Different shape normal metal interlayers between niobium based SIS junctions and niobium titanium nitride leads and their influence on the electron temperature

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Abstract. In this paper we demonstrate the reduction of heating in a niobium superconductor-insulator-superconductor (SIS) junction with aluminum-oxide tunnel barrier embedded in a niobium-titanium-nitride circuit. Nonequilibrium quasiparticles which are created due to the Andreev trap at the interface between the niobium and the niobium-titanium-nitride layers are relaxed by inserting a normal-metal conductor of gold between these two layers. In an earlier work we explained the observed relaxation of nonequilibrium quasiparticles due to the geometrically assisted cooling effect. In this paper we investigate this cooling effect in dependence of the normal-metal layer shape and size. We expect that an adapted normal-metal layer is necessary for implementation in practical terahertz SIS heterodyne mixer circuits. We observe in DC-measurements of a large number of devices a clear relation between the volume of the gold layer and the effective electron temperature in the device. Our central finding is that the shape of the gold layer does not influence the cooling provided that the volume is sufficient.

1. Introduction
Heterodyne receivers are a powerful tool for astronomy at terahertz (THz) frequencies. With their high sensitivity and spectral resolution of the order of $10^5$-$10^6$ they enable the detection of complicated emission-line spectra of astronomical objects like cold molecular clouds. These spectra are used to study the chemical and physical conditions for star formation which takes place in these clouds. In the range of 0.3 to 1.3 THz, heterodyne receivers equipped with SIS devices as frequency mixer offer the highest sensitivity. Due to their superior tunnel barrier quality, mainly Nb-AlO$_x$-Nb junctions are used. These are suitable for mixing up to 1.4 THz which is twice the gap frequency of Nb. Up to its gap frequency of 700 GHz, Nb is also used for the embedding HF circuit of the junction. Above this frequency the loss in Nb increases due to Cooper-pair breaking. In this case a superconductor with a higher gap like NbTiN would be the material of choice. Devices with a NbTiN embedding circuit have been fabricated before and resulted in heating caused by nonequilibrium quasiparticles trapped in the Nb junction [1]. Therefore, the presently best performing mixer devices are fabricated with one layer of the circuit made of a normal-metal conductor where quasiparticles are not trapped [2, 3, 4]. However, this decreases the sensitivity in comparison to the use of a superconductor due to signal losses in the...
2. Heating and device considerations

We want to solve these heating issues by inserting a normal-metal cap of gold between the Nb-junction top electrode and the NbTiN top layer of the embedding HF-circuit. This layer provides extraction of nonequilibrium quasiparticles out of the Nb-junction and transfers their energy to the bath. We have already shown in DC measurements that heating can be significantly reduced with this approach because of the geometrical assisted cooling effect [5]. Here we have shown that heating is substantially weaker in a device with a rather large gold cap. On the other hand, for the development of a mixer device the cap has to be as small as possible to minimize ohmic losses in the HF embedding circuit. Hence, the optimum dimensions have to be determined. Most importantly the lateral shape of the cap will have an impact on the performance of the HF circuit. Fig. 1(b) shows two examples to illustrate this. First, we choose a circular gold cap centered on the junction. In this case a substantial part of the inductive line contacting the junction has gold underneath. Secondly, we choose a half-circular shape and match the edges of gold cap and junction area. Here, the overlap of the gold cap and the matching circuit is minimized, although the penalty is a larger gold cap extending at the other side of the SIS device that will have some influence on the HF circuit as well. For the calculation of the required HF-circuit dimensions the surface impedance of the circuit material is needed. For a conventional homogeneous superconductor it can be calculated with the help of the Mattis Bardeen theory [6]. The circular gold cap together with the NbTiN embedding circuit is effectively a normal/superconducting (NS) bilayer system in which an inhomogeneous superconducting state is created due to the Andreev reflection process (proximity effect) [7]. In this case a more general theory [8] has to be applied to evaluate the surface impedance. The ohmic losses in the gold will have the largest impact if the bilayer covers the part of the circuit with the highest HF current density. For the half-circular cap, compared to the full-circular cap, a smaller part of the circuit consists of a NS bilayer and in the part behind the junction the current density is lower so its contribution in terms of ohmic losses will be smaller. To provide a foundation for future HF circuit designs we quantify in this paper the correlation between electron temperature elevation in the Nb SIS junction and the volume and shape of the gold layer in DC measurements.

![Figure 1](image-url)  
Figure 1. (a) Layer schemes of devices with a 20 nm thick layer of gold and an added 60 nm thick gold cap. (b) Top-view schematics of a NbTiN matching circuit and junction with circular or half-circular gold cap.

