SIS Junctions for Millimeter and Submillimeter Wave Mixers

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SUMMARY We have developed a process for the fabrication of high-quality Nb/AlOx/Nb tunnel junctions with small area and high current densities for the heterodyne mixers at millimeter and submillimeter wavelengths. Their dc I-V curves are numerically studied, including the broadening of quasiparticle density of states resulting from the existence of an imaginary part of the gap energy of Nb. We have found both experimentally and numerically that the subgap current is strongly dependent on bias voltage at temperatures below 4.2 K unlike the prediction of the BCS tunneling theory. It is shown that calculated dc I-V curves taking into account the complex number of the gap energy agree well with those of Nb/AlOx/Nb junctions measured at temperatures from 0.4 to 4.2 K. We have successfully built receivers at millimeter and submillimeter wavelengths with the noise temperature as low as 4 times the quantum photon noise, employing those high-quality Nb/AlOx/Nb junctions. Those low-noise receivers are to be installed in the ALMA (Atacama Large Millimeter/Submillimeter Array) telescope and they are going into series production now.

key words: superconducting tunnel junctions, quasiparticles, density of states, heterodyne mixers, millimeter and submillimeter wavelengths

1. Introduction

Since the signals detected at millimeter and submillimeter wavelengths in radio astronomy are generally extremely weak, the quest for higher sensitivity has led to the development of low-noise heterodyne receivers. The key element in heterodyne receivers is the mixer, in which the observed signal is mixed with a local oscillator to produce a much lower intermediate frequency. Although there are various types of heterodyne mixer receivers, their sensitivities are generally described by the Dicke radiometer equation [1],

\[
\Delta T_{\text{min}} = \frac{T_{\text{RX}}}{\sqrt{\Delta v \Delta t}} \tag{1}
\]

where \(\Delta T_{\text{min}}\) is the minimum detectable temperature, \(T_{\text{RX}}\) is the receiver noise temperature, and \(\Delta v\) and \(\Delta t\) represent the bandwidth and integration time, respectively. It is clear that \(T_{\text{RX}}\) defines the integration time necessary for cosmic signal detection. It is mandatory to reduce the \(T_{\text{RX}}\) in order to keep this integration time to a minimum, because it is quite important to reduce operating costs and to obtain results in a short time.

In the case of the heterodyne receiver system, \(T_{\text{RX}}\) is mostly determined by the heterodyne mixer and a low noise amplifier as the following equation [1]:

\[
T_{\text{RX}} = T_{M} + L_{M} \cdot T_{A}, \tag{2}
\]

where \(T_{M}\) and \(L_{M}\) are a noise temperature and a conversion loss of the heterodyne mixer, respectively, and \(T_{A}\) is a noise temperature of the low-noise amplifier. The heterodyne mixer is required to have not only a very low noise temperature but also a high conversion efficiency to achieve a high-sensitivity heterodyne receiver system.

In principle, any type of nonlinear device is usable for heterodyne mixing and Schottky barrier diodes were most widely used for millimeter- and submillimeter-wave mixers for a long time because they are compact and low power consumption solid-state devices having relatively strong nonlinearity. However, the invention of a Nb/AlOx/Nb superconducting tunnel junction in the 1980s resulted in major progress in the development of low-noise mixers. Due to their excellent performance as high sensitivity nonlinear elements in heterodyne mixers, the Superconductor-Insulator-Superconductor (SIS) tunnel junctions are widely used nowadays for receivers in millimeter and submillimeter radioastronomy [2], [3].

In SIS junctions, the sharp increase in the quasiparticle current at the gap voltage \(V_{g} = 2\Delta /e\), is used for the mixing process, where \(\Delta\) is the superconducting gap energy and \(e\) is the elementary charge. SIS junctions used in receiver systems must satisfy several different requirements. First of all their I-V curve should be sharp enough at the operating temperature to have high conversion efficiency. Additionally, the quasiparticle current, or subgap current, at a voltage below \(V_{g}\) must be as small as possible to keep the current shot noise small. They should also be chemically and mechanically stable for repeated thermal cycling. Although many kinds of SIS junctions made of a variety of superconductors have been reported up to now, only the Nb-based SIS junctions with a tunnel barrier layer of aluminum oxide (AlOx) or aluminum nitride (AlN) meet these requirements at present.

