Investigation of Novel Superconducting Hot Electron Bolometer Geometries Fabricated with UV Lithography

Jonathan Schultz, Student Member, IEEE, and Arthur Lichtenberger

Abstract—While the superconducting community has developed various techniques for the fabrication of nanoscale hot electron bolometers (HEB), the basic structure of an HEB microbridge has been fairly consistent. A typical HEB used in a cryogenic terahertz mixer consists of a thin strip of superconductor contacted on opposite ends by small metal contact pads in a planar configuration. Both the physics and typical fabrication requirements for HEBs inspire this traditional construction. In this paper, however, we demonstrate that alternative HEB geometries are possible, which can in some cases improve the ease of fabrication, alter device characteristics, or alleviate certain device limitations. New HEB structures and associated fabrication processes are presented, building on previous work using the SSNaPS method of nanoscale patterning. These include very short niobium nitride HEBs with self-aligned bridge etch masks, and sidewall-patterned niobium HEB microbridges.

Index Terms—hot electron bolometer, THz, superconducting.

I. INTRODUCTION

The hot electron bolometer, or HEB, has become an important device in the research of highly sensitive superconducting THz mixers. While the HEB is certainly the focus of investigation, the peripheral components of THz HEB mixers require quite a bit of consideration in realizing the fabrication process. Integration of filters, substrate technology, beam leads and other technologies along with superconducting HEBs is becoming an increasingly complex process. In our research of superconducting HEBs for THz mixing applications, we have encountered various integration and fabrication challenges that have caused us to reconsider the HEB structure such that alternative designs might be developed to better resolve these problems.

In a conventional HEB design, metallic contact pads are usually fabricated above a superconductor layer in a planar manner, from which the HEB microbridge is etched. In effect, the structures involved are simple extrusions of two dimensional patterns. However, according to the theories of p-HEB and d-HEB operation [1] [2], this basic fabrication method need not be strictly maintained for a working HEB. For instance, the superconductor could lie above the contacts if all of the HEB structural and dimensional requirements are met. These would include a high quality superconducting-normal interface, proper HEB bridge dimensions for impedance matching and low thermal capacity, and in the case of the p-HEB, a high quality interface between the superconducting thin-film and the substrate for phonon interaction. In this paper, we present two new alternative HEB structures and associated fabrication methods, as well as preliminary testing data and conclusions concerning the electrical properties. We also describe the technical fabrication challenges that led to development of these new structures.

II. THE POST PROCESSED d-HEB

A. Overview

We term the first device a post processed diffusion-cooled HEB (PP d-HEB) which utilizes, as alluded to in the introduction, niobium deposited above the device’s contact pads. The reason for investigating this structure is specific to our Nb d-HEB mixer project, which utilizes ultra-thin silicon mixer chips, as reported in earlier publications [1] [2]. This technology has the potential for intrinsic stress in the silicon-on-insulator (SOI) substrate which is relaxed when the individual mixer chips are etched from the SOI’s thin device layer silicon [?]. We believe that the relaxed stress induces a significant strain on a conventional HEB, possibly causing severe changes in electrical characteristics. On such devices, a loss of superconductivity at or above liquid helium temperature (4.2 K) is observed, whereas such devices on quartz or bulk SOI substrates tend to have a $T_c$ around 5.5 K. The PP d-HEB is designed to overcome this potential problem by utilizing Nb that is deposited on the substrate surface subsequent to the etching of the individual mixer chips. At this point in fabrication, the substrate stress is assumed to be relaxed and the Nb can be safely deposited. This process also avoids possible damage to the Nb from ancillary SOI processing.

