A low-noise micromachined millimeter-wave heterodyne mixer using Nb superconducting tunnel junctions

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A heterodyne mixer with a micromachined horn antenna and a superconductor-insulator-superconductor (SIS) tunnel junction as mixing element is tested in the W-band (75–115 GHz) frequency range. Micromachined integrated horn antennas consist of a dipole antenna suspended on a thin Si_3N_4 dielectric membrane inside a pyramidal cavity etched in silicon. The mixer performance is optimized by using a backing plane behind the dipole antenna to tune out the capacitance of the tunnel junction. The lowest receiver noise temperature of 30 ± 3 K (without any correction) is measured at 106 GHz with a 3-dB bandwidth of 8 GHz. This sensitivity is comparable to the state-of-the-art waveguide and quasi-optical SIS receivers, showing the potential use of micromachined horn antennas in imaging arrays. © *1996 American Institute of Physics.* [S0003-6951(96)04413-6]

The development of waveguide and quasi-optical (SIS) heterodyne receivers has dramatically reduced the required observation time in millimeter- and submillimeter-wave radio astronomy. For a further improvement in the observation of spatially extended sources, imaging arrays of SIS-receivers would be of great benefit. The high cost and mechanical difficulties of building an array of waveguide mixers and the poorer Gaussian beam-quality of quasi-optical designs have thus far limited the efforts to actually develop such arrays. The recently developed micromachined horn antennas offer a relatively easy and low cost fabrication and excellent Gaussian beam properties, and are therefore an attractive candidate for the development of SIS imaging arrays. Additional advantages of these antennas are the scalability to THz frequencies and the possibility of fabricating on-chip (superconducting) electronics on Si (or GaAs) device wafers.

Micromachined integrated horn antennas consist of a dipole antenna suspended on a thin ($\sim1\,\mu$m) Si_3N_4 dielectric membrane inside a pyramidal cavity etched in silicon.[1] Development of a 335-GHz room-temperature heterodyne receiver[2] and a monopulse tracking receiver[3] have already shown the feasibility of room-temperature micromachined integrated horn receivers with semiconductor GaAs diode detectors for applications at millimeter and sub-millimeter wavelengths. In this letter we report on the fabrication and testing of a single element micromachined SIS receiver and demonstrate its excellent noise performance.

The geometry of the micromachined horn-antenna is shown in Fig. 1. A conventional machined section is placed in front of this micromachined part to form a quasi-integrated horn antenna, as described in Refs. 4 and 5. We previously reported on measurements with a SIS micromachined mixer in a horn geometry designed to feed a low capacitive ($C\approx10$ fF) Schottky diode.[2] Analysis showed that this design gave a nearly 5-dB return loss with the highly capacitive ($C\approx70$ fF) SIS junctions.[6] In order to reduce this impedance mismatch we fabricated and tested several horn antennas, where the backing wafers do not form a complete pyramidal cavity, but a reflecting backing plane located at various distances from the dipole antenna. This backing plane can provide an inductive impedance at the antenna terminals, which resonates out the junction capacitance, thereby reducing the impedance mismatch.

A detailed description of the process steps in the fabrication of the micromachined horn antennas is given in Refs. 6 and 7, here we give a short outline. The junction fabrication is performed using a selective niobium anodization process (SNAP).[7,8] The $Nb/Al_2O_3/Nb$ trilayer is deposited by dc-magnetron sputtering on a double-side polished 0.38 mm-thick and (100)-oriented silicon wafer, which was covered on both sides with a 1-μm thick low-stress Si_3N_4 layer.[7] The trilayers are patterned by plasma etch of the Nb layers with CF_4 and a wet etch of the Al layer. The junctions are defined by an anodization process and then a Nb counter electrode is deposited and patterned to connect the junctions. Bonding pads are defined by E-beam evaporation of a 400-nm thick Ti/Au layer followed by a lift-off process.

The patterned trilayer serves as an alignment mark for an infrared alignment, in which the antenna apertures have to be defined on the *opposite* side of the wafer. After patterning,

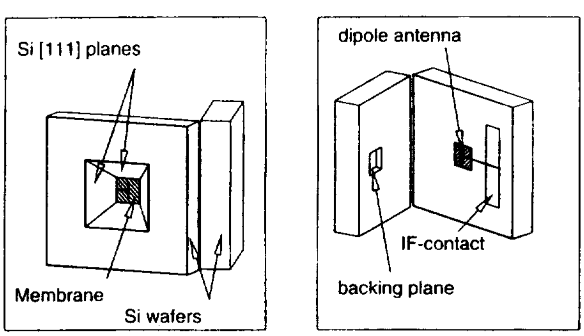

FIG. 1. Details of the micromachined horn antenna before bonding the wafers together. The length of the dipole antenna is 1.2 mm.