In this paper, we first describe the fabrication procedure of Nb/AlOx/Nb SIS junctions. Then measured dc I-V characteristics of those SIS junctions are shown and a novel simulation method for those dc I-V curves, in which a complex gap energy is taken into account, is demonstrated. Finally, we describe the present status of development of the SIS mixers especially for the ALMA (Atacama Large Mil-
limeter/Submillimeter Array) project.

2. Nb/AlOx/Nb Junctions

A typical structure of a Nb/AlOx/Nb junction used for the heterodyne mixer is shown in Fig. 1. The Nb/AlOx/Nb junctions are fabricated with the use of SNIP (Selective Niobium Etching Process) [4] incorporated together with the anodization technique. A photoresist lift-off mask pattern using an image reversal photoresist (AZ 5214) has been formed to define the base electrode configuration on a crystalline quartz substrate (75 mm in diameter and 0.4 mm in thickness). At first, a Nb/AlOx/Nb tri-layer is formed onto the quartz substrate through the photoresist mask. A bottom layer of Nb (200 nm) is deposited by dc sputtering with a 4-inch diameter Nb target and a thin Al film (~10 nm) is successively deposited on to the Nb film by dc sputtering with a 4-inch diameter Al target. Then the substrate is transferred to the next chamber without breaking the vacuum and then the surface of the Al film is exposed to a low-pressure oxygen (O₂) atmosphere introduced to the chamber for 30 minutes or more to form a thin tunnel barrier of AlOx. The oxygen pressure is varied so as to control the critical current density, \( j_c \) (or tunnel resistivity \( \rho_{\text{tr}} \)) of the SIS junction. After the completion of the oxidation, the substrate is again transferred to the sputtering chamber and a top Nb layer (100 nm) is deposited in the same way as the bottom Nb layer.

Note here that it is very important to keep the substrate with the bottom Nb film in a vacuum or a very low-pressure Ar atmosphere for 30 minutes or more before deposition of Al in order to suppress the subgap leakage current. In Fig. 2, we show typical examples of dc I-V curves of SIS junctions fabricated with and without the storage time interval of the substrate in vacuum between the bottom Nb and Al deposition. It is clear that the subgap leakage current is suppressed when the substrate with the bottom Nb film is kept in a vacuum for 1 hour. Some previous papers also mentioned that it is necessary to cool down the temperature of the bottom Nb film by setting a time interval before deposition of Al to prevent the Al diffusion into the Nb film [5, 6]. Since the temperature of the surface of the substrate just after the deposition of the bottom Nb is estimated to be as high as several tenths °C, the diffusion of Al into the Nb film may not be so serious. The surface of the bottom Nb film might be covered with gaseous contaminants such as water vapor and/or O₂ during the time interval and we think that these contaminants may act as barriers to prevent the Al diffusion into the Nb film, because only by the assumption of the thermalization of a Nb film it is hard to explain the phenomenon that the duration of the time interval between the Nb and Al deposition can be considerably shortened if the substrate with the bottom Nb film is kept in an environment with a very low partial pressure of inert gases such as Ar and N₂ [7]. Further investigation is required to study the Al/Nb interface and to clarify the mechanism of preventing the Al diffusion into the Nb film.

Once Nb and Al depositions are completed, the Nb/AlOx/Nb tri-layer on the photoresist is lifted off using acetone. Then a 70-nm thick SiO₂, which is a cap layer to prevent the top surface of SIS junctions from being heavily oxidized during the anodization process to be mentioned later, is sputtered on the whole surface of the quartz substrate. The junction area is defined by a positive photoresist (PFI-38 from Sumitomo Chemical. Co., Ltd.) and an stepper (Canon FPA-3000i5) and an stepper (Canon FPA-3000i5) with a resolution of 0.3 μm. The top SiO₂ layer and Nb layer without being covered with the photoresist are removed by the Reactive Ion Etching (RIE) or Induction Coupled Plasma (ICP) Etching using CF₄+3%O₂ and the junction mesas are isolated. The etching is automatically stopped at the surface of AlOx in the case of the RIE and manually stopped by monitoring the emission spectra from the discharge plasma in the case of the ICP etching. Then anodization is applied to the metal surface without being covered with the photoresist to produce on it a thick oxide layer in an electrolyte, which is a mixture of ethylene glycol, ammonium pentaborate and water [8] and a ~100-nm thick Nb₂O₅ is formed around the junction mesas.

