text{inp}} \); (2) mixer noise, \( T_m \); and (3) IF part noise, \( L_n T_{\text{IF}} \). The noise temperature of the IF part can be estimated from the \( P_{\text{IF}}-V \) curve in the absence of LO power [5,6]. It contributes about 10 K to receiver noise temperature in our measurement system for 270 GHz. The input noise can be obtained by the method of “intersecting line” [7,8]. According to their arguments, when the LO power level is below optimal level, the measured receiver noise temperature is proportional to the relative conversion loss, which is inversely proportional to the difference between the receiver outputs in the hot/cold load measurements. Fig. 6 shows a typical example of \( T_{\text{inp}} \) estimation. It can be seen that the data points form a straight line. The intercept of this line on the vertical axis represents the input noise temperature, \( T_{\text{inp}} \), which is independent of the conversion efficiency of mixer.

In this example, the \( T_{\text{inp}} \) is 60 ± 3 K, which is almost three times higher than Tong’s result. This indicates high loss of the RF part in front of the mixer element in our receiver setup.

4. Summary

The technology of high quality Nb/Al\(_2\)O\(_3\)–Al/Nb SIS junction fabrication is well-established in Taiwan. We have fabricated 230, 300 and 650 GHz mixers using the NTHU process. The RF test results of 230 and 300 GHz mixers show good receiver noise performance. However, some fine tuning of the process is necessary to fabricate mixers with parameters as close as possible to the designed values. In addition, there is also some room for improvement in the receiver setup. For instance, we reduced the angle of the grid polarizer to lower \( T_{\text{inp}} \) by about 20 K, i.e. \( T_{\text{inp}} \approx 80 \text{K} \), in the 240–340 GHz frequency band. The more optimized measurement results will be reported in the near feature.

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