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Fundamental limitations of THz and Niobiumnitride SIS mixers

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Chapter 8

Summary and discussion

The research described in this thesis has focussed on the suitability of Nb and NbN SIS junctions as THz radiation detectors. Suitability, in the context of detectors for astrophysics, basically stands for sensitivity. The sensitivity of a detector is determined by the gain and the noise. The mixer gain is governed by the RF - and IF match to the junction together with the current - voltage characteristics. The noise generated by the junction mainly consists of shot noise resulting from the subgap current. The sensitivity of a THz *receiver* employing a Nb junction however is dominated by the loss in the RF integrated tuning circuit.

8.1 Integrated tuning structures

Upon crossing the 700 GHz limit, the use of Al as stripline material provides lower losses than the use of Nb. However, even clever designs which employ clean, high conductivity Al can couple a maximum of only 40 % of the incoming radiation to the junction. Since the receiver noise is directly proportional to the losses in the RF path, this more than doubles the receiver noise temperature compared to frequencies below the gap frequency. This is the reason that NbN was considered to be a useful candidate as stripline material, where the surface resistance calculations based on the Mattis-Bardeen equations promised negligible RF losses up to 1.5 THz. Unfortunately, NbN layers in practice suffer from large losses related to the granular structure of the material, revealing itself in the DC conductivity which is nearly an order of magnitude lower than that of Nb at room temperature. It furthermore does not improve upon cooling. A quite promising development is the use of NbTiN, which exhibits a DC conductivity which can be much larger than that of NbN. First direct and heterodyne detection measurements indicate that the surface impedance is much smaller than that of NbN at frequencies up to 700 GHz[1]. A number of groups have picked up this research and are currently investigating the optimum deposition conditions of the material after which the DC and RF characteristics will be evaluated. The origin of the improved NbTiN RF properties over those of NbN is unclear; the grain boundary resistance is thought to be of importance, but why this may be lower in the NbTiN case is not yet solved.

8.2 Nb junction results

For a Nb junction the IF match is optimized by employing a junction with a resistance on the order of 20 Ω. To facilitate matching to the RF side a small ($< 1\mu\mathrm{m}^2$) area is required to minimize the intrinsic junction capacitance. This poses severe demands on the tunnel barrier, since it has to be extremely thin, on the order of one to two monoatomic layers. As a consequence, the barrier exhibits defects in which current transport takes place via multiple Andreev reflection rather than tunneling. This increases the current in the subgap regime with nearly an order of magnitude, yet the effect on the gain is small since the subgap current is still much smaller than the current at voltages above the gap and this difference is what matters. Therefore the detector gain is readily optimized, provided that an integrated tuning circuit is present which matches the antenna impedance to the junction impedance.

The effect of the increased subgap current in the junction noise however is striking. Not only is the subgap current increased, moreover, this current is carried in Andreev clusters with charge $q > e$, causing an additional increase in the shot noise which forms the major constituent of the detector noise. With the shot noise measurements of Ch. 7 and the developed theory of Ch. 6 a long - standing question on the origin of excess noise is answered. Because of this effect the mixer noise is doubled. The receiver noise increase at a THz is about 25 % for a Nb junction with Al striplines.

8.3 NbN junction results

A NbN/MgO/NbN junction with size and normal state resistance similar to a Nb junction, has a specific capacitance which is nearly twice that of a Nb junction. Since Al_2O_3 and MgO have similar dielectric constants, the main reason of this discrepancy is most likely the roughness of the NbN surface, which increases the effective ”contact area” of the barrier and therefore the capacitance. The increased capacitance makes it harder to couple the junction to the antenna and hence increases the RF losses in the stripline.

A much more important drawback of the directly deposited MgO barrier compared to the smooth thermally grown AlO_x barrier is the occurrence of pinholes. A theoretical NbN $I - V$ characteristic has a R_s/R_N value of 1500 at 4.2 K, which is huge compared to the already impressive value of 45 for a perfect Nb junction. However, all NbN/MgO/NbN junctions with reasonable current densities show R_s/R_N ratio’s of 5 to 10. This implies that **all** subgap current is carried by pinholes even for relatively thick barriers. The impact on the mixer noise performance is dramatic. Because of the large subgap current of high current density NbN junctions the receiver sensitivity is already dominated by the subgap current, but again because of the MAR current transport, the mixer noise is doubled. For this reason, although NbN junctions at 1 THz operate below the gap frequency, their mixer noise is much larger than that of a Nb junction operating at the limit of its frequency range.