As mentioned above, at this anodization step the SiO₂ cap layer on the junction dots plays an important role in preventing the Nb top surface from being heavily anodized.

Once the anodization is completed, the photoresist
mask is removed by acetone. Then a 300-nm thick SiO$_2$, which acts not only as an insulating layer between the base and wiring layers but also as a dielectric layer of microstrip lines for tuning circuits and impedance transformers, is deposited on the whole surface of the substrate. Then using a photoresist mask the SiO$_2$ layer just above the SIS junctions is removed by the RIE or ICP etching and contact windows for wiring connection are prepared. After the removal of the photoresist mask, the surface of the top Nb of the junction dots is cleaned by Ar plasma and 600-nm thick Nb layer is deposited on the whole substrate. The Nb layer is patterned into wiring by the RIE or ICP etching using CF$_4$+3%O$_2$. The quartz substrate is then diced into chips and each device resistance is measured at room temperature to screen out defective devices.

To achieve an SIS mixer with a low noise temperature it is quite important to suppress the subgap leakage current as much as possible at the operating bias voltage. Since it was thought that in most cases the subgap leakage current is attributed to conductive paths related to defects in the tunnel barrier, considerable effort has been devoted to making a defect-free AlOx thin layer for the tunnel barrier. It has been pointed out that the amplitude of the subgap leakage current is strongly dependent on the magnitude of stress in the base Nb film [9]. We have found that such a subgap leakage current, which is linearly proportional to subgap voltage, shown in Fig. 2 (a) can be gradually suppressed as the stress of the base Nb becomes compressive and very much reduced in the case of the base Nb film with a compressive stress of >0.5 GPa. This result is in discrepancy with the common knowledge that low-stress Nb films are preferable for making high-quality junctions [9]. While the lower electrode of the Nb/AlOx/Nb tri-layer is generally formed by etching, it is formed by lift-off in our case. At present we suppose that the discrepancy might be related to the difference in the formation of the lower electrode of Nb/AlOx/Nb tri-layer and further investigation is required to fully understand the discrepancy.

By this processing route, Nb/AlOx/Nb SIS junctions with an area as small as ~ 0.5 $\mu$m$^2$, a current density as high as $j_c$ ~15 kA/cm$^2$, and a quality factor $R_{SG}/R_N > 15$ can be made with a high processing yield, where $R_{SG}$ and $R_N$ are the subgap resistance at 2 mV and the normal resistance at 4 mV, respectively.

3. Subgap Current

3.1 Subgap Current at 4.2 K

We have sometimes obtained Nb/AlOx/Nb junctions with a dull or rounded structure just below the gap voltage but having very low leakage current at the voltage far below the gap. Such a junction with the rounded feature of nonlinearity is not suitable for the heterodyne mixer, because the mixing efficiency is lowered and the shot noise is increased. Since this kind of junction with a rounded nonlinearity has usually been obtained in the early period of recovery of the vacuum after purging the sputtering chamber with air, we thought that such degradation of nonlinearity near the gap voltage is related to the quality of the superconducting Nb film. Here, we assume that the subgap current of the SIS junction is dependent on the quality of the Nb films and to confirm the assumption we have made theoretical calculations of the quasiparticle current in the SIS junctions.

Since the gap energy is assumed to be real in the conventional calculation, there is no quasiparticle state inside the energy gap and quasiparticle densities of states show an infinitely steep peak at the gap energy. Thus a very sharp step-like rise of current is predicted at the gap voltage on the I-V characteristics of a SIS junction. However, the current rise at the gap voltage is rounded in the actual SIS junctions. To explain the rounded I-V characteristics near the gap voltage, a complex number of superconducting gap energy, expressed as $\Delta(E) = \Delta_1(E) + i\Delta_2(E)$, is introduced [10], [11], where $E$ is a quasiparticle energy and $\Delta_1(E)$ and $\Delta_2(E)$ are real numbers.

