Fabrication of a Diffusion Cooled Superconducting Hot Electron Bolometer for THz Mixing Applications

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Abstract---Recent interest in bolometers for heterodyne mixing applications has prompted development of microbridges which are small enough to allow electron diffusion to dominate over electron-phonon interaction as a cooling mechanism. Prior results at 533 GHz have demonstrated several GHz intermediate frequency (IF) bandwidth. Here we describe our processing method in which the bolometer element is a 1000l thin film of niobium defined by electron beam lithography down to dimensions of 80nm. This microbridge is embedded in a normal metal (Au) antenna stricture for 1.2 and 2.5 THz applications.

I. INTRODUCTION

not electron bolometric (HEB) mixers have gained interest in the field of sub-mm radio astronomy because of the promise of lower noise and lower local oscillator (LO) power requirements than existing alternatives in the THz range [1]. Results at 533 GHz have shown double side band (DSB) receiver noise temperature to be 650K with an IF bandwidth of 1.7 GHz [?]. Other results obtained with experiments at ≈10 GHz have extended the -3dB rolloff of the response up to 6 GHz using shorter structures [3].

Diffusion controlled cooling of the superconducting transition edge HEB requires that dimensions of the microbridge link be reduced below the electron -phonon scattering length and ideally near the electron-electron inelastic scattering length. The choice of niobium for the link material along with the resistance required for circuit matching sets the geometry of the device. Film thickness determines tile sheet resistance anti transition temperature (T_c). Niobium films of 10 nrn thickness exhibit a T_c of about 6 K with a normal state resistivity just above the transition (ρ_{10K}) in the range of 20-50 μΩcm. Microbridge resistance values are designed between 50 to 100 Ω which gives a nominal length of 300 nm fora width of 100 nrn. “l'hick gold pads serve to define the length of the microbridge and to prevent Andreev reflections from trapping heat in the microbridge. Lithographic alignment difficulty arises if the Nb is to spread completely under the normal metal heat sinks for improved conduction. We have thus developed a self-aligned processing method which results from overlapping the link section with the pads section and using the composite as the etch mask.

II. FABRICATION PROCESS

The 1'117 HEB devices for quasioptical receivers are fabricated either on quartz wafers for 1.2 THz double dipole antenna structures or on silicon wafers for 2.5 THz twin slot antenna structures. All wafers are 76 mm in diameter and 0.2.S4 mm thick. Silicon substrates are 2000 Ωcm, (1 11) orientation and the quartz arc single crystal z-cut. A simple organic solvent cleaning procedure is used on both and is followed by a dilute (1 O: 1) HF dip for the Si substrate just prior to loading into the vacuum system.

Our process chamber is a load-locked ultra-high vacuum system with a base pressure of 5 x 10”^{8}Pa . Substrates are mounted with edge clips on a 13 mm thick aluminum disk which keeps them near room temperature during processing. The substrates are argon ion beam cleaned *in-situ* at 150 eV, 0.?5 mA/cm^2 (measured at source) for 30 seconds. The niobium link layer is then magnetron sputtered at a distance of 80 mm from a 76 mm target, A blanket Nb film thickness of 10 nm is controlled by time using a deposition rate of 0.7s nm/s. Then a gold capping layer is thermally evaporated to a thickness of 15 nrn to prevent Nb oxidation. The result is shown in Fig. 1 a.

All features ≤1μm in size are patterned by direct write electron beam (e-beam) lithography using a JEOL-5 system. Larger structures arc patterned by optical lithography using either a Karl Suss contact aligner or a GCA 5:1 projection I-line stepper / aligner.

Blanket coated wafers are next optically patterned with alignment marks for subsequent steps. Four equally spaced 10 x 100 μm sized crosses are placed near the wafer edge. We do this by using A75214 photoresist in an image reversed mode for good lift-off of 90 ntn Au on 10 nrn Ti.