The PP d-HEB structure must meet two major requirements in order to be useful in the manner described above. First, the Nb that is deposited in the HEB bridge region of the device must be relatively contiguous across the contact-bridge boundaries, necessitating a contact pad profile that is not abrupt. Tapered contact pads offer such a profile. Tapering involves reducing the thickness of the contact pad from a given value (typically around 2000 Å for our device) to near zero at the contact-HEB boundary, producing a ramp-like profile on which to drape HEB Nb. The second requirement is the addition of some sort of self-aligning masking element to aid in the etching and patterning of the Nb film to define the HEB width. This is necessary because lithography cannot be easily performed on these individual chips.
B. Fabrication

Our PP d-HEB fabrication process begins in a straightforward manner based on our SSNaPS technique [7]. However, prior to the contact pad and planar circuit fabrication, a 5000 Å thick rectangular SiO$_x$ pad is formed adjacent to the HEB region of the device by e-beam evaporation. The pad is patterned by evaporation over a photoresist lift-off stencil. The direction of evaporation is angled slightly relative to the normal of the wafer surface in order to achieve about a 20 degree angle overhanging the HEB region. The SSNaPS processing steps are then employed to form the 2000 Å thick Au planar circuitry and integrated contact pads. The SSNaPS technique utilizes thin suspended wires of titanium (Ti-lines), initially formed on the sidewalls of a polyimide sacrificial layer, to act a liftoff stencil for this evaporation step. Effectively, a suspended Ti-line masks the portion of the HEB region where the HEB bridge will be formed and defines the HEB length by producing a gap between the Au contact pads. We have found that increasing the height dimension of the suspended Ti-line has a tendency of generating the type of contact pad tapering that we require for the PP d-HEB. We hypothesize that this occurs by way of two possible mechanisms: additional shadowing of evaporant that arrives at the wafer at slightly oblique angles, and by increased accumulation of evaporant on the Ti-line that broadens its profile over time. Fig. ?? shows the resulting contact pad geometry.

Peripheral processing of the device follows, along with the etching of the ultra-thin silicon substrate to pattern and separate the individual mixer chips. The next step involves the deposition of the HEB Nb on the individual mixer chips, which is performed by DC magnetron sputtering in our UHV sputtering system. The Nb sputter gun is aimed normal to the chip surface in order to achieve a relatively uniform coating over the Au metallization and contact pad edges. However, inherent in sputtering is a distribution of angled sputter material that arrives at the wafer surface at slightly oblique angles. We take advantage of this property to deposit an amount of Nb under the angled sidewall of the SiO$_x$ pad. The resulting profile of HEB Nb is not uniform across the HEB width, but tapers toward the SiO$_x$-Si edge. This and other geometrical characteristics of the PP d-HEB are illustrated in Fig. ??.

The SiO$_x$ effectively defines one side of the HEB’s width in the deposition process. By using a subsequent RIE process to etch the Nb outside of the HEB, the SiO$_x$ overhang defines the opposite side of the HEB’s width by acting as an etch mask. The SiO$_x$ pad’s thickness and edge angle, therefore, determine the HEB width through this self-aligning process. The effective electrical cross section of the HEB, however, is somewhat more difficult to determine due to the tapering effect caused by the deposition process. Also, the device likely does not have uniform thickness along its length, due to complex sputter shadowing effects from the Au lying along the SiO$_x$ sidewall. However, reasonable approximations of the various HEB dimensions can be made.

C. Testing and Results

A series of PP d-HEB devices were initially fabricated on thick (approx. 300 μm) silicon substrates for proof of concept and DC cryogenic testing. These devices have a bridge length of approximately 175 nm and a width of approximately 170 nm. Because the sputter flux distribution of our niobium sputter gun could not be easily determined prior to the fabrication of these devices, various gun-sample distances and deposition thicknesses (open-field) were tried to experimentally determine optimal conditions. The gun’s niobium target is a 3 inch diameter circular disk. The conditions and resulting room temperature resistance values are shown in Table 1. Interestingly, the resistance is quite low at distances of approximately 4 inches and below, but rises quickly at 5 inches. This suggests that the distribution of the sputtered material falls off quickly at increasing angular deviation from the gun’s axis. Unfortunately, the effective HEB Nb thickness is difficult to precisely control as a result. Sputtering at an angle equal to the SiO$_x$ sidewall angle from a large distance could possibly alleviate this problem by allowing for a more uniform device thickness. For reference, a typical HEB mixer requires a room temperature resistance of a few tens of Ohms.

Cryogenic DC measurements were taken in liquid helium. Resistance versus temperature data were collected for device 3

Fig. 1. SEM image of the Au contacts evaporated over a SiO$_x$ pad. Note the taper in the edges of the contacts which has an average angle of approximately 24 degrees to the normal. Some thin Au residue resides between the contact gap which is later removed by a weak wet etchant.

