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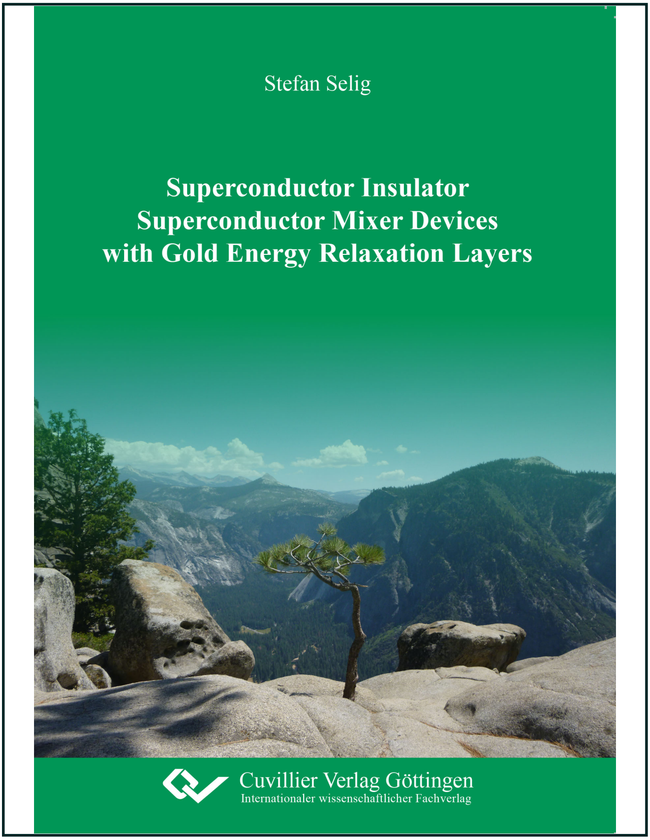
Superconductor Insulator Superconductor Mixer Devices with Gold Energy Relaxation Layers



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Chapter 1

Introduction

The goal of this work is the development of superconductor insulator superconductor (SIS) devices that can be used as detector elements with quantum limited sensitivity in heterodyne receivers for 800 and 1100 GHz. Existing mixers do not reach quantum limited sensitivity at these frequencies because they use normal conducting RF matching circuits instead of superconducting ones. Within this work existing device technology from the HIFI[1] and SMART[2] projects is improved using fully superconducting RF matching circuits. This is enabled by an additional *Au* layer that provides energy relaxation i.e. "cooling" of the junction of the device.

This development is meant for the use in radio astronomy to improve sensitivity and make observations at the mentioned frequencies more effective. In this chapter we give a short introduction to the field of THz astronomy and the detector types that are commonly used. Then we will briefly describe the developed device and give a more detailed motivation of our approach.

1.1 THz Astronomy

Understanding the formation of stars is one of the main goals of astronomers. Stars form from molecular clouds in cold regions of the interstellar medium. These clouds contract by their own gravitation, induced by external triggers like jets and outflows, and form young stellar objects (YSO), which evolve to stars later on. The regions in which stars form typically have temperatures from 10-100 K and thus they emit radiation in the submillimeter or THz regime.

An important part of the emission from these clouds originates from molecular transitions that can be observed as emission lines in recorded THz spectra. From

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[1] Heterodyne Instrument for the Far-Infrared [1]

[2] Sub-Millimeter Array Receiver for Two frequencies [2]