Now let us consider the quasiparticle tunneling current in a SIS junction with an ideal tunnel barrier and take into account the complex number of the superconducting gap energy which is a parameter representing the quality of superconducting Nb. The quasiparticle tunneling current, $I_T$, through an ideal tunnel barrier in a SIS junction is generally given by [12],

$$I_T = A \int_{-\infty}^{\infty} D_r(E) D_l(E+eV)[f_r(E+eV)-f_l(E)] dE,$$

(3)

where $A$ is a constant and $D_{r,l}(E)$ and $f_{r,l}(E)$ are densities of states and Fermi distribution function at energy $E$, respectively, defined as

$$D_{r,l}(E) = -\frac{1}{\pi} \text{Im} \sum_k G_{11}(k, E)$$

$$= N(0) \text{Re} \left( \frac{E}{\sqrt{E^2 - \Delta_{r,l}^2}} \right)$$

(4)

and

$$f_{r,l}(E) = \frac{1}{1 + \exp(E/k_B T)},$$

(5)

where $k_B$ is the Boltzmann constant and

$$G_{11}(k, E) = \frac{EZ(E) + \epsilon_k}{Z^2 E^2(E) - \phi_{r,l}^2(E) - \epsilon_k^2}.$$  

(6)

The subscripts $r$ and $l$ represent right and left superconductors and $\Delta(E) = \phi/Z(E)$ are the complex gap energies for an electrode superconductor. $N(0)$ is the density of states of normal electrons at the Fermi level. $Z(E)$ and $\phi(E)$ are a renormalization factor of a quasiparticle and a pair potentials between the two quasiparticles. Since $Z(E)$ is generally a complex number, $\Delta(E)$ must be also treated as a complex number. Note here that it is more reasonable to treat $\Delta(E)$ as a complex number than the Dynes formula [13], in which
an imaginary part is added to energy as $E - i \Gamma_D$ keeping $\Delta(E)$ real, where the parameter $\Gamma_D$ is real. Assuming that $\Delta(E)$ is a complex constant near the gap edge, it is written as $\Delta = \Delta_1 + i \Delta_2$, where $\Delta_1$ and $\Delta_2$ are real numbers and is assumed to be independent of $E$ near the gap edge.

Calculated densities of states using Eq. (4) for a superconductor with (dotted and broken lines) and without (solid line) the imaginary part of gap energy are shown in Fig. 3. It is clearly shown that the infinitely steep peak at the gap energy is suppressed when the imaginary part of the gap energy is taken into account. It is also interesting that a few but finite number of quasiparticle states are produced at the energy deep inside the gap when the gap energy has an imaginary part. It is expected that there is a finite amplitude of tunneling current flowing through those quasiparticle states inside the energy gap at the subgap voltages. The amplitude of the quasiparticle tunneling current at a subgap voltage must increase as the magnitude of the imaginary part of the gap energy increases.

To determine the magnitude of the imaginary part of the gap energy of Nb films in actual Nb/AIOx/Nb junctions, curve fitting between calculated and measured I-V characteristics at 4.2 K is made. A small knee structure just above the gap voltage and a reduction of gap voltage are usually observed on the dc I-V curves of Nb/AIOx/Nb SIS junctions, which come from the superconducting proximity effect at the Nb/AI interface of the bottom electrode. The proximitized gap energy in the Al layer is obtained by solving McMillan’s recursive equations [14], taking a complex number of energy gap for Nb into account, and is used to calculate the tunneling current, and details of the calculation are described in [11]. The energy gap of the top electrode is assumed to be free from the proximity effect and identical to that of the Nb film in the bottom electrode. The imaginary part of the energy gap is determined so as to give a best fit to the measured I-V curve at 4.2 K. The measured dc I-V curves of two Nb/AIOx/Nb junctions at 4.2 K are plotted by open circles in linear (upper panel) and logarithmic (lower panel) scales in Figs. 4(a) and (b). Solid lines in Fig. 4 represent calculated quasiparticle tunneling current as a function of voltage. The measured dc I-V characteristics are quite consistent with calculated ones when we take into account the imaginary part of the gap energy. It is found that the rounding of the gap structure and a little increase in the subgap current just below the gap voltage are well reconstructed by the increase in the magnitude of the imaginary part of the gap energy, $\Delta_2$. It is also noted that amplitude of calculated quasiparticle tunneling current at a subgap voltage quantitatively agrees well with the measured ones as shown in the lower panels of Figs. 4(a) and (b). This indicates that the measured subgap current is nearly identical to the theoretical lower limit of quasiparticle tunneling current in magnitude and indicates that an almost ideal tunnel barrier is achieved in the present SIS junction.