‘i'he width of the bolometer link is defined in the first e-beam lithography step. We have chosen a bilayer stencil technique which is composed of two layers of polymethylmethacrylate (I'MMA) of different molecular weights , where the top layer is the higher molecular weight (lower sensitivity) [4]. This technique provides smoother edges for metal lift-off than a single layer process. Fir-st a layer of 950 K PMMA (K = units in Kg/mole) is spun on to a thickness of 100nm and baked on a hot plate at 115 °C for 15 minutes. The bake temperature is kept low due to single crystal quartz wafers being extremely sensitive to thermal strain. A second layer of 2,300 K I'MMA is applied in the identical way Application of the second layer is clone while

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the wafer is spinning to prevent intermixing between the two layers since chlorobenzene is the solvent in both. Another way to address the intermixing problem is to use a different solvent in the top layer [5]. After e-beam exposure and development, a gold film 25 nm thick is deposited at 1 nm/s by electron beam evaporation in a vacuum system with a base pressure of 3×10^{-5} Pa. The gold lines remaining after lift-off are between 50-200 nm wide and several microns long. This result is depicted in Fig. 1 b,

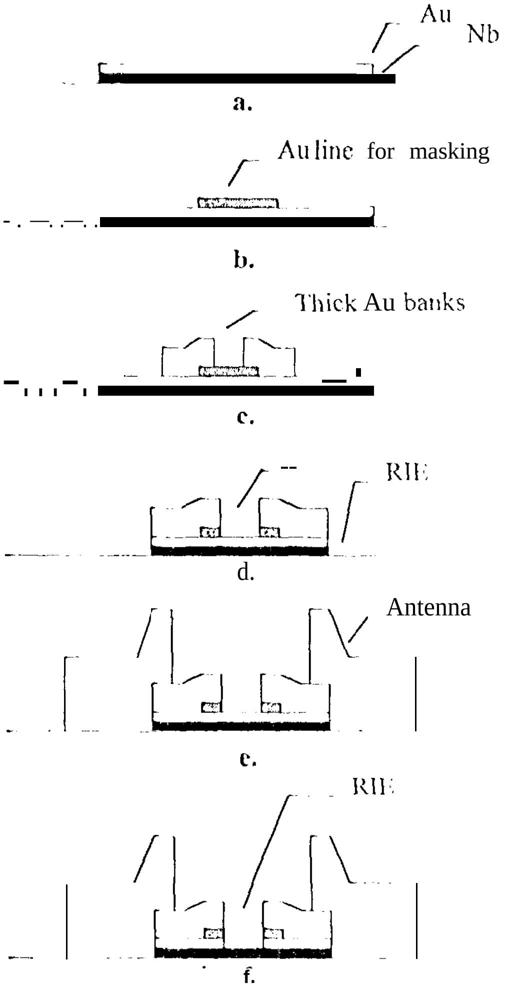

Fig. 1. Sketch of steps for self-aligned process.

The length of the bolometer is defined by the second e-beam lithography step. We again use the bilayer PMMA stencil technique described above. Two gold pads of 110 nm thick with a narrow gap 50-300 nm long are positioned over the existing line. This composite side view is shown in Fig. 1c. and is better visualized from a top view in the center of Fig. 2.