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the silicon nitride is etched (with reactive ion etching) in a mixture of freon-23 with 4 % oxygen. The chip is then mounted in a Teflon KOH etching mount which isolates the front and backside of the wafer by sandwiching the wafer between two O-rings. The freestanding membrane is formed by etching the silicon in a solution which contains 20% KOH by weight at 80 ^{0}C for 4-5 hours and another hour of etching at 60 ^{0}C. The slower etching of the last hour is used to create smoother sidewalls of the aperture. The final fabrication step is the deposition (with E-beam evaporation) of a 400-nm Ti/Au layer on the sidewalls of the aperture through a ceramic shadowmask.

The micromachining of the horn apertures is similar to the etching process described above. The wafers with the backing planes are fabricated by removing them from the KOH-etchant before they are completely etched through. Backing planes at distances of 95, 240, and 345 μm have been fabricated, with etching times of (approximately) 1, 2, and 3 hours. The separate parts of the horn aperture are aligned under a microscope and bonded together with UV- and heat-curing Norland optical glue and Krazy Glue Cyanobond. The stack of 5 Si-wafers forming the micromachined horn section is glued with cyanobond to the backplate of a mixermount. The machined horn section is placed in front of the backplate, mounted in an xyz-stage which allows the alignment with the micromachined section.

The noise and gain properties of the heterodyne receiver are measured by using millimeter-wave absorbing foams at two different temperatures (295 K and 77 K) as a calibrated blackbody signal source. A 75–115 GHz tunable Gunn-oscillator provides the local oscillator (LO) power. The mixerblock and cold stage of the amplification chain for the intermediate frequency (IF) are mounted in an Infrared Laboratories HD3-8 dewar. The signal and LO-power are combined by a 97% transmission beam splitter and enter the cryostat via a 25-μm thick polypropylene vacuum window of 3 cm diameter. On the 77 K radiation shield a 750-μm thick quartz plate covered with black polyethylene serves as a cooled low-pass filter. A F=28 mm TPX (methylpentene polymer) lens is placed at focal length in front of the horn.

The IF-chain consists of a bias-tee circuit in the mixerblock, a Pamtech LTE 1268K isolator, and a Berkshire Technologies L-1.5-30HI IF-amplifier (40-dB gain, $T_{\mathrm{noise}} \approx 3$ K). A further amplification of 60 dB is provided by room-temperature amplifiers outside the dewar. The IF-power is measured in a 35 MHz bandwidth with an HP-436A power sensor at a center frequency of 1.5 GHz (set by a tunable bandpass filter).

The mechanical ruggedness and cooling properties of the micromachined horn antenna were previously discussed in Ref. 5. Experiments showed that the superconducting tunnel junctions can be adequately cooled on the thin membrane, and that the devices withstand repeated thermal cycling in the vacuum dewar.

Several combinations of devices and backing planes have been tested. In the measurements with the backing plane located at 90 μm, the pumped (LO-power applied) I-V curve exhibits regions of negative dynamic resistance. This is a consequence of the quantum nature of the tunneling process, and indicates that the geometrical capacitance of the

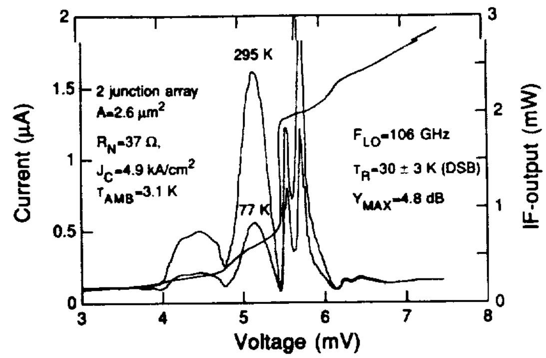

FIG. 2. Pumped I-V characteristics of an array of two SIS junctions at a LO frequency of 106 GHz and the measured IF-output power with a 295 K and 77 K input load.

junction is completely tuned out. Figure 2 shows the result of a heterodyne measurement at a LO-frequency of 106 GHz with an array of two junctions and the backing plane located at 345 μm. The array has a normal state resistance of $R_N = 37\ \Omega$ and each junction has an area of 2.6 μm^2 (the critical current density is $J_c = 4.9$ kA/cm^2). Figure 2 shows the dc I-V curve measured with the 106 GHz local oscillator radiation applied (at a mixer mount temperature of 3.1 K) and the IF-output power (P_{IF}) with a 77 K and 295 K blackbody input signal.

