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Ti–TiO$_2$–Al normal metal–insulator–superconductor tunnel junctions fabricated in direct-write technology

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Abstract

We present a novel Ti-based direct-write technology for fabricating Ti–TiO$_2$–Al tunnel junctions for bolometer and thermometry applications. The goal of our research is to develop simple and efficient technology for fabricating SIS tunnel junctions between Ti and Al with TiO$_2$ as an insulating barrier. The key point of this technology is the deposition of a Ti film as a base electrode and deposition of an Al electrode after oxidation of the Ti.

This approach allows one to realize any geometry of the tunnel junctions and of the absorber with no limitation related to the area of the junctions or the thickness of the absorber. In particular, a very thin and completely flat absorber can be created with no bending parts, which is not possible using the shadow evaporation technique or standard trilayer technology. Besides, the proposed new approach does not require one-cycle evaporation for deposition of tunnel junctions which gives us more freedom in the geometry of the counter-electrodes.

The junctions are to be used for bolometer applications, such as the fabrication of microwave receivers for sensitive measurements in new generation telescopes, e.g. CLOVER and BOOMERANG projects including polarization cosmic microwave background radiation measurements, and the OLIMPO balloon telescope project which is dedicated to measuring the Sunyaev–Zeldovich effect in clusters of galaxies.

As the first step, SIN tunnel junctions have been fabricated and characterized.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

A tunnel junction between a superconductor and normal metal or superconductor–insulator–normal metal (SIN) tunnel junction can be used for temperature measurements and detection of microwave radiation. Both applications are based on the dependence of the current–voltage characteristics of the SIN junction on the temperature. Superconducting detectors are the most sensitive detectors of microwave and infrared radiation, 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 its 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

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radiation detection such as high sensitivity, high speed, capacitive coupling to the antenna, and an option to remove the hot electrons from the absorber [5].

One of the key parameters of a CEB is the volume of the absorber as it determines the bolometer sensitivity due to the principle of CEB operation. Therefore, it is extremely important to make the absorber as thin as possible. This feature is not fully ensured in the existing technologies where the absorber is the top layer of the SIN tunnel junction.

The proposed approach allows one to realize thicknesses of the absorber down to 5 nm as the absorber is deposited prior to the other electrode and the tunnel junction is created after deposition of the absorber. Another advantage is the ability to realize a fully flat absorber with no bending parts, which are inevitable in the existing processes and often create problems related to leakage currents and deteriorate the high-frequency properties of the microwave detector.

Since the absorber is patterned before creating the tunnel junctions, we have no limitation for the width of the absorber related to lithography resolution due to limited resist baking temperature, which is an issue for some available technologies, such as standard trilayer technology. For example, tunnel junctions made of Al as a base electrode and aluminium oxide as an insulator are sensitive to overheating and therefore a resist spun after creating such junctions is often baked at a lower temperature than recommended for the best resolution of most e-beam resists (such as PMMA or ZEP). Alternatively, photo lithography is often used for this kind of tunnel junction due to the even lower temperature of baking the photo resist (e.g. 110 °C for Shipley-1813 versus 170 °C for PMMA), which limits the resolution in comparison with e-beam lithography.

SIN tunnel junctions and cold-electron bolometers have traditionally been manufactured using the so-called shadow evaporation technique based on one-cycle deposition of both the superconducting electrode and normal metal absorber [5]. This is a very straightforward method of creating Al-based tunnel junctions which allows one to avoid overheating the Al oxide layer. However, it is not the most appropriate technique for CEB fabrication as it has many drawbacks and limitations.

First of all, the main limitation is related to the size and geometry of the 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 the small size of the 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 the chip (rotation by 90° is not possible etc). And, finally, this technique does not allow for use of magnetron sputtering which is commonly used for manufacturing high-quality tunnel junctions.

The motivation for our work was the necessity to develop a direct-write technology for manufacturing SIN tunnel junctions operating at 100–300 mK, that is the temperatures at which the bolometer operation is most efficient in terms of responsivity ($\mathrm{d}V/\mathrm{d}P$) and sensitivity (low noise).