### 3.2 Subgap Current at Low Temperature

It is well known that the subgap current of a SIS junction at very low temperatures is strongly dependent on voltage unlike those predicted by the BCS theory. We expected that it is possible to explain such a strong voltage dependence of subgap current of a SIS junction using a formula in which the imaginary part of the gap energy is taken into account. Although we first measured the dc I-V curves of Nb/AIOx/Nb junctions at low temperature, it was quite difficult to precisely measure their dc I-V curves because their current below the half gap voltage showed large fluctuation for some reason which is not yet understood. On the other hand, it was found that the current of Nb/AI/Nb junctions below the half gap voltage was so stable that we were able to precisely measure the dc I-V curves very easily. For this reason, we used Nb/AI/Nb junctions instead of Nb/AIOx/Nb junctions to examine the above mentioned expectation.

The Nb/AI/Nb junctions were fabricated in the same way as the Nb/AIOx/Nb junctions described above. Instead of an AIOx tunnel barrier, a very thin AlN layer was formed by the nitridation of the surface of the 10-nm thick Al on the base Nb film. The nitridation was done by using the neutral nitrogen beam irradiation to the surface of the Al film. De-
tails of the fabrication of the Nb/AlN/Nb SIS junctions are described in [15].

In Fig. 5 dc I-V curves of a Nb/AlN/Nb SIS junction measured at 4.2 and 2.0 K are shown by open circles and squares, respectively. The solid and broken lines are calculated ones using Eqs. (3) and (4) with the complex energy gap at 4.2 and 2.0 K, respectively. Although the calculated subgap current at 4.2 K is in very good agreement with the measured one, a large discrepancy between the measured and calculated subgap current at 2.0 K is observed above the half gap voltage. It is noted here that such a structure of increasing subgap current near the half gap voltage is usually found in the Nb/Al-AlOx-Nb [16] and Al/AlOx/Al junctions [17]. This discrepancy between the measured and calculated subgap current above the half gap voltage indicates that a localized quasiparticle state with a finite width is located near the center of the gap, in addition to the quasiparticle states induced by the imaginary part of the gap energy. Shiba has shown that a magnetic impurity can form a bound state near the center of the superconducting energy gap by the spin exchange interaction [18]. According to Shiba’s theory, we introduced a localized density of states (LDOS) inside the energy gap in the form

\[ D_{LDOS}(E) = \frac{C \gamma}{(E - E_R)^2 + \gamma^2}, \]

where \( C, E_R \) and \( \gamma \) are a scaling factor, bound state energy and broadening parameter of the bound state, respectively and they are assumed to be independent of temperature and constant. Then effective quasiparticle density of states \( D_{eff}(E) \) is given by \( D_{eff} = D(E) + D_{LDOS}(E) \), where \( D(E) \) is defined by Eq. (4).

Note here that although such a step-like structure of current near the half-gap voltage in SIS junctions is usually attributed to the multi-particle tunneling (MPT) [19], the contribution of the multi-particle tunneling to the subgap current is neglected in this analysis. This is because that no current structure is clearly observed at \( V = V_g/n \), where \( n \) is an integer of \( n \geq 3 \), on the I-V curve at 2.0 K and also because current density of the present junction is so low that the thickness of the tunnel barrier is much thicker than those considered in the analysis of the MPT [19].

In Fig. 6, measured dc I-V curves at 4.2, 1.6 and 0.4 K are shown by open circles. It is clear that the subgap current above the half gap voltage shows a saturation of reduction below 1.6 K. On the other hand, the subgap current below the half gap voltage continues to decrease to 0.4 K. As a result, a very large current step, whose height is dependent on temperature, can be seen just below the half gap voltage. Since the amplitude of two peaks just below and above 1 mV on the measured dc I-V curve at 0.4 K was strongly dependent on the strength of magnetic field applied and oscillatory decreases with increasing strength of the magnetic field, the peaks are attributed to Fiske steps. It is, however, so difficult to suppress them completely that some remnant of the peaks are still observed on the I-V curves at 1.6 and 0.4 K as shown in Fig. 6. Thus, the actual dc I-V curve is assumed to be given by the lower envelope of the curve. The calculated dc I-V curves using Eqs. (3) and (4) for the corresponding temperatures are shown by solid lines in Fig. 6. As shown in Figs. 5 and 6, it is clearly demonstrated that the calculated dc I-V curves are in very good agreement with the measured ones at the temperature from 4.2 K to 0.4 K.

