Disclosed is a method for fabricating an edge geometry superconducting tunnel junction device comprising two niobium nitride superconducting electrodes (14, 28) and a magnesium oxide tunnel barrier (24) sandwiched between the two electrodes. The NbN electrodes are preferably sputter-deposited, with the first NbN electrode deposited on an insulating substrate maintained at about 250° to 500° C. for improved quality of the electrode.

21 Claims, 2 Drawing Sheets
Fig. 2c.

Fig. 2d.

Fig. 3.

Fig. 4.

Current, $\mu A$ vs. Voltage, mV
METHOD FOR PRODUCING EDGE GEOMETRY SUPERCONDUCTING TUNNEL JUNCTIONS UTILIZING AN NbN/MgO/NbN THIN FILM STRUCTURE

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 U.S.C. 202) in which the Contractor has elected not to retain title.

This is a division of application Ser. No. 07/387,928, filed Aug. 1, 1989 now abandoned.

TECHNICAL FIELD

The invention relates to superconductive devices, and, more particularly, to such devices utilizing superconductor-insulator-superconductor tunnel junctions.

BACKGROUND ART

Since their first use as quasiparticle mixers, SIS (superconductor-insulator-superconductor) tunnel junctions have become the lowest noise broadband mixers from 30 GHz to 760 GHz. Sensitivity of these mixers has approached the quantum limit (hv power per unit bandwidth) at frequencies up to 110 GHz. A comprehensive theory of these devices has been developed which predicts excellent performance for SIS tunnel junctions as mixers well below millimeter wavelengths. However, actual development of submillimeter SIS mixers has been limited by currently used lead alloy junctions. Lead alloy junctions give excellent mixer results in the near-millimeter wave region, but have poor chemical, thermal, and electrical stability because lead is a soft, low melting point material.

For high speed switching or high frequency detection applications utilizing SIS tunnel junctions, devices with very thin tunnel barriers and correspondingly high current densities (Ic) are required. This constraint arises from the fact that the junction resistance decreases exponentially with decreasing barrier thickness, while the capacitance only increases linearly as the barrier thickness is reduced. Thus, the maximum operating frequency, which is inversely proportional to the resistance-capacitance (RC) product, can be increased by reducing the tunnel barrier thickness. Practical applications also require that the junction resistance be large enough (typically ≥ 50 Ω) to allow impedance matching to external circuits. Because the RC product is independent of area while the resistance increases as the junction area is decreased, this requirement can be met by fabricating small cross-sectional area tunnel junctions.

To obtain junctions with adequate resistances and frequency response above 200 to 300 GHz, it is necessary to produce junctions with areas less than approximately 1.0 μm², which are difficult to achieve using conventional photolithography. Practical applications require that the junction resistance be large enough (typically ≥ 50 Ω) to allow impedance matching to external circuits. Because the RC product is independent of area while the resistance increases as the junction area is decreased, this requirement can be met by fabricating small cross-sectional area tunnel junctions.

One useful technique for fabrication of small area tunnel junctions utilizes an edge geometry to achieve very small junction areas without resorting to high resolution lithography. Superconducting edge junctions have been fabricated in a variety of materials systems, including Pb/Sn, PbSn/Pb, Nb/Pb-alloys, and NbN/Pb. However, relatively little work exists on all-refractory edge junctions, with only brief reports on Nb/NbOx/Nb and NbN/Si/NbN junctions.

STATEMENT OF THE INVENTION

Accordingly, it is an object of the invention to provide a superconducting device with a very small junction area.

It is another object of the invention to provide a process for fabricating an edge-geometry superconducting tunnel junction device utilizing NbN electrodes and an MgO tunnel barrier.

It is still another object of the invention to provide a process for fabricating an edge-geometry superconducting tunnel junction device utilizing NbN electrodes and an MgO tunnel barrier.

In accordance with the invention, edge-geometry NbN/MgO/NbN superconducting tunnel junctions are provided. The use of an edge-geometry allows very small junction areas to be obtained, while the all-NbN electrodes permit operation at 8 to 10K, with a potential maximum operating frequency above 1 THz.

Also in accordance with the invention, a novel technique for producing very small area tunnel junctions with conventional photolithography uses an edge geometry to define the junction area. Edge geometry tunnel junction fabrication relies on the formation of a tunnel barrier on the exposed edge of a superconducting film. The junction is completed by deposition and patterning of a superconducting counterelectrode. Because the top surface of the base superconductor is covered by a thick insulator, the contact area between the counterelectrode and the base electrode is determined by the thickness of the base layer and the width of the top electrode tip. Because the base electrode thickness can easily be in the 0.1 μm range, junction areas on the order of 0.1 μm² are readily attainable using conventional photolithography at the 1 μm resolution level. A somewhat more subtle advantage of the edge geometry is that the in-line structure minimizes current-crowding effects that can lead to electrode transitions in high-current-density, planar-geometry junctions.

