Direct-write trilayer technology for $Al-Al_2O_3-Cu$ superconductor-insulator-normal metal tunnel junction fabrication

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The authors present a novel direct-write trilayer technology for bolometer and thermometry applications. The technology is based on *in situ* evaporation of the superconductive electrode followed by the oxidation and the normal counterelectrode as a first step and deposition of normal-metal absorber as a second one. This approach allows one to realize any geometry of the tunnel junctions and of the absorber with no limitation related to the size of the junctions or the absorber, which is not possible using shadow evaporation technique. The proposed new approach is perfectly suited for fabrication of microwave receivers for high-precision measurements in new generation of telescopes such as CLOVER ground-based telescope and OLIMPO balloon telescope projects. Measurements performed at 300 mK showed high quality of fabricated tunnel junctions, low leakage currents, and Rd/Rn ratio of 500 has been achieved at that temperature. The junctions were characterized as temperature sensors, and voltage versus temperature dependence measurements have shown a dV/dT of 0.5 mV/K for each single junction, which is typical for this kind of tunnel junctions. © *2007 American Vacuum Society.* [DOI: 10.1116/1.2743655]

I. INTRODUCTION

A tunnel junction between a superconductor and normal metal or semiconductor-insulator-normal metal (SIN) tunnel junction is a superconductor device which can be used for temperature measurements and detection of microwave radiation. Both applications are based on the dependence of current-voltage characteristics of SIN junction on the temperature.

Superconducting detectors are the most sensitive detectors of microwave and infrared radiations, and cold-electron bolometers are superior in sensitivity among the large number of different kinds of detectors.[1]

A cold-electron bolometer (CEB) is a microwave detector which is made of a strip of a normal metal that changes in temperature as it absorbs the incoming radiation.[2] The most efficient technique to measure that change in temperature is based on the unique properties of the SIN tunnel junctions.[3,4]

Cold-electron bolometers with SIN tunnel junctions have a number of features which make them very attractive for radiation detecting such as high sensitivity, high speed, capacitive coupling to the antenna, and an option to remove the hot electrons from the absorber.[5]

SIN tunnel junctions and cold-electron bolometers have traditionally been manufactured using so-called shadow evaporation technique based on one-cycle deposition of both superconducting electrode and normal-metal absorber. This technique has, of course, certain advantages and has therefore been used for years for CEB fabrication, especially in laboratory and academic environment as it does not involve too advanced equipment. However, it is not the most appropriate technique for mass production in industry and has many drawbacks and limitations.

First of all, the main limitation is related to the size of tunnel junctions which cannot be made as large as required due to the principle of shadow evaporation. It makes the shadow evaporation technique very useful for single-electronics where a small size of tunnel junctions is advantageous. But for bolometer fabrication this approach can only be used within certain frequency ranges. Second, geometry considerations impose severe limitations on the layout and orientation of the structures on chip (rotation by 90° is not possible; both wires to the internal tunnel junctions should be placed on the same side from absorber, etc.). Finally, this technique does not allow for use of magnetron sputtering which is commonly used in industry for manufacturing of high-quality tunnel junctions.

The motivation of our work was the necessity to develop a direct-write technology for manufacturing Al-based SIN tunnel junctions operating at 300 mK, that is the temperature at which the bolometer operation is most efficient in terms of responsivity (dV/dP) and sensitivity (low noise).

This technology allows us to manufacture SIN tunnel junctions both in laboratory/academic environment for the research in CEB applications and in the future in industry for mass production of microwave detectors and cryogenic thermometers. Furthermore, this technology is advantageous for bolometer application as the deposition procedure and direct writing of both superconductive layer and absorber do not impose any unnatural requirements on deposition of both layers in one vacuum cycle of evaporation. That simplicity of technology gives us additional freedom in realizing any possible layouts in any geometry.