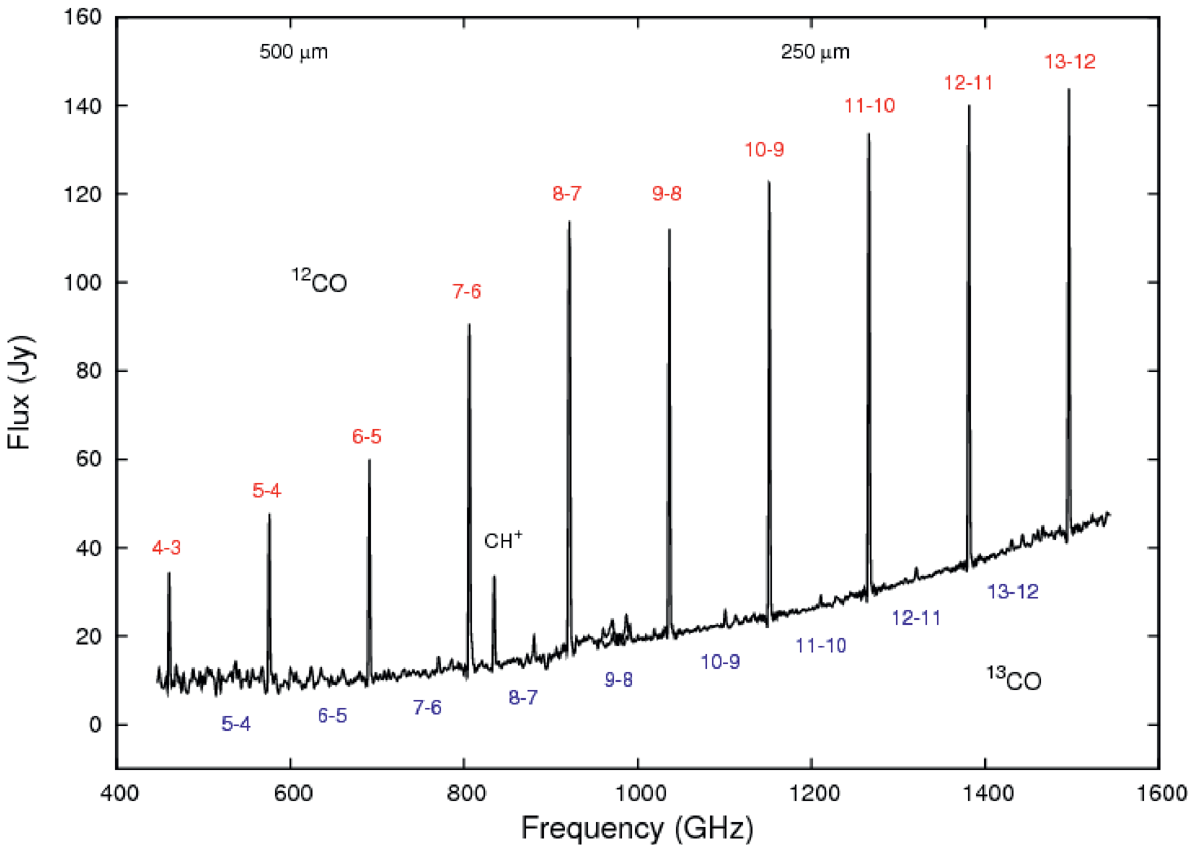

Figure 1.1: This plot shows a part of the CO rotational spectrum between 400 GHz and 1.6 THz. It was recorded with the SPIRE Instrument on the Herschel satellite, pointing at the planetary nebula NGC 7027 [3]

these, astronomers can determine many chemical and physical properties of the gas like the abundance of species, velocity and physical conditions like pressure, temperature and density. This allows to investigate in detail the preconditions and the processes of star formation.

One of the most important species for astronomy is the CO molecule because of its high abundance and therefore high line intensities. It is commonly used to determine the kinetic temperature of molecular clouds and to trace H_2 which is not as easily detectable. Its rotational transition lines are observable from 115 GHz ($J = 1 - 0$) on in intervals of the same value. Fig. 1.1 shows a part of the CO rotational transition spectrum. Because of the atmospheric absorption, only the lower lines are observable from the ground. The highest transition observable from earthbound observatories is at 1037 GHz ($J = 9 - 8$) which lies well within the atmospheric window from 1000 to 1060 GHz at the APEX (Atacama Pathfinder Experiment) telescope site in Chile. The SIS device technology developed in this