The proposed approach allows us to manufacture SIN tunnel junctions for fabrication of microwave detectors and cryogenic thermometers and is particularly advantageous for bolometer fabrication as the deposition procedure and direct writing of both the superconductive layer and the absorber do not impose any requirements on deposition of both layers in one vacuum cycle of evaporation. That simplicity of technology gives us the freedom to realize any possible layouts in any geometry.

Cold-electron bolometers based on tunnel junctions fabricated in this technology will be used as detectors of very weak microwave signals, e.g. cosmic microwave background (CMB) radiation. Cold-electron bolometers are planned to be implemented into the balloon telescope OLIMPO, aimed at measuring the Sunyaev–Zeldovich effect in clusters of Galaxies, the ground-based telescope CLOVER for cosmic microwave background polarization measurements [6], and the balloon telescope BOOMERANG also dedicated to the CMB measurements.

Another application of the SIN junctions made in this technology is temperature measurement, which is also a part of bolometer operation [7]. For example, SIN junctions were used as temperature sensors for temperature stability measurements in a Heliox cryogen-free cryostat recently fabricated by the company Oxford Instruments. The high accuracy, high speed of operation and wide temperature range of SIN thermometers make them very attractive for future use [8], e.g. for temperature control inside cryostats.

In the future, we are planning to further develop the technology for manufacturing SIS tunnel junctions with Ti as a weak superconductor. This type of tunnel junction is a good choice for using in superconductive cold-electron bolometers with JFET readout due to the high dynamic resistance in the operation point [6].

2. Fabrication

In this paper, we present the process developed by us for fabricating Ti–TiO_2–Al tunnel junctions. The process uses *ex situ* Ti oxidation to create a TiO_2 insulating barrier. The process includes two steps of lithography and deposition: first the Ti film is deposited, patterned and oxidized and then the Al counter-electrode is deposited and formed. The details of the fabrication process are shown in figure 1.

As the first step, a Ti film is deposited by magnetron sputtering on a thermally oxidized silicon substrate (figure 1(a)). Then a photo resist is spun and baked for the following optical lithography. After exposure and development (figure 1(b)) the Ti film is patterned by chemical wet etching using a 1% solution of HF in water (figure 1(c)). After resist removal (figure 1(d)) and oxygen plasma etching, the surface of the Ti is cleaned using ion milling in an Ar ion beam (figure 1(e)) and oxidized in open air for 10 h at 150 °C (figure 1(f)). Then an Al film is deposited (figure 1(g)) and patterned by lithography (figure 1(h)) and chemical wet etching (figure 1(i)). The final structure after resist stripping is shown schematically in figure 1(j) and in the optical images in figure 2.

3. Results and discussion

Fabricated Ti–TiO_2–Al tunnel junctions have been characterized at 300 mK. Ti was not superconductive at 300 mK, and the tunnel junctions showed typical behaviour of SIN junctions at