Fig. 2. Schematic illustrations of the PP d-HEB structure and integrated bowtie antenna from various perspectives. Note part d) with detail of the HEB cross section (not to scale). The sputter and etch angles, along with the SiO$_x$ mask, determine the size and shape of the HEB bridge.
of Table I, shown in Fig. ???. Interesting is the gradual slope to the fully normal state which completes at around 7.9 K. This temperature is quite high for superconductivity in thin Nb films of a few hundred Angstroms in thickness. However, this device was fabricated with 400 Å of sputtered Nb and the side of the bridge nonadjacent to the SiO$_x$ pad likely has a thickness close to this value, raising the $T_c$ close to the bulk value. The large $\Delta T_c$ is therefore likely a result of the HEB bridge being generally thicker in its center than the ends, due to the masking effects of the Au on the SiO$_x$ sidewall, thereby producing a $T_c$ gradient along the bridge length. This is, perhaps, an interesting side effect of the PP d-HEB’s unusual geometry and could possibly result in low thermal fluctuation noise in RF mixer operation, as theorized by Schoelkopf et al. [?].

We are currently working toward fully functioning PP d-HEB mixers on ultra-thin silicon chips. More work must be done to optimize the niobium sputter deposition process to obtain optimal film thickness and device resistance.

![Image](image-url)

**TABLE I**

<table>
<thead>
<tr>
<th>Device Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun Distance (in.)</td>
<td>3.5</td>
<td>3.5</td>
<td>4.1</td>
<td>4.5</td>
</tr>
<tr>
<td>Open-field Nb Thickness (Å)</td>
<td>300</td>
<td>100</td>
<td>400</td>
<td>300</td>
</tr>
<tr>
<td>Room Temp. Res. (Ω)</td>
<td>40</td>
<td>4</td>
<td>4</td>
<td>40</td>
</tr>
</tbody>
</table>

III. THE EDGE CONTACT P-HEB

A. Overview

We have utilized the SSNaPS process for fabricating NbN phonon-cooled HEBs on ultra-thin Si, relying on a highly reactive solution of nitric acid, buffered oxide etch, and deionized water to perform the etch of the niobium nitride. We find the wet etchant to be very effective for this application, as reactive ion etching (RIE) or inductively couple plasma (ICP) etching, in contrast, tend to produce a niobium nitride p-HEB of unexpectedly high resistance. However, the wet etchant presents a logistical problem when other easily oxidizable or oxide containing materials are utilized in the mixer design, such as the case with SiO$_x$ insulators. For this reason, it would be advantageous to be able to use a fluorine based plasma process, rather than our reactive wet etchant, for the NbN etch. A device that appears to at least partially solve this problem is our edge contact p-HEB (EC p-HEB). This p-HEB scheme utilizes a combination etch mask / passivation layer precisely placed between two specialized contact pads. Resulting is a structure that allows for both very short niobium nitride p-HEB bridges (down to 50 nm) and presents a very robust plasma etch mask.

B. Fabrication of the EC p-HEB

Our process begins by using UV lithography to pattern a resist stencil on the substrate, which is pre-coated with a 30 Å layer of NbN provided by Moscow State Pedagogical University [?]. Over the stencil is deposited a 100 Å layer of Ti for adhesion, followed by 1000-2000 Å Au, another 100 Å Ti for adhesion, and finally a few 1000 Å of Ge. The resist stencil is lifted off by dissolution in solvent. The remaining series of layers serve as the first contact pad and would possibly incorporate planar transmission line patterns in a practical mixer. The substrate is then coated with additional Ge by sputtering. Use of a small target-substrate distance helps to deliver the Ge at shallow angles and achieve conformal deposition on the sidewalls of the contact pad. An anisotropic fluorine-based RIE process is then used to etch away the Ge on the open-field wafer surface, leaving the Ge above the contact pad and on its sidewalls. Finally, another lithography process generates a pattern for the second contact pad in a resist stencil. After a brief ion clean, 1000-2000 Å Au is sputtered on the wafer, followed by liftoff of the resist stencil. The resulting contact pad is designed to overlap the first contact pad by a few micrometers. The width of the overlapping section is also a few micrometers and subsequently serves as an etch mask to define the width of the HEB. The length of the p-HEB is effectively defined by the thickness of the sputtered sidewall Ge, which spaces the metallic contacts, while the evaporated Ge provides a thicker layer of insulation for the overlapping regions.