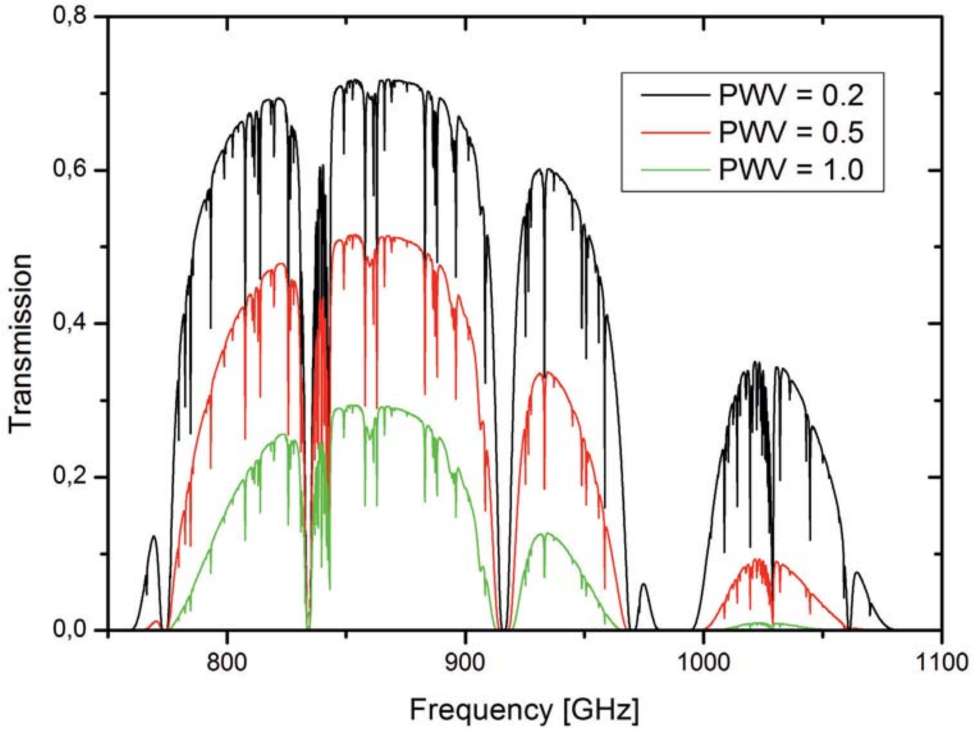

Figure 1.2: This plot shows the transmission of the atmosphere at the APEX site for three different values of precipitable water vapour (PWV) in the atmosphere in the frequency range of 750 GHz to 1.1 THz. The transmission windows around the center frequencies of 850 GHz, 930 GHz and 1.04 THz are obvious [4].

work is planned to be used in a 10 pixel receiver for APEX in that frequency range and may later on also be used in a possible 800 GHz receiver for the yet to build Cerro Chajnantor Atacama Telescope (CCAT).

The high frequency channel of the SMART receiver may be upgraded with devices using the technology of this work. This array receiver was built mainly for the simultaneous mapping of the two fine structure lines of neutral atomic carbon at 492 GHz and 809 GHz using two subarrays centered at 490 and 810 GHz. Additionally the lines of ^{12}CO at 807 GHz ($J = 7 - 6$) and ^{13}CO at 880 GHz ($J = 8 - 7$)) can be observed.

One possible application of this technology in the more remote future is a receiver for the Stratospheric Observatory for Infrared Astronomy (SOFIA). But this only makes sense if this technology can be extended for the use at 1.4 THz and above and if it leads to SIS mixers that are competitive in terms of noise temperature with HEB mixers that are currently used in this frequency range. In any case, this is beyond the scope of this thesis.

1.2 Heterodyne detection

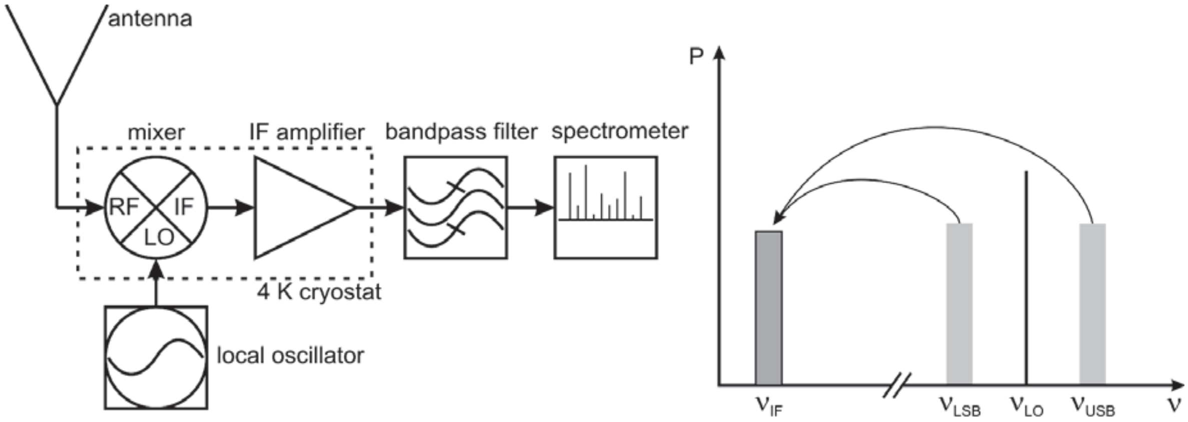

Figure 1.3: Schematic setup of a heterodyne receiver (left) and downconversion of the RF to the IF band (right).

