Journal of Alloys and Compounds, 195 (1993) 719–722
JALCOM 7566

Fabrication aspects of microwave devices, including ramp-type high-Tc Josephson junctions and log-periodic antennas.

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Abstract

We describe the development of high-T_c Josephson junction devices for applications at millimeter wave frequencies. These devices consist of ramp type YBCO/PBCO/YBCO Josephson junctions that are equipped with a noble metal log-periodic antenna. Growth conditions of all layers, as well as etching, cleaning and annealing procedures are being optimized, to guarantee well-defined device properties. Lowering the deposition temperature of the thick PBCO layer strongly improved its isolating properties, which is of extreme importance for good reproducability of junction fabrication. Special attention is being focused on the optimization of the contact of noble metal to YBCO as well its adhesion to the substrate. Best results are obtained using sputtered gold contacts, after a soft Ar ion sputter clean treatment of the damaged YBCO surface, followed by an anneal procedure.

1. Introduction

Josephson junctions made of high-T_c materials are expected to be very attractive for building highly sensitive detectors for (sub-) millimeter wave radiation, because of their high energy gap values and the possibility to operate them at temperatures higher than 4.2 K, up to 77 K. Several studies have been reported showing very promising results of direct detection and mixing experiments in high T_c Josephson junction devices, up to W-band frequencies, see, e.g., [1-6]. Most of the devices used in these studies, however, have properties that severely weaken their sensitivity as high frequency detectors, like low normal state resistances and strongly suppressed I_cR_n products. For optimal performance, a large number of requirements must be met, which are presented in table 1.

In this contribution we report on the design and fabrication of a ramp-type $YBa_2Cu_3O_7$(YBCO)/ $PrBa_2Cu_3O_7$(PBCO)/$YBa_2Cu_3O_7$ all high-Tc Josephson junction, integrated with a noble metal log-periodic antenna, suitable for high frequency applications. Optimization of junction preparation and the production of a metal antenna, with good electrical contact to YBCO and good adhesion to the substrate, will be discussed.

Table 1.
Requirements for optimal device performance

Operating temperature $T_{op} \sim 70$ K
Critical temperature $T_c \sim 85$ K
Critical current $I_c(T_{op}) >>$ noise current $I_n(T_{op})$
    $I_{n,thermal}(77\ K) \sim 3\ \mu A$
Normal state resistance $R_n \sim$ 10-100 Ω, for impedance matching to incoming radiation and output amplifiers
I_cR_n products maximal, for optimal gain
RSJ like IV characteristics
Low noise
Substrates with low ε_r and tanδ, for low reflection and dielectric losses
Efficient, broadband coupling to (sub-) mm-wave radiation

2. Design and Fabrication

2.1 YBCO/PBCO/YBCO ramp junctions

Ramp-type YBCO based Josephson junctions with an artificial PBCO barrier are used in this study. Details of the fabrication process have been published previously [7,8]. Shortly, a bilayer of YBCO/PBCO is deposited, forming the base electrode and the electrical isolation between the two superconducting electrodes. As substrate we use Yttria Stabilized ZrO_2 (100). The edge of the junction is created by low-angle (20-25°) Ar ion milling, to avoid possible polycrystallinity of the

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These investigations in the program of the Foundation for Fundamental Research on Matter (FOM) have been supported by the Netherlands Technology Foundation (STW).

0925-8388/93/$06.00

top electrode near the edge of the junction. After additional cleaning of the edge surface with a soft Ar ion beam, the thin PBCO barrier layer and the top YBCO electrode are deposited. The desired structure is subsequently defined by photolithographic patterning and Ar ion beam etching (Kaufman source, 3 cm beam width, E = 500 eV, I = 10 mA), in a pulsed mode (8 sec. on, 10 sec. off), to avoid excessive heating of the substrate.

Scaling behavior of these junctions has been published [7,8]. It was found that the critical current density J_c varies from 10^1-10^3 A/cm^2 at 4.2 K, and decreases exponentially for barrier thicknesses L larger than 6 nm. The specific junction resistance R_nA varies from 10^{-7}-10^{-5} Ωcm^2, where A is the junction area. For a given J_c the corresponding R_nA value is higher than for all other high-T_c junctions published upto now. Using L ~ 15 nm, an R_nA value of about 10^{-6} Ωcm^2 can be combined with J_c ~ 150 A/cm^2, which agrees with the requirements.

Much work was done to optimize the junction fabrication, especially concerning the isolating PBCO layer. PBCO, when deposited at the same temperature as YBCO (about 740°C), grows hetero-epitaxially on YBCO. Outgrowths that are initiated in the bottom YBCO electrode therefore, will continue to grow through the isolating PBCO layer, making it locally effectively thin. This causes a strong shunting of the junction region, reducing its R_nA value and of course the reproducibility of the fabrication process. To solve this problem, the overlap area was minimized, to lower the chance of outgrowths being in there. Furthermore, the deposition temperature of the insulating PBCO layer was lowered to about 640°C, at which the growth mechanism is different, though still epitaxial. Such a PBCO layer will stop the formation of outgrowths through the barrier and have a smoother surface by itself.