At this point the device is nearly complete, requiring only a plasma etch process to define the HEB bridge width. A fluorine-based inductively coupled plasma (ICP) etch is used to simultaneously etch the exposed Ge and NbN, with the overlying contact pad acting as an etch mask to both layers. The sidewall Ge, though deposited perpendicularly to the wafer surface, etches due to the isotropic nature of our ICP etch process. This happens quickly, as the etch rate of Ge in fluorine plasma is quite high, and exposes the small amount of underlying NbN. This NbN, as well as the open-field NbN, then etches at a relatively slow rate. Resulting is a finished EC p-HEB device. A schematic of the basic elements of the fabrication process are shown in Fig. ??a.

C. Testing and Results

We have fabricated a limited number of test EC p-HEB devices for preliminary DC testing, but the results are promising. Final resistance for typical devices is a few Ohms at room temperature. Device dimensions are approximately 4 μm wide by 50 nm long. The precise length is difficult to determine because the thickness of the sidewall Ge is not necessary equal to the thickness of the open-field layer, though...
by using an arbitrarily large thickness of Ge above the first capacitance between the contact pads. This could be reduced heat related. The relatively large volume and close proximity of the masking elements of the EC p-HEB may be quite effective at transferring heat away from the underlying NbN bridge.

A possible side effect of our fabrication process is the shadowing of Ge deposition at the contact edge. As a result, the Ge thickness at the base of the first contact pad is thinner than the open-field Ge, as illustrated in Fig. ??a. When the Ge is anisotropically etched to completion, the NbN directly under the shadowed region is revealed first and a narrow notched region is formed as this NbN is etched. The second contact pad, therefore, makes a connection to the NbN along some portion of its cross section rather than the top surface of the film. We believe that this may result in boundary effects in the NbN superconductor that produces a Tc gradient along the end of the p-HEB [?], visible in the ramp feature of the R vs. T curve of Fig. ??a. It is not clear if this is useful for practical p-HEBs in RF operation, but could have the benefit of reducing thermal fluctuation noise, as possibly in the case of the PP d-HEB. A more traditional contact geometry would be possible by use of a 45 degree angled evaporation of sputtering of Ge. This would result in a more conformal coating and would eliminate the notching effect, illustrated in Fig. ??b.

Fig. 5. Resistance vs. temperature for a EC d-HEB test device. Source current is 100 microamperes.

A drawback to the EC p-HEB design is the potentially large capacitance between the contact pads. This could be reduced by using an arbitrarily large thickness of Ge above the first contact, or by using a low-k dielectric instead of Ge. Any material substitute for Ge should etch rapidly in a fluorine-based plasma to meet fabrication requirements. Also, a cross configuration for the contacts could be utilized to reduce the overlap area, while simplifying alignment and improving the resolution of the features in the UV lithography process. This geometry is illustrated in Fig. ??b. Such an arrangement would result in two parallel HEBs, or the NbN from one side of the first contact could be etched prior to EC p-HEB fabrication.

Fig. 6. A possible EC p-HEB layout for minimizing the overlap capacitance, while simplifying alignment between contacts.

IV. CONCLUSION

We have demonstrated that novel HEB geometries can be fabricated using UV lithography coupled with innovative microfabrication techniques. These devices have interesting characteristics that may make them well suited to specialized mixer applications. Though these HEB designs are in their infancy, it appears that they could be refined and integrated into practical terahertz mixer circuits. The unique aspects of the structure of these devices has provided some insight into thin film superconductivity that is likely to be useful in other kinds of HEB and superconducting device design.

ACKNOWLEDGMENT

The authors would like to thank Gregory Gol’tsman and Boris Voronov for their contributions to this work.

REFERENCES

[8] Moscow State Pedagogical University, Moscow 119435, Russia.