For high resolution spectroscopy in THz astronomy, heterodyne receivers are essential. They typically offer a spectral resolution of $\Delta\nu/\nu = 10^5 - 10^6$. The detection principle is depicted in Fig. 1.3. A THz frequency (RF) signal incident from the sky is picked up by an antenna which feeds it to the mixer. There it is combined with a local oscillator (LO) signal. The result of the mixing process is the intermediate frequency (IF) signal, with a frequency that equals the difference of the LO and the RF signal, typically in the low GHz range. The IF signal is then amplified, filtered and analyzed by a spectrometer.

In general, without taking any special measures, the mixer converts two so-called sidebands, the lower sideband (LSB) and the upper sideband (USB) down to the IF band $\nu_{IF} = |\nu_{LO} - \nu_{signal}|$. This can be confusing when lines from both sidebands appear in the IF spectrum. To overcome the confusion in this so called double-sideband (DSB) mode, the LO is tuned to a somewhat different frequency. Lines from one sideband will eg. move up in the IF frequency, whereas lines from the other sideband will move in the opposite direction. That makes it possible to determine which line originates from which sideband. A more elegant way to avoid this problem is to use a detector that works in the sideband separating (2SB) mode and thus both sidebands have different output ports from the mixer.

The sensitivity of a heterodyne receiver is typically given in terms of the receiver (input) noise temperature T_{rec}. The noise temperature of an electrical component is the temperature an ideal resistor would have that produces the same (white) noise power like the regarded component. A typical receiver consists of several components like it is shown in Fig. 1.3. Each component produces noise and gives a contribution to T_{rec} as follows [5, 6]:

$$T_{rec} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots = T_1 + \sum_{i=2}^{n} \frac{T_i}{\prod_{j=1}^{i-1} G_j} \tag{1.1}$$

T_i and G_i are the input noise temperatures and gains of the individual components. Typically T_1 and G_1 are contributed by the mixer, with $G_1 \leq 1$ whereas the later stages usually have $G_n \gg 1$, so that the mixer sensitivity (T_1 small, G_1 large) is important. For highest sensitivity a superconducting mixer is used.

The minimum detectable signal temperature ΔT is determined by the receiver noise temperature T_{rec}, the IF bandwidth $\Delta\nu$ and the integration time τ:

$$\Delta T = \frac{T_{rec}}{\sqrt{\tau \Delta\nu}} \tag{1.2}$$

with the detection bandwidth $\Delta\nu$.

At present superconducting mixers have the highest sensitivity (lowest T_{rec}).

1.3 Superconducting Mixers

At KOSMA two different types of superconducting mixers are constantly developed further for the use in heterodyne receivers: superconductor insulator superconductor (SIS) and superconducting hot electron bolometer (HEB) mixers. The maximum operation frequency of a SIS mixer is limited by the superconducting gap of the junction electrode material, which in this case is niobium. The mixing limit is twice the gap frequency which is $\nu_{gap} = 700$ GHz for Nb. SIS mixers are preferably used from 0.1 to 1.4 THz because of their wide instantaneous IF bandwidth, combined with possible quantum limited sensitivity. Beyond 1.4 THz, HEB mixers are used. They do not have an intrinsic upper operation frequency limit but they have a smaller instantaneous IF bandwidth than SIS mixers. In the following we address both mixer types in greater detail.

1.3.1 Superconducting hot electron bolometer (HEB) mixers

Superconducting HEB mixers detect radiation with a several nanometers thin and several hundred nanometers long superconducting microbridge. Incident radiation is absorbed by the electron gas in the superconducting microbridge which causes variations of the normal state resistance. If the HEB is biased with a constant bias voltage the fluctuating current causes power over the IF output load, that fluctuates with the beat frequency of RF and LO signal.

Fig. 1.4 shows a scanning electron microscope (SEM) image of a 4.7 THz HEB device. The first devices of this type were developed in the 1990s [8, 9].