This is believed to be the first successful fabrication of edge-geometry tunnel junctions utilizing two niobium nitride electrodes with a magnesium oxide tunnel barrier. The combination of an all-NbN electrode structure with an MgO barrier results in very rugged tunnel junctions with very high quality I-V characteristics and junction areas as small as 0.1 μm². In addition, the process described below has produced NbN/MgO/NbN edge junctions with current densities up to 1.5×10⁴ A/cm², which is sufficient for junction operation at frequencies in the 500 GHz range. These devices have demonstrated excellent performance in preliminary
3 receiver tests at 205 GHz, yielding receiver noise tempera-
tures as low as 380K.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of an edge-geometry
superconducting tunnel junction utilizing an
NbN/MgO/NbN thin film structure in accordance
with the invention; Figs. 2a, 2b, 2c, and 2d are cross-sectional views
depicting the edge junction process of the invention at
various stages;

FIG. 3 is a schematic top plan view of the thin film
structure; and

FIG. 4 is a plot, on coordinates of current and voltage,
depicting the I-V characteristics of a 0.1
m2/NbN/MgO/NbN edge junction, with the vertical scale in
10 μA/division and the horizontal scale in 2
mV/division.

DETAILED DESCRIPTION OF THE INVENTION

The NbN/MgO/NbN thin film structure is depicted in
FIG. 1. The edge-geometry tunnel junction comprises a base electrode contact 10 of a patterned aluminum
metal layer 12 formed on a NbN layer 14, formed
on an insulating substrate 16. The aluminum layer 12 is patterned to provide an edge 18. A layer 20 of Al2O3 is then formed and patterned to overlap the edge 18 of the aluminum layer 12. The patterned Al2O3 is used to define an edge 22 in the NbN layer 14. A very thin layer of MgO 24 is then deposited on the edge 22. Next, a counterelectrode contact 26 comprising a layer 28 of NbN is formed on the substrate, overlapping the MgO-
coated edge 22 of the first NbN layer 14. The portion of the counter-electrode overlapping the edge 22 is patterned to provide a small area contact 30 with the MgO-
coated edge of NbN.

The basic NbN/MgO/NbN edge junction process is described below. The key fabrication steps are shown in
FIGS. 2a-2d. While specific parameters are given, it
should be understood that these are exemplary only,
and that other process parameters which provide the
described result are within the scope of the invention.

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lower energy (80 to 150 eV) Ar ion beam cleaning step is done to remove any surface damage caused by the high energy edge definition process. The use of low energy ions minimizes the thickness of the damaged surface layer, which is especially important for a short coherence length material like NbN.

After the edge cleaning, the MgO tunnel barrier 24 and NbN counter-electrode layer 26 are deposited, using RF magnetron sputtering for the MgO and DC magnetron sputtering for NbN.

MgO is RF sputtered from pressed MgO targets using a 2 inch diameter planar magnetron sputter gun. Ar flow rates are 20 to 150 sccm, and the Ar pressure is 100 mTorr. MgO is deposited intermittently by rotating the substrate over the sputter gun; this provides better thickness control and helps promote uniformity in the typically 1 nm thick MgO barrier 24. Following the MgO deposition, the barrier is exposed to a brief oxygen plasma discharge.

The MgO barrier film is blanket-deposited to a thickness of about 5 to 30 Å and, more preferably, to a thickness of about 5 to 20 Å. At least about 5 Å (about one monolayer) is required for high quality tunneling barriers, while thicknesses greater than about 30 Å defeat tunneling.

The NbN counter-electrode layer 28 is formed, using the same process as above for the deposition of NbN layer 14, except that the substrate is not intentionally heated. The NbN counter-electrode was also coated with an evaporated 300 Å gold layer (not shown) to aid in making contact to the junctions.

Finally, the counter-electrode is patterned using standard photolithography and reactive ion etching in a CF4/O2 gas mixture (FIG. 2c and 3).

Using the above process, edge junctions with areas ranging from 0.1 to 0.8 μm2 have been fabricated. These are the first reported NbN/MgO/NbN edge junctions. The areas of the edge junctions may range from about 0.01 to 1 μm2.

FIG. 4 presents the current-voltage characteristics of a typical 0.1 x 1 μm2 junction with a current density of 1 x 104 A/cm2, a junction resistance of 325 Ω, and a gap voltage of 4.9 mV. For this junction, the value of Vm (V_m=I_mR_m) is 61 mV where R_m is measured at 3 mV and 4.2K, and the gap spread is approximately 0.7 mV. The junction parameters obtained for these all-NbN edge junctions are superior to parameters for prior art trilayer NbN/MgO/NbN junctions of similar current density as described in U.S. Pat. No. 4,768,069. In particular, the edge junctions of the invention show lower subgap leakage than the devices of U.S. Pat. No. 4,768,069 for junctions of a given current density, as evidenced by the high values of VM (at 3 mV) obtained for the edge junctions of the invention.