The effective density of states \( D_{eff}(E) \) obtained from the previous fitting calculations of dc I-V curves at several temperatures is plotted in Fig. 7. The density of states in the subgap regime, except the LDOS peak located near the center of the energy gap, decreases as temperature is lowered from 4.2 K to 1.6 K, while it does not decrease and shows saturation at temperatures below 1.6 K.

In Fig. 8, the imaginary part of gap energy, \( \Delta_2 \), which is obtained by fitting of the measured dc I-V curves, is plotted as a function of the inverse of temperature. The imaginary part of the gap energy decreases exponentially from 4.2 K to 1.6 K as shown by the broken line in Fig. 8, which is consistent with the prediction of the strong coupling theory [13], [20]. It is saturated in magnitude and becomes almost constant below 1.6 K. Since the quasiparticle life time \( \tau \) is defined by the following equation [10]:
Fig. 7 Density of states which gives the best fit to the measured I-V curves of a Nb/AlN/Nb junction at 0.4, 1.6, 2.0, and 4.2 K shown in Figs. 5 and 6.

Fig. 8 Imaginary part of the energy gap $\Delta_2$ obtained by the fitting of the dc I-V curves as a function of inverse temperature.

$$\tau = \frac{\hbar}{2\Delta_2}$$

This result indicates that the quasiparticle life time reaches its limit at very low temperature, where $\hbar$ is the Dirac constant. We think that this is strongly related to the fact that the subgap current at low voltages (typically <0.5 mV) of the SIS junctions reach a lower limit at very low temperatures, because the subgap current at low voltages is saturated at very low temperatures in the case that the gap energy has a finite magnitude of the imaginary part [11].

Although the question of why the subgap current of SIS junctions shows a saturation of reduction at low temperature has been left unresolved for a long time, now it is resolved that such saturation of the subgap current occurs when the tunneling current passing through the quasiparticle states inside the energy gap dominates over the thermally-excited quasiparticle current at low temperatures. The amplitude of the tunneling current passing through the quasiparticle states inside the energy gap must be dependent on the magnitude of the imaginary part of the gap energy $\Delta_2$, because the number of quasiparticle states inside the energy gap strongly depends on the magnitude of $\Delta_2$.

4. SIS Mixers for the ALMA

ALMA (Atacama large millimeter/submillimeter array) is a large-scale aperture synthesis radio telescope located in the Atacama desert, 5,000 m above sea level in northern Chile and is the biggest telescope in the world to provide an angular resolution as high as 1/100 arcsecond, which is 10 times better than that of the Hubble Space Telescope. ALMA has an observation frequency ranging from 30 to 950 GHz (10–0.3 mm in wavelength), and is divided into 10 frequency bands. ALMA’s receivers, which cover 80 GHz (band 3) or higher, use SIS mixers based on Nb/AlOx/Nb junctions. The National Astronomical Observatory of Japan is responsible for building receivers for three frequency bands: 125–163 GHz (band 4), 385–500 GHz (band 8), and 787–950 GHz (band 10), to provide more than 200 SIS receivers in total.

For the ALMA band-4 and -8 receivers, the above-mentioned Nb/AlOx/Nb junctions are being employed for the SIS mixers [21], [22]. In Fig. 9 typical performance of a band-8 receiver using the Nb/AlOx/Nb junction for the SIS mixer. A Typical noise temperature $T_{RX}$ of the band-8 receiver as shown in Fig. 9 is as low as 70 K in DSB (Double Sideband) mode, which is approximately $4\hbar\omega_S/k_B$, where $\hbar\omega_S/k_B$ is the quantum photon noise at the signal frequency $\omega_S$. All the ALMA receivers at the frequency bands below ~690 GHz, which is the gap frequency of Nb, must have noise temperature below from 3 to 4 times the quantum photon noise of $\hbar\omega_S/k_B$. Note that only SIS mixers using the Nb/AlOx/Nb junctions can achieve such a low noise temperature at present.