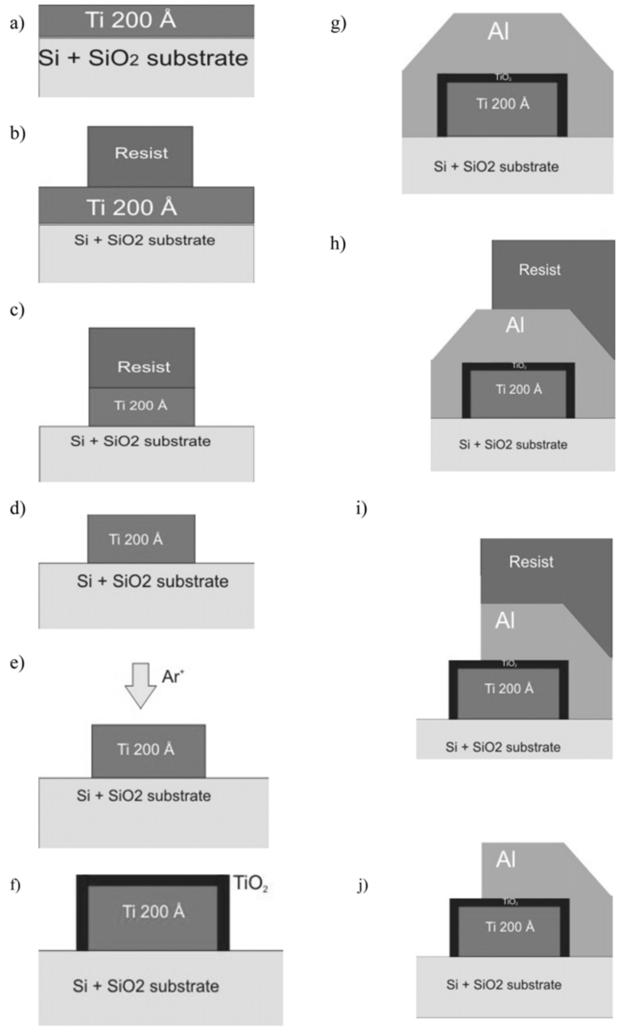

Figure 1. Fabrication procedure.

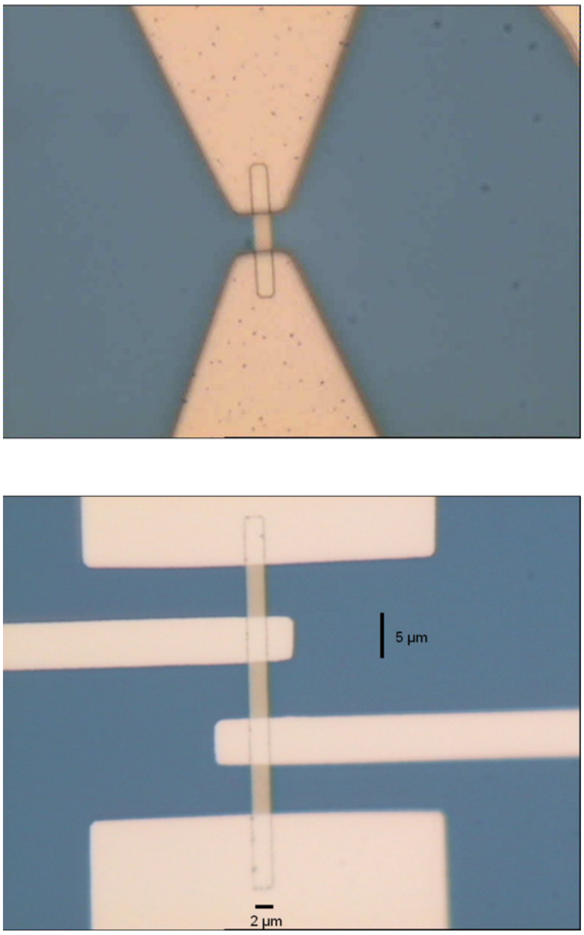

Figure 2. Optical images of two and four tunnel junctions fabricated using the proposed technology.

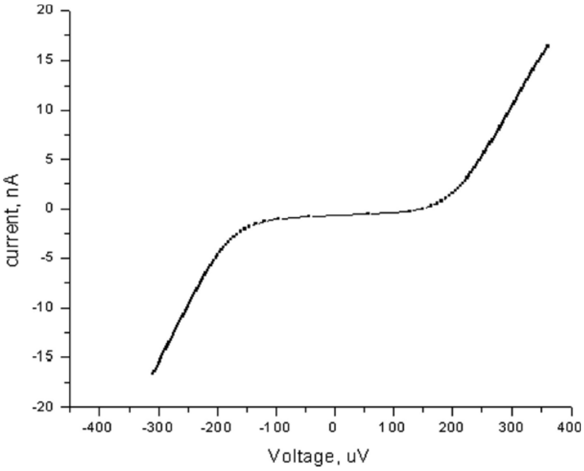

Figure 3. I–V curve of a single tunnel junction.

that temperature. An I–V curve of a single SIN tunnel junction is shown in figure 3.