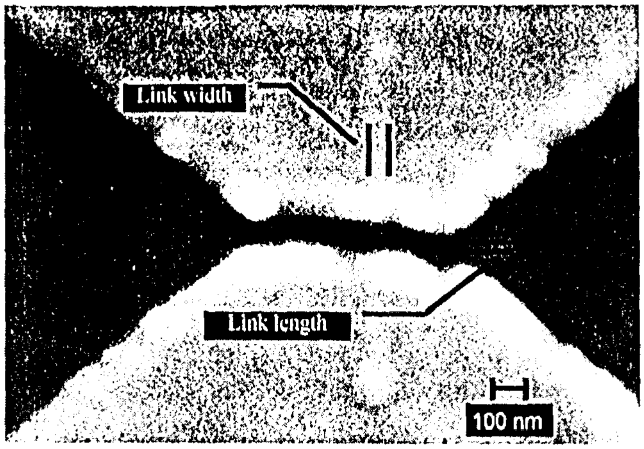

Fig. 2. 80nm x 80nm Nb microbridge with Au parts

The composite structure of gold pads and line forms a self-aligned mask for etching out the link leaving, niobium under the entire pads area. Gold and niobium in the surrounding field are etched in a two step reactive ion etching (RIE) process. Argon plasma etching removes the 15nm of gold over the field and leaves 25 nm remaining over the bolometer link area. To achieve Nb etch directionality we use a chlorine containing gas (freon) mixture at 3.9 Pa with flow percentages of 62% CCl_2F_2 + 31% CF_4 + 7% O_2. The RIE system electrode is 30 cm in diameter and is powered by a 13 MHz RF generator at 200 watts through a matching network. Typical electrode floating potential is 300 - 400 volts. Table 1 below gives the etch rates for various gas - etch material combinations of concern here. Although, with the rather short etch times involved, latency in the etch process requires visual monitoring for end point detection. Care is taken not to over etch since the Nb etch will also remove some gold. A sheet resistance measurement is taken on the field area after the etch to verify that the Nb has been completely removed. Water rinsing of the wafer after etching is necessary to remove residual chlorine compounds which may attack the Nb and degrade device lifetime. The isolated link with pads after RIE is depicted in Fig. 1 d: note that a thin gold layer still protects the link itself.

TABLE 1.
Etch rates (nm/min)

	Freon mix	Ar	Ar + O_2	O_2
Au	30	15	7	1.3
Nb	100	4	<1	<1
resist	65	50	100	150

Antenna structures for THz coupling to the HEB are fabricated of gold to reduce losses. The 1.2 THz dipoles are large enough to use optical lithography with a projection stepper, whereas, the 2.5 THz slot structures require e-beam lithography mated to optically exposed contact areas. Both applications are done by lift-off of 300 nm of e-beam evaporated Au with a 3 nm Ti adhesion layer. This result is shown in Fig.1e and the top views of the actual antennas are displayed in Fig. 3.

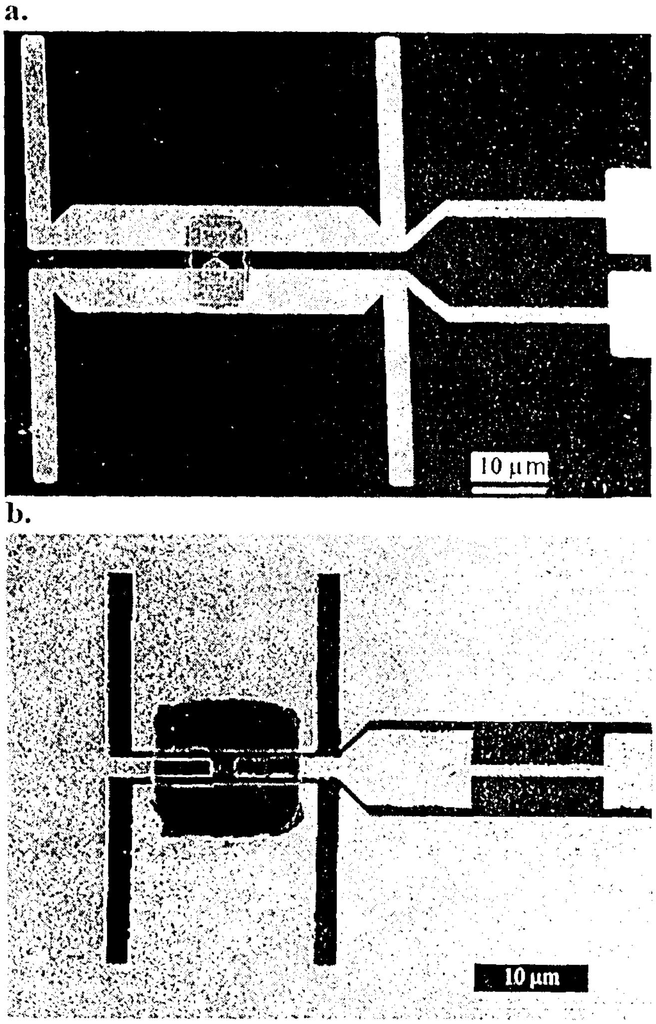

Figure 3 (a) 1.2 THz Dipole antenna, (b) 2.5 THz slot antenna

Our antenna lift-off stencil employed in the 1.2 THz dipole design consists of bilayer of OCG 897-12i photoresist on S00 nm thick PMMA. After the top resist layer is patterned, the mixed interlayer is removed by oxygen RIE. The PMMA is exposed with deep UV anti developed out with 1:3 methyl isobutyl ketone (MIBK): isopropanol This method produces a stepped edge profile with the resist overhang of about 300 nm which enables lift-off of structures clown to 1 µm.