The maximum Y-factor ($=P_{\mathrm{IF}}^{295}/P_{\mathrm{IF}}^{77}$) is measured at the first photonstep below the gap voltage and is 4.8 dB, which results in a 30± 3 K receiver noise temperature (without any correction). Analysis of the mixer data, where we take into account the noise and gain contributions of the rf input and the IF chain, shows that the mixer gain is 1.2 ±0.8 dB and the mixer noise temperature is 7.6± 5 K.

The measured noise temperature as a function of LO frequency of this device is shown in Fig. 3, along with its video response measured using a Fourier transform spectrometer (FTS). The 3-dB bandwidth of the mixer is ≈8 GHz. Because of this narrow bandwidth and the 3 GHz separation between the upper and lower sideband frequencies, the rf-coupling at the two sidebands will differ significantly. The quoted noise temperatures are therefore not truly double

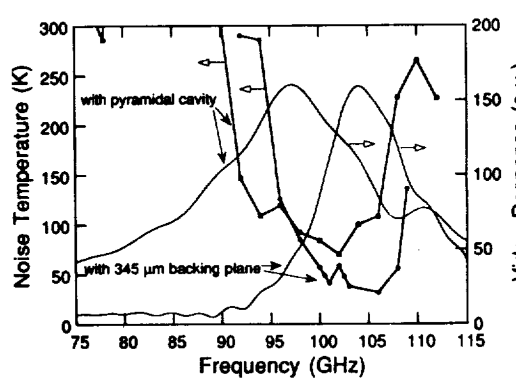

FIG. 3. Video response and noise temperature of the micromachined SIS-mixer as a function of LO frequency. Two sets of curves correspond to the micromachined structure with a 345 μm backing plane and a pyramidal backing cavity, respectively.

sideband (DSB) noise temperatures. Figure 3 also shows results of a measurement with the same array of junctions but used in a horn with the pyramidal shaped backing cavity. The best results obtained then are a noise temperature of 70 K and a 3-dB bandwidth of 15 GHz,[6] which shows the effectiveness of the backing plane in reducing the rf-mismatch. The lowest noise temperatures measured with the 240 μm and 95 μm backing plane are 35 K and 66 K, respectively.

Figure 3 shows that the resonance frequency increases and the bandwidth decreases when the backing plane is used instead of the pyramidal shaped cavity. Measurements with the two other backing planes (located closer to the dipole) showed a further increase in resonance frequency and decrease in bandwidth. This can be understood qualitatively if we assume a simple waveguide model of the hornstructure, where the impedance (Z_{bp}) of a plunger located at distance d in a waveguide with impedance Z_0, is given by $Z_{bp}=jZ_0\tan(2\pi d/\lambda_g)$ (with λ_g the guide wavelength). This inductive impedance should resonate out the junction reactance $1/(j2\pi fC)$ (with C the junction capacitance). For small values of d, this gives a resonance frequency of $f_{res}\sim 1/(2\pi)\sqrt{(1/\mu_0 Cd)}$, which increases with a decreasing d. With the same model it can also be shown that the bandwidth decreases with a decreasing backing plane distance.

The current state-of-the-art waveguide and quasi-optical receivers for the 90-115 frequency range have DSB noise temperatures of 19 K and 38 K, respectively.[9-13] Our results show that the sensitivity of the micromachined SIS-mixers is comparable to the best waveguide and quasi-optical mixers. The bandwidth of our current mixer is limited by the tuning range of the backing plane. In future designs we will use on-chip integrated tuning elements to tune out the junction capacitance, which will likely increase the bandwidth to 15%, which is the bandwidth of the dipole antenna in the micromachined horn.

In summary we have shown the operation of a low noise micromachined SIS mixer for the W-band frequency range. The feasibility of micromachined SIS-mixers is demonstrated: the complete micromachined mixer is robust and can be thermally cycled in a cryogenic vacuum environment and the tunnel junctions can be sufficiently cooled. The use of a micromachined backing plane is an effective way of optimizing the rf coupling to the superconducting tunnel junctions. The measured minimum noise temperature of 30 K is comparable to the best results obtained with conventional waveguide and quasi-optical SIS-receivers and is encouraging for the use of SIS micromachined mixers in imaging arrays.

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