The subgap current of a 20 Ω junction of 1 μm^2 area is so large that even the gain is affected, causing an additional decrease in the sensitivity.

Of course, at frequencies above 1200 GHz, the Nb voltage nonlinearity is insufficient for heterodyne mixing and NbN will be the only material suitable for SIS junctions which will operate in the range 1.2 to 2 THz. A question not yet fully answered is the loss in the junction electrodes. With increasing frequencies the wavelength in the junction (which in fact is also a stripline[2]) cannot be considered infinite compared to the junction dimensions. This implies that RF currents can flow laterally through the electrodes, which, particularly at these high frequencies, have large RF losses. Therefore the signal is partly absorbed in the electrodes before it reaches the barrier where it can be mixed. First theoretical results indicate nearly complete signal loss beyond 1.4 THz[3].

8.4 Future development of THz detectors

Current research topics in the development of THz detectors are the use of NbTiN as stripline material, which will enable receivers employing Nb SIS junctions to operate with noise temperatures reduced by a factor of 3, therefore a receiver noise temperature of 300 K at 1 THz should be obtainable with Nb junctions.

An obvious expansion of this route is the use of all - NbTiN structures, which would expand the receiver operating range to about 1500 GHz, slightly above the gap frequency of NbTiN. Because of the excess shot noise present in these junctions the noise temperature will be increased compared to Nb junctions, but may still be competitive with other THz detection mechanisms. An estimated noise temperature at 1.2 THz of an optimized receiver with Mylar windows, an IF chain with 3.2 K noise temperature employing a NbN junction with R_N =20 Ω, an area of 1 μm^2 and an Al stripline is 3500 K, mainly due to the mixer noise temperature of 600 K and stripline transmission of 20 %. If now this stripline transmission is increased to 80 % with the aid of nearly lossless NbTiN, the receiver noise temperature may reach a value as low as 1000 K at 1200 K and comparable noise values up to the gap frequency of NbTiN.

For frequencies beyond 1500 GHz, depending on the normal state conductivity of NbTiN, the use of NbTiN is inevitable as junction electrode material if the electrode loss predictions of Honingh et al[3] are correct. However, the estimated noise temperature at 2 THz of a receiver with Mylar windows, an IF chain with 3.2 K noise temperature employing a NbN junction with R_N =20 Ω, an area of 1 μm^2 and an Al stripline is 10000 K, mainly due to the mixer noise temperature of 1200 K and stripline transmission of 15 %.

Recent progress in the hot electron bolometer development has been substantial. The uncorrected receiver noise temperatures are 1880 K at 1267 GHz[4], up to 3000 K at 2.5 THz[5] for diffusion-cooled bolometers. When comparing the mixing characteristics of Nb and NbN SIS junctions with those of the hot electron bolometers, a number of conclusions can be drawn.

- Between 800 and 1100 GHz, the Nb SIS junctions are likely to outperform the HEB's, especially when equipped with lossless NbTiN striplines.

- Between 1100 and 1500 GHz, the HEB receiver noise temperatures are lower than those expected for NbN junctions with Al striplines because of the large shot noise generated in the NbN junctions. However when equipped with NbTiN striplines the noise temperatures may be comparable, if the NbTiN stripline loss compensates for the large shot noise inherent to the Nb(Ti)N junctions.

- Beyond 1500 GHz, the Nb(Ti)N SIS junctions will have to rely on Al tuning circuits, hence the receiver noise temperatures will increase rapidly with increasing frequency.
- An advantage of the HEB's over SIS is the low LO power required. At increasing frequencies the LO power generated via doublers and triplers falls off rapidly, therefore this low power requirement is quite important for airborne or space application of supra-THz detectors.
- Both diffusion-cooled Nb and the phonon-cooled NbN bolometers have demonstrated the ability to utilize IF bandwidths of several GHz, which is large enough for the applications in submillimeter astronomy and atmospheric sensing.

In conclusion, Nb SIS junctions are still unbeaten in the frequency range of 300–1100 GHz. Unless a wetting and thermal oxidation technology together with low-loss superconductor layer technology is developed, NbN SIS junctions are outperformed by hot electron bolometers beyond 1 THz.

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