Fabrication and Characterization of Niobium Diffusion-Cooled Hot-Electron Bolometers on Silicon Nitride Membranes

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ABSTRACT

We have successfully fabricated niobium diffusion-cooled hot-electron bolometer (HEB) mixers on membranes of silicon nitride less than one micron thick. This advance has allowed us to construct a 1x5 HEB receiver array intended for operation at 1.45 THz. This poster provides an overview of the integration of the HEB array chip with silicon micromachined backshorts and feedhorns, discusses materials issues surrounding the device fabrication, reports resistance and I-V measurements, and compares HEBs fabricated on silicon nitride to similar devices on quartz substrates.

Device Basics and Fabrication

The main area of this research is the fabrication of HEB mixer circuits on silicon nitride membranes, supported by a Si wafer “backside.” The microscale components of the mixer are produced by liftoff patterning of Nb and Au, resembling the patterning of Fig. 2. At the HEB region lying at the apex of the semicircular probe, the unannealed HEB is milled using a Focused Ion Beam (FIB) from the metal layers previously deposited. Three separate milling patterns (FIB1,2,3) are used to precisely define the coplanar waveguide of the probe, the HEB bridge width, and the HEB bridge length, respectively. Fig. 1 shows the HEB region after these milling steps where HEB Ni/Au sits atop a deep mesa. Ar ion bombardment is then used to etch away remaining Au atop the Nb bridge. The completed HEB block becomes a section of the complete Si micromachined receiver array.

HEB Au Etch Details

After the FIB milling steps, it is then necessary to remove the exposed gold remaining atop the HEB microbridge. We have attempted this using an iodine-based wet etchant with devices on a quartz substrate, often with good results (resistances uniform within 10%). However, undercutting of the 30 nm niobium mask at the ends of the bridge is a problem, and the reactant seems to damage the niobium film, causing devices to open-circuit over a time frame of a few weeks. Therefore it is necessary to remove the microbridge gold with a physical etch of Au ions in an RIE. An RIE self-bias of 150 Volts produces reasonable results after long etch times (2 hours is typical). The current density vs. implanted gallium dose is typically 1-2%.

FIB Ga Contamination of HEB Nb

Because of the nature of Ga bombardment in the FIB milling of the HEB structure, the FIB2 step is especially likely to implant a significant amount of gallium into the microbridge, but only into its edges. Since the microbridge is typically at least 1000 Å wide, it is reasonable to estimate that 50% or more of the width of the HEB should be free of contamination. Nevertheless, it is of interest to consider what the effects of this contamination might be. To this end, several HEBs were prepared, implanted with gallium using the FIB, and measured.

Simulations in SIMION “The Stopping and Range of Ions in Matter”, www.ssim.org predicts that 35% of the ions incident upon the HEB structure will stop within the niobium layer, although with a very non-uniform dose profile. The average dose within the field is therefore estimated to be on the order of 10^13 atoms/cm^2. The correlation between average dose and transition temperature for two sets of samples is shown in Fig. 4.

Fig. 1. Diagram of the HEB blocks before milling. The Si wafer is removed, and the gold foil (partially visible) is removed from the backside. HEB21 is milled, and annealed after the completed 1x5 mesa etched away.

Fig. 2. Diagram of the Si micromachined backshort which includes the microbridge, and backshort for the sample shown in the previous figure: the Niobium film was milled using the FIB from the metal layers previously deposited, and annealed after the completed 1x5 mesa etched away.

Fig. 3. The completed HEB bridge after Au etching.

SUMMARY

We have successfully fabricated the HEB block portion of a 1x5 receiver array for operation at 1.45 THz, and made substantial progress in the fabrication of the corresponding micromachined backshort and feedhorn blocks, and other associated hardware. Materials issues involving film stress, gallium contamination, and the physical etching of gold as a key step in the fabrication process were addressed. In general, the device resistance of this FIB fabrication process is not as controllable as we might desire, for which the difficult physical properties of gold in combination with the substantial thickness of the final layer of Au (atop the bolometer) to be sputter etched removed, required in this FIB process, are largely to blame. Germanium films were incorporated into the process successfully as a passivation material. Electrical measurements of the FIB defined HEBs indicate working devices which respond appropriately to RF radiation. Future work will involve RF testing of these elements at 1.45 GHz.

Fig. 4. Normalized R-T transitions for HEBs before (open circles) and after (solid triangles) Au etch.

Fig. 5. Measurements of critical temperature, Tc, normalized to the nominal transition temperature of the Nb film deposited in our multi-target sputtering cell, 29K, as a function of gallium dose. The one set of data, shown by the crosses, indicates that the implanted native growth is 50% or more. The two sets of samples were processed along with the arrays.

Fig. 6. shows, for comparison, resistive transitions of an unannealed device on a quartz substrate, and a Ga-passivated device on a silicon nitride membrane. The resistivity ratios, R(10 K)/R(10 K), were 1.6 and 1.4, respectively. Nb films on quartz in this work have generally had higher transition temperatures than films or silicon nitride.

Fig. 7. 1-5 curves for HEB on a Si substrate (10 GHz LO).