The 2.5 THz slot antenna design requires lift-off of features down to 0.5 µm. E-beam lithography is used to pattern PMMA on layers of 20 nm Nb covering 700 nm of polyimide. The Nb layer is used both for anti-charging during e-beam writing and to prevent interaction between polyimide and PMMA. A 30 nm film of chromium is lifted of with the PMMA Large mating structures are patterned using AZ52 14 photoresist to reduce writing time on the e-beam lithography system. The composite mask of Cr and resist serves as an RIE mask for the Nb / polyimide below. Nb is etched with CF_4 + 10’% O_2 and the polyimide is etched in pure O_2. RIE is done at 1.3 Pa, 200 watts rf in a system with graphite electrodes and kapton sheet lined walls to eliminate “grassy” residue [6]. Here the Nb develops a slight overhang which allows for good lift-off when the polyimide is dissolved in dichloromethane.

Finishing the process involves removal of the remaining gold which has protected the link during processing and then applying silicon-monoxide as a protective insulator. The wafer is patterned by A7,5214 resist with window openings over the link area, Gold is etched off using RIE with 800/0 Ar + 20% O_2 which will only produce a thin oxide over the Nb link and not substantially etch it. Etch selectivity data is given in table 1. SiO is deposited in another vacuum system immediately after RIE. The SiO is thermally evaporated to a thickness of 40 nm with the sample rotating at near normal incidence. lift-off of the field SiO is done in acetone. Photoresist is applied for protection during diamond saw dicing of the wafer into chips and later handling.

III. ELECTRICAL CHARACTERIZATION

The device wafers also contain several test chips designed for diagnostic purposes at low frequency. Both T_c and sheet resistance were inspected on links ranging in size from 80 nm to 5 µm in width and length. The yield is generally acceptable with typical results given in table 2 below. These results are representative of three different wafer runs of 1.2 THz dipole devices and three different wafer runs of 2.5 THz slot devices. Resistance values are taken at 10 K. Critical current values are given for devices in liquid He at 4 K. Resistance vs. temperature data are taken at current levels lower than 10% of the 4 K critical current and the transition midpoint is given in the table. Device characteristics vary from run to run, also depending on device size, and the location on the wafer. The width of the transition point is typically 0.3 K, but tends to get wider with decreasing link size.

Typical 4 K resistivity for our gold films is 1 µΩcm. We assume this accounts for up to 0.5 ohms of series resistance near the link and =1.5 ohms of series resistance in the IF filter section.

Preliminary THz receiver results will be presented elsewhere in these proceedings [7,8}. Some of the test chips from the 1.2 THz wafers have been characterized by the Yale group more extensively for link size variations at 10GHz and performance at lower temperatures [3].

TABLE II

Typical results from device wafer runs

	R (Ω/sq.)	Jc (A/ cm^2)	Tc (K)
1.2T D1	25	3×10^6	6
1.2T D2	35	2×10^6	5
1.2T D3	20	5×10^6	6.5
2.5T S1	44	3×10^5	4,5
2.5T S2	15	1×10^7	7
2.5T S3	20	8×10^6	6.4

IV. SUMMARY

We have presented the details of our processing procedure for submicron HEB devices with Nb bridges and gold heat sinks. Our method utilizes an overlapping, mask technique which produces a self-aligned heat sink with the link material extending fully beneath it. Examples are shown of how these elements are embedded in rf circuits for application in quasi optical heterodye receivers operating at 1.2 THz with double dipole antenna and 2.5 THz using twin **slotted** antennas. Testing of the devices shows that they can be fabricated within reasonable design tolerances for dimensions down to about 80 nm.

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