Cold-electron bolometers based on SIN tunnel junction will be used as detectors of very weak microwave signals, e.g., cosmic microwave background (CMB) radiation. Cold-

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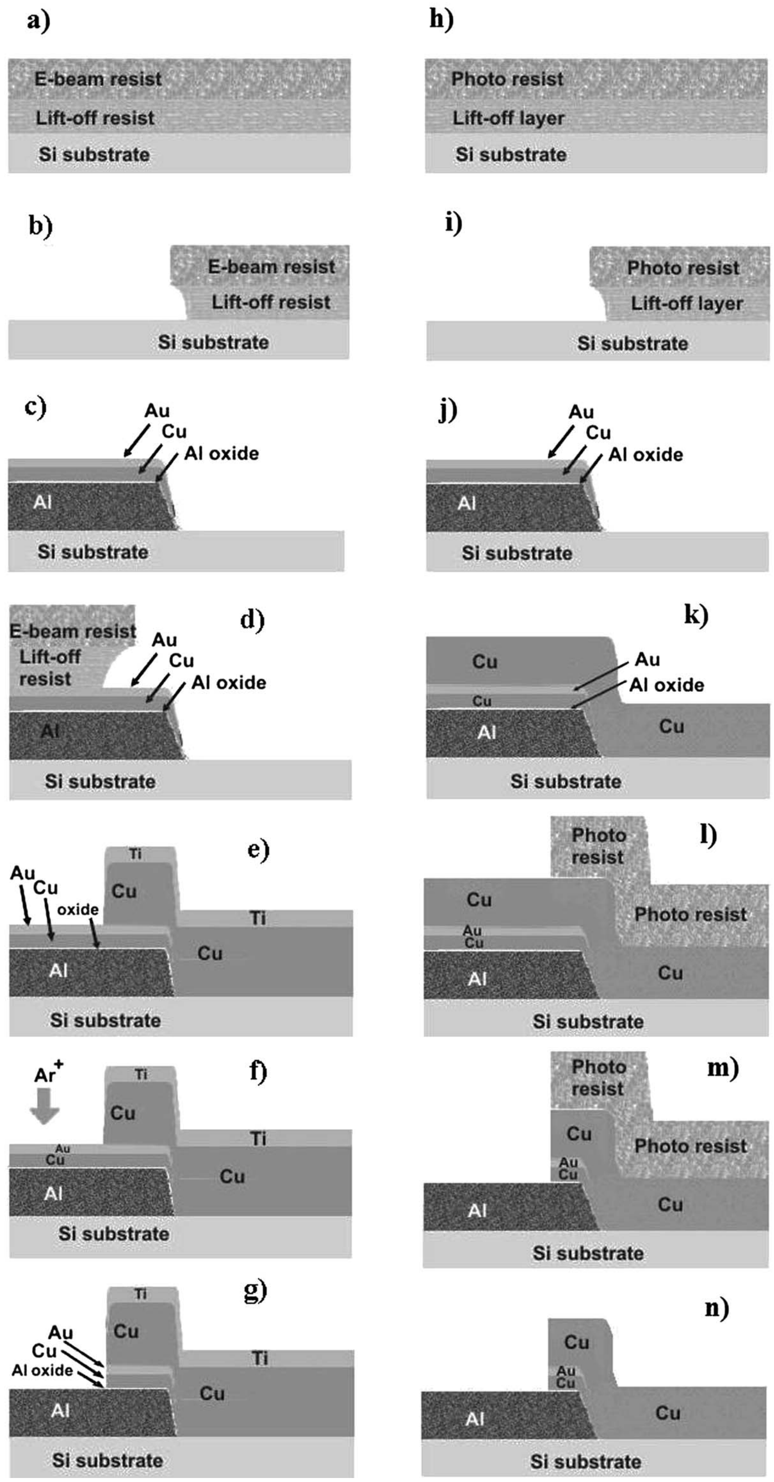

FIG. 1. Comparison between the two versions of the fabrication procedure: Technology 1 (column to the left); Technology 2 (column to the right).

electron bolometers are planned to be implemented into the balloon telescope OLIMPO, aimed at measuring the Sunyaev-Zeldovich effect in clusters of galaxies and the ground-based telescope CLOVER for cosmic microwave background polarization measurements.[6]

SIN junctions made in this technology are used for temperature measurement, which is also a part of bolometer operation. For example, the samples have been used for temperature stability measurements in Heliox cryogen-free cryostat recently fabricated by the company Oxford Instruments.