Both dynamic resistance at zero voltage R_d and the normal resistance R_n have been measured, and the ratio R_d/R_n is estimated as a measure of the quality of the tunnel junctions.

Measurements showed the high quality of the fabricated tunnel junctions, low leakage currents, and a R_d/R_n ratio of 600–1000 was achieved at 300 mK. This value is comparable to previously reported results for Al-based tunnel junctions fabricated by the shadow evaporation technique [9]. In that work, a ratio of 900 was achieved at 300 mK.

The maximum achieved R_d/R_n value of 1000 exceeds the previously reported result of 900 at that temperature, though the deviation of that parameter from the average value of 800 was relatively high, about ±20%. Because of medium on-chip and chip-to-chip reproducibility, some optimization work is required in order to achieve optimal oxidation conditions during creation of the tunnel barrier.

Although both the dynamic resistance and normal resistance are spread over the wafer, it is still possible to use arrays of SIN tunnel junctions for thermometry applications. The total responsivity of such an array is determined by the voltage drop across the array and its total dynamic resistance. It has already been shown [7, 10] that the total voltage response of such an array at fixed biasing current is proportional to the number of junctions, whereas the noise of the junctions should be proportional to the square root of that number. Therefore, by increasing the number of junctions in the array, one can

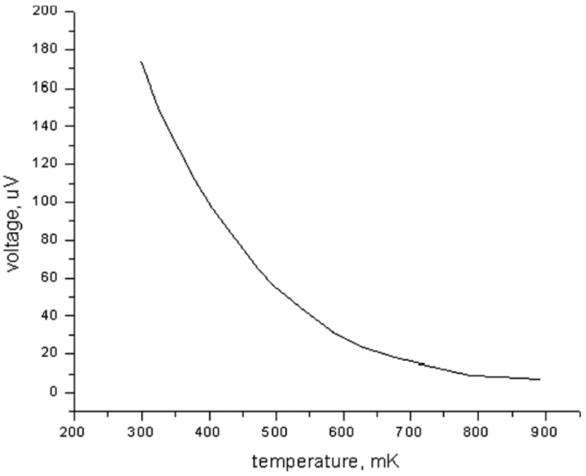

Figure 4. Voltage versus temperature for a single tunnel junction.

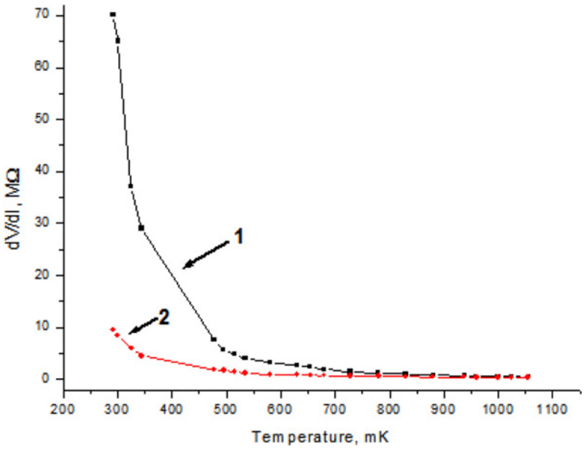

Figure 5. R_d versus temperature dependence at zero voltage (curve 1) and at 175 μV (curve 2).

increase the temperature sensitivity of the whole array and compensate for the poor quality of some single junctions in the array, if the number of relatively poor junctions is negligible in comparison with the total number of junctions in the array. This is fully confirmed for an array of 100 Al-based tunnel junctions [11], where the $\mathrm{d}V/\mathrm{d}I$ of 52 mV K^{-1} has been achieved for 100 junctions in series, which corresponds to 0.52 mV K^{-1} for each single junction, very close to the value of 0.5 mV K^{-1} for a standalone junction.