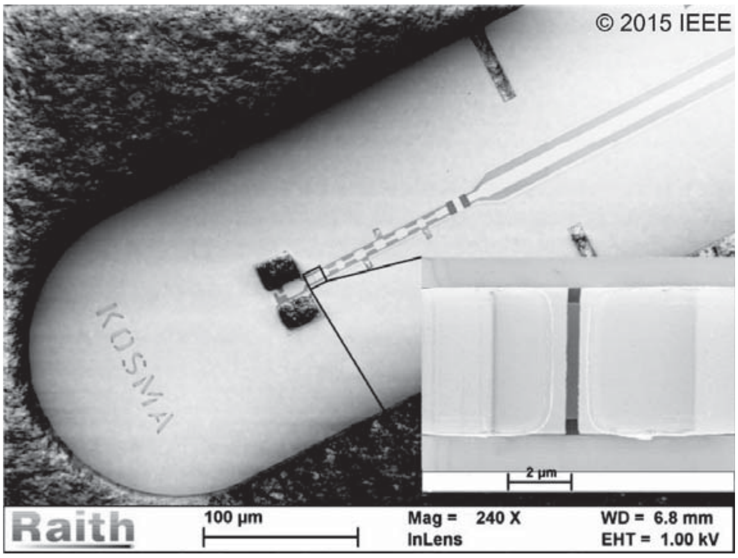

Figure 1.4: SEM image of a 4.7 THz HEB device [7]. The inset shows a magnified image detail of the superconducting microbridge, which is the dark grey layer between the bright Au terminals.

Since then several projects using superconducting HEB mixers have been realised, the CONDOR receiver, a 1.5 THz receiver for the RLT observatory, a 1.3 THz balanced waveguide HEB mixer for the APEX observatory, bands 6 and 7 of the HIFI instrument on the Herschel satellite and the GREAT and upGREAT receivers for the SOFIA observatory at 1.4, 1.9, 2.5 and 4.7 THz. [1, 10–17].

1.3.2 Superconductor Insulator Superconductor (SIS) mixers

The first SIS mixers where reported in 1979 [18, 19]. Since then they have been widely used for spectroscopic observations in the submm and the THz regime. SIS mixers have been successively developed further up to presently 1.4 THz [20]. Projects where KOSMA was involved, are the HIFI instrument on the Herschel satellite, the SMART receiver that was developed for the KOSMA telescope and later transferred to NANTEN [1, 2]. For HIFI, KOSMA delivered SIS mixers for one band (band 2). For the remaining bands, mixers were delivered by LERMA[3]

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[3] Laboratoire d'Études du Rayonnement et de la Matière en Astrophysique et Atmosphères, Paris, France

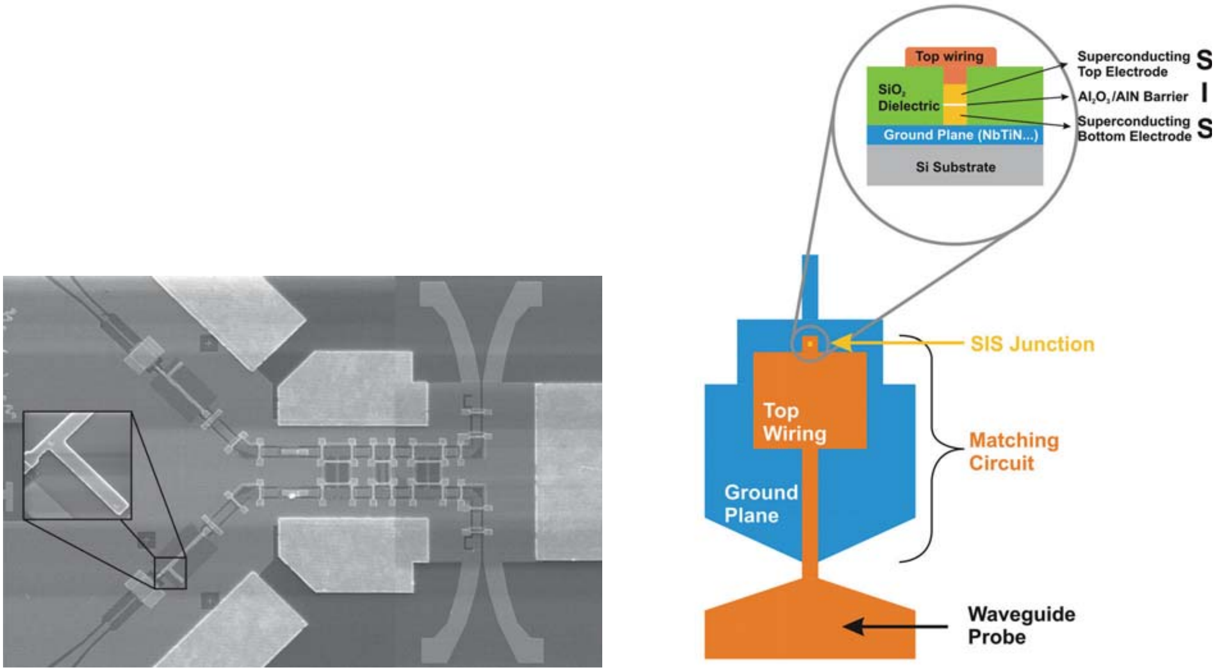

Figure 1.5: The SEM image to the left shows an SIS mixer for 490 GHz. The inset shows a magnified view of its two junctions and a part of the matching circuit [22]. The drawing to the right shows the general layout of a SIS mixer with one junction.