3. Device variations and fabrication

We fabricated devices with a variety of gold layers between the Nb top electrode and the NbTiN top wiring layer. Fig. 1(a) shows layer schemes of devices with and without such a gold cap. The devices are fabricated on a 525 µm thick low resistivity silicon substrate. The NbTiN-Nb-AlO_x-Nb-Au layers are patterned by optical UV-lithography and are deposited by DC magnetron sputtering. The NbTiN groundplane has a thickness of 350 nm and the Nb junction electrodes
Table 1. Selection of devices with parameters for the gold cap.

| #  | cap type   | $t_{\text{Au}}$ [nm] | $r_{\text{Au}}$ [µm] | $V_{\text{Au}}$ [µm$^3$] |
|----|------------|----------------------|----------------------|--------------------------|
| 1  | -          | -                    | -                    | 0.02                     |
| 2  | half-circular | 60                   | 1.07                 | 0.13                     |
| 3  | half-circular | 60                   | 1.57                 | 0.25                     |
| 4  | circular   | 60                   | 1.57                 | 0.48                     |
| 5  | half-circular | 60                   | 2.57                 | 0.64                     |
| 6  | circular   | 120                  | 3.59                 | 4.86                     |

are both 100 nm thick. The barrier is formed by thermal oxidation of a 8 nm thick Al layer. The 20 nm thick gold layer on top provides a clean interface to the thicker gold cap. To pattern the junction area we use electron beam lithography (EBL) and reactive ion etching. An AlN etch mask is patterned on top of a polyimide layer by EBL and liftoff using PMMA as EBL resist. After etching, the SiO$_2$ insulating layer is deposited by RF magnetron sputtering followed by the self-aligned liftoff of the junction etch mask supported by chemical mechanical polishing (CMP). After this step, gold caps with a thickness of 60 nm are patterned on top by EBL and liftoff. In the last step the 400 nm NbTiN top wiring layer is patterned by UV-lithography and liftoff. All measured devices have the same junction area size of 1 µm$^2$. We used circular and half-circular shaped gold caps like those shown in Fig. 1(b) and varied the cap diameters. In table 1 a selection of the devices and their gold layer dimensions are summarized.

4. Analysis of the measurement results
In this section we present measured DC I-V curves of the fabricated devices. Since the electron temperature in the Nb electrodes depends on the current through the device these have a negative slope in the quasiparticle current onset (backbending). Datapoints from this part of the I-V curve can be translated into effective electron temperatures ($T_e$) using the BCS theory [9]:

$$
\frac{1}{N(E_F)V} = \int_0^{k_B\theta_D} \frac{de}{\epsilon^2 + \Delta(T_e)^2} \left[ 1 - 2f\left(\frac{\epsilon^2 + \Delta(T_e)^2}{\epsilon^2 + \Delta(T_e)^2}\right)^{1/2}\right].
$$

Here $N(E_F)$ is the single-spin density of states at the Fermi energy, $V$ is the average attractive electron-phonon interaction potential, $k_B$ is the Boltzmann constant, $\theta_D$ is the Debye temperature of the material, $\epsilon$ is the independent quasiparticle energy relative to the Fermi energy and $\Delta(T_e)$ is the electron temperature dependent superconducting gap-energy of the Nb junction and $f$ is the Fermi distribution function at the same electron temperature. For more details we refer the reader to [5]. Fig. 2(a) shows I-V curves of the devices specified in table 1 and Fig. 2(b) shows the corresponding electron temperature in the Nb junction as a function of the DC power $P$. The phonon bath temperature in all measurements was 4.2 K. For all devices except #6 we observe an elevation of $T_e$ over the phonon bath temperature. The I-V curves of devices #1 to #5 in Fig. 2(a) show backbending which decreases with increasing gold layer volume. No signs of backbending are found for device #6 suggesting an electron temperature equal to the phonon bath temperature. An effective heat-transfer coefficient $\alpha$ can be extracted from the $T_e(P)$ plots in Fig. 2(b), which is equal to the inverse of the slope of the curves. The larger the gold volume, the higher is $\alpha$ and the more the heat transfer is enhanced by the gold cap. In fact there is an approximately linear relation between $\alpha$ and the gold cap volume as it is illustrated in Fig. 2(c). Additionally, we find that the shape of the gold cap has no impact on $\alpha$. E.g. for devices with a 0.23 µm$^3$ circular cap we find 0.41 ± 0.09 µW/K in comparison to 0.44 ± 0.05 µW/K for a 0.25 µm$^3$ half circular gold cap.
5. Conclusion and outlook

We have shown that the heat transfer out of the junction depends on the volume but not the shape of the added gold layer. This is an important finding because we can avoid the drawbacks of a circular shape like discussed in section 2 and don’t lose cooling efficiency because of the different shape. HF measurements with well matched devices and an optimized gold cap geometry will have to show if the heating effects due to THz radiation are eliminated in the same way as DC heating. If this is successful this new device type will be the basis for future developments of very high sensitivity mixers at 800 GHz and 1.1 THz.

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