Due to the oxidation temperature of 150° one can expect the junctions to be of better quality than the ones created at room temperature when the molecules of water and/or hydrogen atoms can be involved in the process of creating the tunnel barrier. One of the key points of *in situ* evaporation is the deposition at very low pressure and oxidation at the same low base pressure, when the influence of water and hydrogen is more or less eliminated, apart from contamination and other issues, which deserve separate discussion. In our case, the temperature exceeds the water evaporation temperature, which ensures that no water is condensed on the surface of the sample. With regards to other sources of contamination which can deteriorate the quality of the tunnel junction, such as residues of organic materials etc, we try to eliminate them by oxygen plasma etching followed by subsequent ion milling, which completely removes any compounds of Ti with other elements, eventually built on the surface. Measurement shows that this step is the most critical of the whole fabrication procedure as the quality of the tunnel junction strongly depends on the ion milling time. If this time is not long enough, that is below 4 min at an ion gun voltage of 500 V, the quality of the tunnel barrier is very poor. Increasing this time to 5.5 min or longer at the same ion gun voltage assures the complete removal of any substances from the surface which would deteriorate the quality of the tunnel barrier.

Normal resistance R_n ranges from 20 to 80 kΩ for junction areas between 4 and 20 $\mu\mathrm{m}^2$. Temperature dependent voltage and dynamic resistance have also been measured (figures 4 and 5), and $\mathrm{d}V/\mathrm{d}T$ of 1 mV K^{-1} has been achieved for two junctions in series, which corresponds to 0.5 mV K^{-1} for each junction. Increasing the number of junctions in series will allow us to achieve higher sensitivity [7, 10], which will enable the use of SIN tunnel junctions fabricated using this technology for thermometry applications.

4. Conclusions

We developed a novel technology for fabricating tunnel junctions between Ti and Al using titanium as a base electrode and titanium oxide as an insulating barrier. We fabricated Ti–$\mathrm{TiO_2}$–Al NIS tunnel junctions and characterized them at 300 mK. The fabricated junctions are rather high-ohmic devices due to the very long oxidation time used to create the tunnel barriers. Shortening the oxidation time combined with a proper choice of temperature should allow us to create more low-ohmic tunnel junctions. Thus, more development work is needed to realize low-ohmic junctions that are more suitable for CEB applications. Although photo lithography has been used to manufacture the samples here, e-beam lithography and negative e-beam resists can be used in order to achieve better resolution and therefore a smaller volume of absorber which is critical for the performance of CEBs [1].

Increasing the number of junctions in series will allow us to achieve higher sensitivity [7, 10], which will enable the use of SIN tunnel junctions fabricated using this technology for thermometry applications.

References

[1] Kuzmin L 2004 Ultimate cold-electron bolometer with strong electrothermal feedback *Proc. SPIE* **5498** 349–61

[2] Kuzmin L 2000 On the concept of a hot-electron microbolometer with capacitive coupling to the antenna *Physica* B **284–288** 2129

[3] Kuzmin L, Devyatov I and Golubev D 1998 *Proc. SPIE* **3465** 193–9

[4] Golubev D and Kuzmin L 2001 Non-equilibrium theory of a hot-electron bolometer with normal metal–insulator tunnel junction *J. Appl. Phys.* **89** 6424

[5] Agulo I *et al* 2004 *Nanotechnology* **15** S224–8

[6] Kuzmin L *et al* 2005 Superconducting cold-electron bolometer with JFET readout for OLIMPO balloon telescope *ISSTT2005: Proc. 16th Int. Symp. on Space Terahertz Technology* pp 549–54

[7] Agulo I J and Kuzmin L 2007 An array of SIN tunnel junctions as a sensitive thermometer *Supercond. Sci. Technol.* submitted

[8] Pekola J 2004 Trends in thermometry *J. Low Temp. Phys.* **135** 5–6

[9] Kuzmin L *et al* 2004 *Supercond. Sci. Technol.* **17** S400–5

[10] Kuzmin L 2007 Ultra-sensitive cryogenic thermometer based on an array of the SIN tunnel junctions *Phys. Lett.* A submitted

[11] Otto E, Tarasov M, Pettersson G, Gustavsson D and Kuzmin L 2007 An array of 100 Al–Al203–Cu SIN tunnel junctions in direct-write trilayer technology *Supercond. Sci. Technol.* submitted