High accuracy, high speed of operation, and wide temperature range of SIN thermometers make them very attractive for future utilization,[7] e.g., for the temperature control inside the new cryostats. We are developing thermometers for measurements of the temperature in cryostats. We are

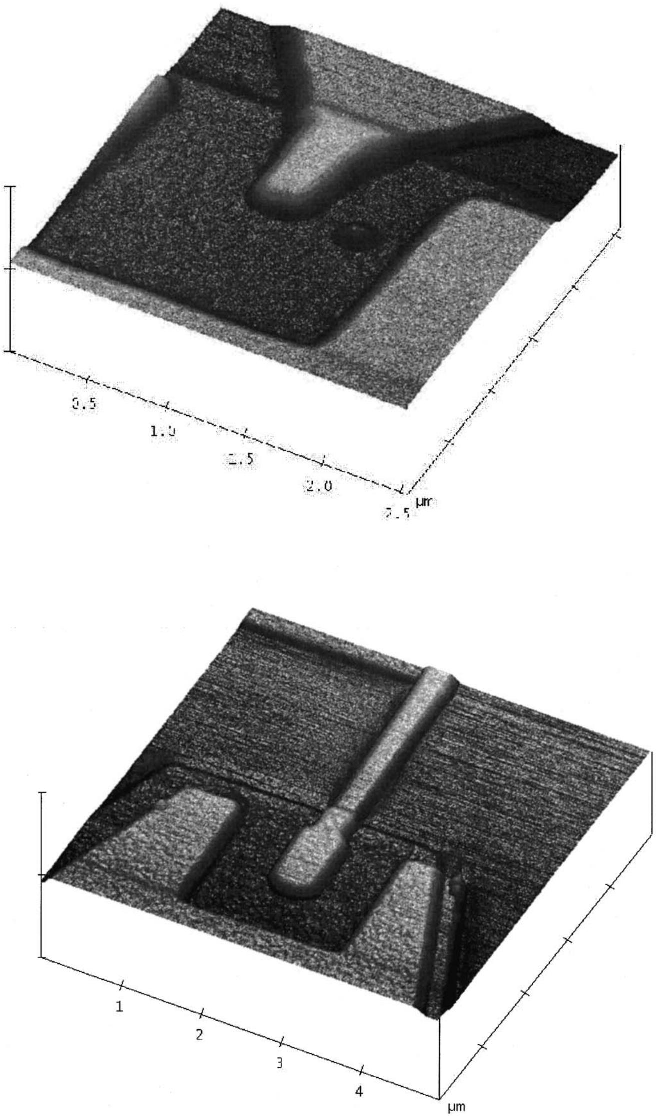

FIG. 2. AFM images of the tunnel junctions manufactured in Technology 1.

planning to install our thermometers in the new models of Heliox cryostats, developed by the company Oxford Instruments.

II. FABRICATION

Two versions of the technological procedure have been used for the fabrication of the samples (Fig. 1). In the first approach [Fig. 1(a-g)] both trilayer structure and normal-metal absorber have been patterned by lithography followed by deposition and lift-off. In the second version [Fig. 1(h-n)] the trilayer structure has been patterned in the same way as in the first one, whereas the normal-metal absorber was deposited on the whole wafer and patterned thereafter by negative exposure and subsequent etching. As a final step, part of the gold and normal metal covering the trilayer structure was removed by ion-beam etching in both versions of the fabrication procedure.

III. DETAILED DESCRIPTION OF THE TECHNOLOGY

A. Technology 1

A silicon wafer, oxidized thermally to obtain 400 nm oxide thickness, was covered by a lift-off layer and a photoresist and then baked. Then, contact pads were patterned by a standard process of photolithography and lift-off and a thin gold layer was deposited after the e-beam lithography for better alignment with the following layers.

For patterning the superconductive electrode, a lift-off resist and e-beam resist were spun over the wafer [Fig. 1(a)], exposed in e-beam lithography system, and developed [Fig. 1(b)]. Then an Al layer was deposited at a pressure of 4×10^{-7} mbar and oxidized during 2 min in oxygen ambient at 5×10^{-2} mbar to create the tunnel junction. Then Cu was evaporated as a normal-metal electrode of a tunnel junction and covered by Au for passivation [Fig. 1(c)]. Next, the normal-metal Cu absorber was patterned by e-beam lithography and thermal evaporation [Figs. 1(d) and 1(e)]. Finally, argon ion beam etching was used to remove Cu and Au from the top of the trilayer structure, see Figs. 1(f) and 1(g). The atomic force microscopy (AFM) images of the final structures are shown in Fig. 2.