To achieve ALMA band 10 receivers it is necessary to introduce several new technologies. Since the frequency of ALMA band 10 exceeds the gap frequency of Nb (~690 GHz), it is necessary to use a low-loss superconductor instead of Nb for transmission lines and tuning cir-
circuits in order to reduce the loss of signal and thus to lower the receiver noise temperature. At present, NbTiN is the most promising material for the signal transmission line for this frequency band due to its high transition temperature of ~14 K and low surface resistance. The structure of an SIS junction for ALMA band 10 is shown in Fig. 10. To reduce the signal transmission loss, microstrip lines with a groundplane made of NbTiN and strip line made of Al are used for the impedance transformer and the tuning circuit, while the Nb/AlOx/Nb is still used for the mixer junction because dimensions of the junction are so small that losses at the electrodes of Nb are negligibly small. Note here that a serious instability is observed at the gap voltage of I-V curve, if the Nb/AlOx/Nb junction is sandwiched by the NbTiN films for the groundplane and microstrip, because significant Joule heat generated at the Nb/AlOx/Nb junction is confined in it due to the difference in the gap energy between the Nb and NbTiN and thus the junction gets significantly heated up by itself and becomes thermally unstable [23]. To avoid such a confinement of the Joule heat and thus to reduce the thermal instability, the normal conductor of Al at 4.2 K is used for the strip line. A SEM image of a mixer device at the band-10 frequency band is shown in Fig. 11. It has been successfully demonstrated that the world’s best receiver performance has been achieved in the prototype receiver using the mixer device, confirming that it is basically possible to build the ALMA band 10 receivers to meet the ALMA requirement [24], [25].

There still remains an issue to be resolved in the near future that the frequency coverage of the mixer is not sufficiently wide due to a relatively low current density \( j_C \sim 8 \text{kA/cm}^2 \) of the Nb/AlOx/Nb junction at present, and the margin for the required frequency band is barely secured. Thus, it is quite important to achieve a large margin between the specification and actual mixer performance by extending the frequency coverage of the SIS mixer, because such a large margin can absorb a little shift in the frequency coverage of the SIS mixer caused by the size variation of patterns of mixer circuits and consequently increase the production yield of mixer devices. To expand the frequency coverage of the SIS mixer, it is definitely necessary to develop a high-quality SIS junction with not only a high current density of \( j_C = 15 \text{kA/cm}^2 \) or more but also an area of 1 \( \mu \text{m}^2 \) or less. Instead of conventional AlOx, AlN is a promising candidate for the tunnel barrier of a high-current-density and high-quality SIS junction. We have been developing a high-quality and high-current-density Nb/AlN/Nb SIS junction. A dc I-V curve of a Nb/AlN/Nb junction with \( j_C \sim 30 \text{kA/cm}^2 \) is shown in Fig. 12. Although this result is promising in terms of applicability to the band-10 SIS mixers, further substantial improvement of the junction quality as well as the repeatability in fabrication of the junctions is required at present.

5. Conclusion

Using high-quality Nb/AlOx/Nb and Nb/AlN/Nb junctions, it is shown experimentally and theoretically that the subgap current of SIS junctions is strongly dependent on the quasiparticle states in the energy gap. The behavior of the subgap current is well predicted by the theory taking into account not only the quasiparticle states induced in the energy gap by the imaginary part of the gap energy but also a bound state near the Fermi level. It is also found that the magnitude of the imaginary part of the gap energy reaches lower limit at low temperature, which means that the quasiparticle lifetime is saturated at low temperatures.

We have successfully built SIS mixers employing the
high-quality Nb/AlOx/Nb junctions for the frequency band ranging from 80 GHz to 950 GHz. Using those mixers, we have achieved the noise temperature of the receivers as low as 4 times the quantum limited photon noise of $\hbar\omega/|k|$. These high performance receivers are to be installed in the ALMA telescopes in the near future and series production of those receivers is in progress.

Acknowledgments

The authors would like to thank Y. Fujii, M. Kroug and A. Miyachi for their help and valuable discussions on the fabrication of Nb/Al SIS junctions. The authors also would like to express thanks to A. Endo of TU Delft for preparing AlN-barrier SIS junctions. The authors express special thanks to all the members of the ALMA receiver development group at NAOJ for valuable comments and encouragement during the work.

References


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Toyoaki Suzuki was born in Kanagawa, Japan in 1978. He received the Ph.D. degree in Physics from Tokyo University in 2007. In 2008, he moved to the National Astronomical Observatory of Japan and developed an SIS photon detector with high sensitivity for the purpose of astronomical observations in space. In 2010, he moved to the Institute of Space and Astronomical Science, Japan Aerospace Exploration Agency. His current research interests are the development of a high sensitive photoconductor device and the study of physical understanding of star formation processes in nearby galaxies.

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