The present edge junction characteristics are suitable for SIS mixer testing in the 300 to 500 GHz range. Thus, there has been disclosed a superconducting tunnel junction device comprising a tunnel junction region comprising an MgO film sandwiched between two NbN electrodes, the MgO film being formed on a portion of an edge of one of the electrodes. It will be readily apparent to those skilled in this art that various changes and modifications of an obvious nature may be made. All such changes and modifications are considered to fall within the scope of the invention, as defined by the appended claims.

We claim:

1. A process for fabricating a superconducting tunnel junction device comprising a tunnel junction region comprising a thin tunnel barrier oxide film sandwiched between first and second electrodes, said process comprising:

(a) forming said first electrode consisting essentially of NbN on an insulating substrate;

(b) forming an insulating layer overlapping said first electrode and patterning said insulating layer to expose a portion of said NbN electrode;

(c) defining a sloped edge region in said NbN electrode by ion milling and removing said exposed portion;

(d) forming said thin tunnel barrier oxide film consisting essentially of MgO on at least a portion of said sloped edge region of said NbN electrode, said MgO tunnel barrier film ranging in thickness from about 5 to 30 Å; and

(e) forming said second electrode consisting essentially of NbN to overlap said MgO-covered edge region of said first NbN electrode.

2. The process of claim 1 wherein said insulating substrate is selected from the group consisting of Al2O3, SiO2, and MgO.

3. The process of claim 2 wherein said insulating substrate is selected from the group consisting of sapphire and quartz.

4. The process of claim 2 wherein said substrate consists essentially of SiO2 and a buffer layer of MgO is formed on said substrate prior to formation of said first NbN electrode, said buffer layer formed to a thickness of about 200 to 500 Å.

5. The process of claim 1 wherein said first and second NbN electrodes are formed by sputter deposition.

6. The process of claim 5 wherein said substrate is heated to a temperature of about 250° to 500° C. during deposition of said first NbN electrode thereon.

7. The process of claim 6 wherein said substrate is heated to a temperature ranging from about 300° to 450° C.

8. The process of claim 1 wherein said NbN electrodes each range from about 100 to 10,000 Å in thickness.

9. The process of claim 8 wherein said electrodes each range from about 1,000 to 2,000 Å in thickness.

10. The process of claim 1 wherein said MgO film ranges from about 5 to 20 Å in thickness.

11. A process for fabricating a superconducting tunnel junction device comprising a tunnel junction region comprising a thin tunnel barrier oxide film sandwiched between first and second electrodes, said process comprising:

(a) forming said first electrode consisting essentially of NbN ranging in thickness from about 100 to 10,000 Å on an insulating substrate, said insulating substrate selected from the group consisting of Al2O3, SiO2, and MgO and heated to a temperature ranging from about 250° to 500° C.;

(b) forming a base electrode contact on a portion of said NbN electrode, leaving a portion of said NbN electrode exposed;

(c) forming a mask layer on said exposed portions of said NbN electrode;

(d) using said mask layer to protect unexposed portions of said NbN electrode while defining a sloped edge region in said NbN electrode by ion milling and removing exposed portions thereof;
(e) forming said thin tunnel barrier oxide film consisting essentially of MgO on at least a portion of said sloped edge region of said NbN electrode, said MgO tunnel barrier film ranging in thickness from about 5 to 30 Å and in area from about 0.01 to 1 μm²; and

(f) forming said NbN electrodes to overlap said MgO-covered edge region of said first NbN electrode, said second NbN electrode ranging in thickness from about 100 to 10,000 Å.

12. The process of claim 11 wherein said base electrode contact comprises a metal which can be selectively etched relative to said NbN.

13. The process of claim 12 wherein said metal comprises aluminum, which ranges from about 0.1 to 2 μm in thickness.

14. The process of claim 11 wherein said mask layer comprises an insulating material having an ion milling rate less than or comparable to that of NbN.

15. The process of claim 14 wherein said insulating material comprises at least one of aluminum oxide and silicon oxide, ranging from about 0.1 to 0.8 μm in thickness.

16. The process of claim 11 wherein said insulating substrate is selected from the group consisting of sapphire and quartz.

17. The process of claim 11 wherein said substrate is heated to a temperature ranging from about 300° to 450° C.

18. The process of claim 11 wherein said substrate consists essentially of SiO₂ and a buffer layer of MgO is formed on said substrate prior to formation of said first NbN electrode, said buffer layer formed to a thickness of about 200 to 500 Å.

19. The process of claim 11 wherein said electrodes each range from about 1,000 to 2,000 Å in thickness.

20. The process of claim 11 wherein said MgO film ranges from about 5 to 20 Å in thickness.

21. The process of claim 11 wherein said NbN electrodes are formed by reactive DC sputtering from a Nb target in an Ar-N₂ atmosphere.