B. Technology 2

A silicon wafer with 400 nm oxide layer was covered by a lift-off layer LOL2000 and a positive photoresist S1813 and baked, see Fig. 1(h). After exposure in UV mask aligner and development by MF-319 [Fig. 1(i)] the wafer was cleaned using standard reactive ion etching process in oxygen plasma for 30 s.

The trilayer structure was then deposited using thermal evaporation at a pressure of 1.1×10^{-5} mbar during evaporation and 1.6×10^{-6} mbar base pressure. First, a 600 Å layer of aluminum was evaporated and oxidized in oxygen at a pressure of about 5×10^{-2} mbar during 30 min. Then a 300 Å layer of Cu was deposited to build normal-metal electrode of the tunnel junction and covered by 250 Å of gold to protect it from oxidation in the air [Fig. 1(j)]. To create the normal-metal absorber, a layer of copper has been evaporated thermally on the whole wafer, see Fig. 1(k). Then it was covered by a photoresist S1813 and baked at 110 °C.

The resist was then exposed in the UV mask aligner and developed by MF-319, see Fig. 1(l). After dicing the wafer, the normal-metal absorber was patterned by etching Cu in a mixture of nitric acid and hydrogen peroxide of a concentration of 1:200 for 10 s. As a last step, Cu and Au were then removed from the top of the trilayer structure using argon ion beam etching [see Fig. 1(m)]. The photoresist was then removed using Shipley 1165 remover [see Fig. 1(n)]. An optical image of a final structure is shown in Fig. 3.

IV. SAMPLE CHARACTERIZATION

IV curves of the sample fabricated in Technology 1 and 2 are shown in Figs. 4 and 5, respectively. The normal resistance of the tunnel junctions is different in the two cases due

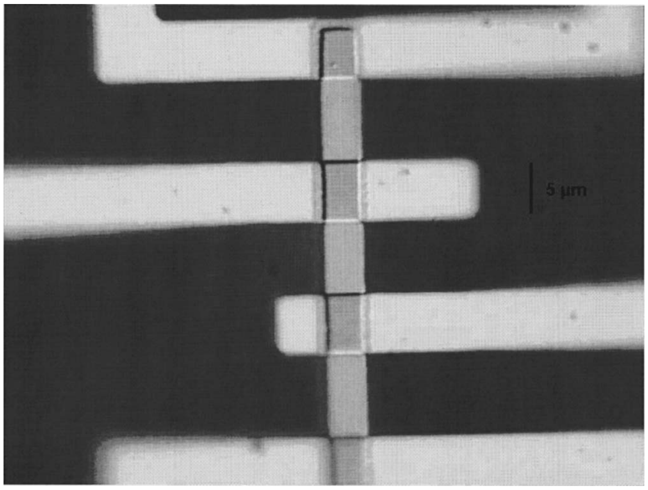

FIG. 3. Optical image of four tunnel junctions fabricated in Technology 2.

to different oxidation conditions and different areas of fabricated junctions ($\sim$0.25 μm^2 vs 10–25 μm^2). The resistance normalized to unit area of the junction is about 40 Ω μm^2 in the second case, which is approximately 25 times lower than in the first one because of longer oxidation time (30 min vs 2 min).

Measurements showed high quality of fabricated tunnel junctions, low leakage currents, and Rd/Rn ratio of 500 has been achieved at 300 mK.

Voltage versus temperature dependence has also been measured, and dV/dT of 1 mV/K has been achieved for two junctions in series, what corresponds to 0.5 mV/K for each junction (Fig. 6). Increasing number of junction in series will allow us to achieve higher sensitivity,[5,8] which enables for use of SIN tunnel junctions fabricated in this technology for thermometry application.

Comparison of the measurement results for the two technologies does not show any significant difference in quality of the fabricated junctions. Technological procedure for the Technology 2 is more advantageous for the industrial fabrication as it allows one to use magnetron sputtering rather than thermal evaporation for the deposition of metals. On the other hand, chemical wet etching used in that technology poses certain limitations on the achievable resolution. Using ion-beam etching for all etching processes (including the Cu electrode patterning) allows one to achieve higher resolution, comparable with the one in the first version of the technology.