(band 1), SRON[4] (bands 3 and 4) and JPL[5]/Caltech[6] (band 5). A more recent important project is the ALMA [21] observatory. ALMA is equipped with SIS receivers from IRAM[7], HIA[8], NAOJ[9], NOVA[10], NRAO[11] and OSO[12].

The detecting element of an SIS mixer is the superconductor insulator superconductor junction. It is embedded in a superconducting RF matching circuit, that connects it to a (waveguide) antenna and the IF output. SIS mixers offer the highest sensitivity for heterodyne detection. The fundamental sensitivity limit for SIS mixers is the quantum limit coming from the Heisenberg uncertainty principle for coherent detectors. SIS mixers often reach a sensitivity close to this limit.

Fig. 1.5 shows an SEM image of a SIS mixer for 490 GHz and a drawing of the general layout of a SIS junction. The SIS tunnel junction consists of two

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[4] Netherlands Institute for Space Research, Utrecht, Netherlands

[5] Jet Propulsion Laboratory, Pasadena, USA

[6] Califorinia Institute of Technology, Pasadena, USA

[7] Institut de Radio Astronomie Millimétrique, Grenoble, France

[8] Herzberg Institute of Astrophysics, Victoria, Canada

[9] National Astronomical Observatory of Japan, Mitaka, Japan

[10] Nederlandse Onderzoekschool voor Astronomie, Groningen, the Netherlands

[11] National Radio Astronomy Observatory, Charlottesville, USA

[12] Onsala Space Observatory/Chalmers University, Onsala, Sweden

superconducting electrodes that are separated by an insulating barrier that is thin enough to allow tunneling of Cooper pairs and quasi-particles between the two superconducting electrodes. It is embedded in a RF circuit which ideally consists of superconductors too. The top layer and the groundplane of this circuit are usually separated by a SiO_2 layer. Up to 700 GHz, the gap frequency of Nb, the junction electrodes as well as the layers of the RF circuit are made of Nb. Above that frequency Nb has to be replaced by superconductors with higher gap frequencies or normal conductors for the RF circuit material.

Typically $Nb - Al_xO_x - Nb$ junctions are used for mixer devices because this material combination has proven to offer superior junction quality compared to other material combinations. Also $Nb - AlN - Nb$ and $Nb - AlN - NbTiN$ junctions have been reported [20,23,24]. AlN barriers offer higher current densities which is important to maintain a large enough bandwidth for frequencies beyond 1 THz.

1.4 SIS mixers with Au energy relaxation Layer (ERL)

For frequencies above 700 GHz, state of the art SIS mixers have normal metal leads for at least one of the electrodes of the embedding RF circuit (see Fig. 1.6). The reason for this is that above this frequency Cooper pairs are broken in Nb, which leads to high dissipation in the circuit if it is made of the same material. The most obvious solution is the use of a different superconductor with a higher gap energy, but other materials do not offer the same junction quality in combination with Al based barriers. So Nb is still used as junction electrode material because Nb junctions can theoretically mix RF signals up to 1.4 THz and different materials, which promise less dissipation, are used for the embedding RF circuit.

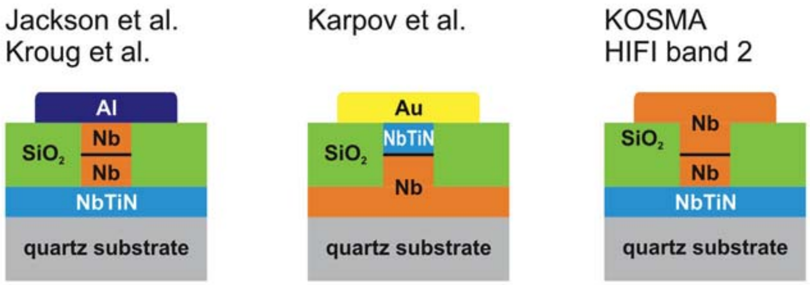

Figure 1.6: State of the art SIS devices. Above 700 GHz the Nb wiring leads can be regarded as normal conducting. These devices have been published in [20, 25–27]