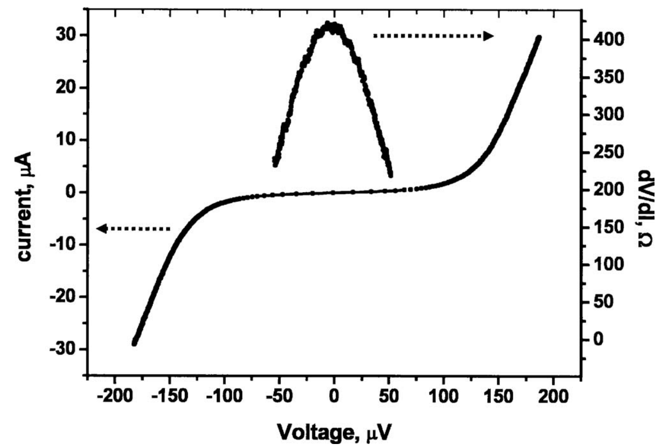

FIG. 5. IV curves and dV/dI at 300 mK, Technology 2.

V. CONCLUSIONS

We have developed an advanced process for fabrication of SIN tunnel junctions. The fabricated tunnel junctions demonstrate typical properties of SIN tunnel junctions with small leakage currents and the measured temperature dependence corresponds to a behavior of tunnel junctions of this type.

Increasing the number of junction in series will allow us to achieve higher sensitivity, which enables the use of SIN tunnel junctions fabricated in this technology for thermometry application. Further development of technology focused

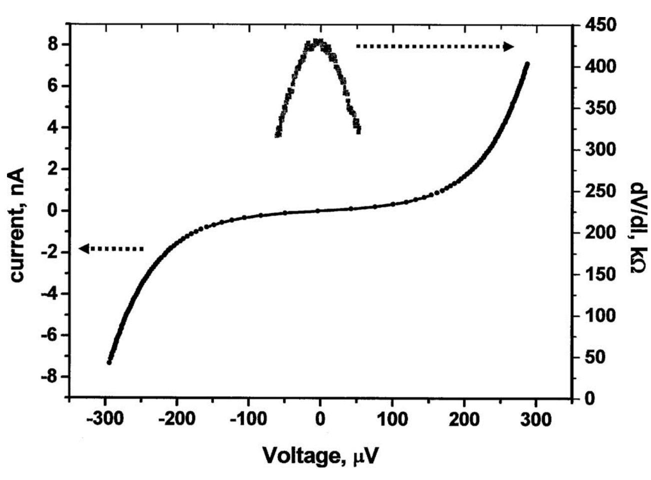

FIG. 4. IV curves and dV/dI at 300 mK, Technology 1. Dynamic resistance around zero voltage is inserted in the middle; arrow to the right.

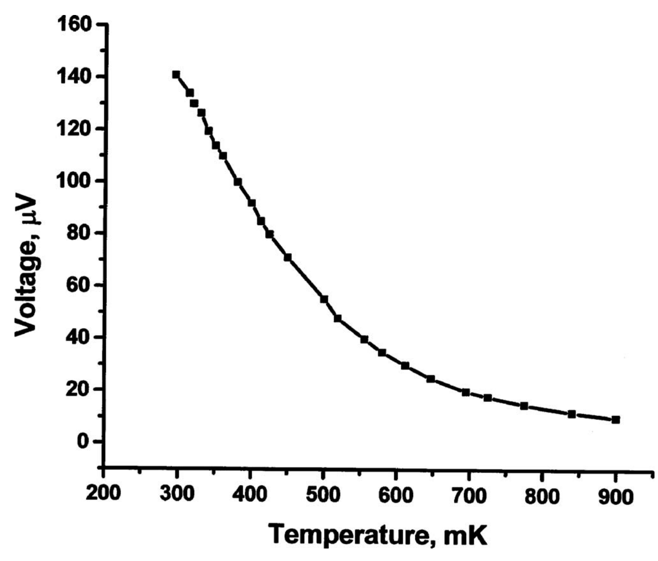

FIG. 6. Voltage vs temperature dependence of a single tunnel junction. The chosen biasing current corresponds to maximum dV/dT.

on decreasing the volume of the absorber will make it possible to use the technology for fabrication of bolometers.

ACKNOWLEDGMENTS

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