2.2 coupling to millimeter waves

To improve the coupling of high frequency radiation into the junction, it is placed between the terminals of an antenna. In this study we use a self complementary planar log-periodic antenna, shown in figure 1. This type of antenna produces a nearly frequency independent, linearly polarized beam pattern, with maxima in the direction perpendicular to the plane of the antenna [9,10]. The covered frequency range is determined by the wavelengths resonating at the inner boundary of the smallest tooth, and at the outer boundary of the largest tooth. Mounted on a dielectric half sphere the antenna pattern is practically unidirectional, radiating predominantly through the dielectric. The impedance Z of the antenna in such a configuration is real and given by $Z = 377/(2(1 + \varepsilon_r))^{1/2}$ [11].

2.3 integration of junction and antenna

Recent studies of the surface resistance of YBCO show that at frequencies higher than about 100 GHz, the losses in YBCO are larger than those in a high conductivity normal metal [12]. For optimal sensitivity of the device it is desirable to have minimal losses in the antenna itself, so we chose to make it from metal. To avoid parasitic losses, the YBCO junction leads should have minimal area. Figure 2 shows the configuration near the terminals of the antenna.

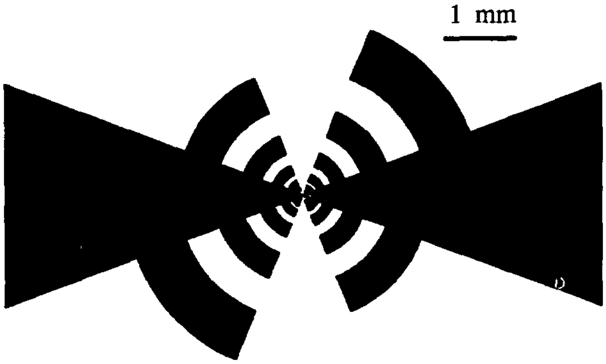

Figure 1. Log-periodic antenna.

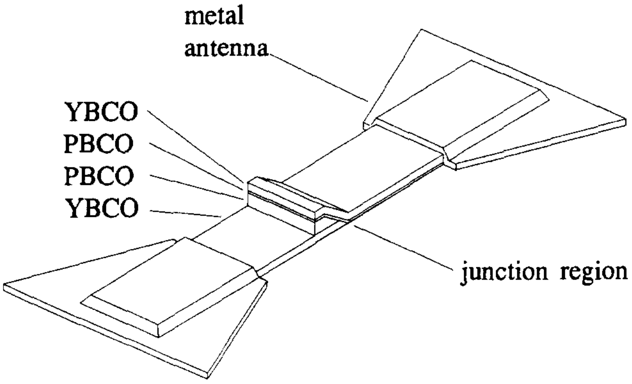

Figure 2. Terminal region of the antenna.

The process described in *2.1* is finished by structuring the junction leads, leaving a relatively large YBCO area near the junction region to avoid damage to the junction by exposure to various chemicals during the following processing steps. The device is then completed by depositing the metal film, as will be described in the next section, and structuring it into the antenna shape using lift off. The contact area between antenna terminals and junction leads is 30 x 500 μm^2. In a final Ar ion beam etching step the shape of the junction is defined.

Although for current-voltage (IV) measurements of the device a proper four terminal configuration is preferable, the presence of separate voltage leads will disturb the antenna pattern or increase the losses. Both current and voltage contacts will therefore be connected to the outer region of the antenna. This procedure gives rise to several fabrication problems. Firstly, the metal-YBCO contact resistance must be minimized and linearized, to avoid Joule heating, offset in IV measurements, and possible parasitic rectifying effects obscuring the properties of the junction itself. Secondly, since most of the metal is deposited directly on the substrate, good adhesion is required. To solve these problems, the optimimal conditions for metal deposition must be found.

2.4 antenna fabrication

The preparation of low ohmic metal contacts to YBCO thin films has also been studied by several other groups [13-15]. From these studies it is clear that the only materials easily available that do not reduce the YBCO material are Au and Ag. The used deposition processes for both these materials are described in table 2. Procedures used for cleaning or annealing, to improve the electrical contacts, as well as the deposition of additional layers for improved adhesion, are also described.

The configuration described in *2.3* is not suited for a quantitative determination of contact resistivities [16], but in our case it does give a proper qualitative indication comparing several deposition techniques.

'As deposited' contacts, without any cleaning or annealing, are found to be very poor. Contact resistances R_c, measured at 77 K, are about 10 Ω. Most likely, the surface layer of YBCO has metal-like or even semiconducting properties due to multiple exposures to air and several chemicals during fabrication steps prior to the metal deposition [13-15]. The adhesion of the metals to the substrate is also poor. It never survived the simplest pulling test conceivable, using just a piece of adhesive tape.

Annealing of the Ag contact reduced R_c by about one order of magnitude, probably because of strong Ag diffusion into the YBCO. The sticking to the substrate also improved. The surface of the Ag layer however, being smooth and shiny prior to the anneal, became rough and diffuse. This agrees with similar experiments reported in literature [15], where island formation in the Ag layer was found at temperatures above 370°C. Annealing the Au contact also reduced the contact resistance slightly, although the sticking properties were still poor. The surface of the Au film remained mirror like.

Table 2. Procedures for Ag/Au deposition

	Ag	Au
method	evaporation pressure 10^{-7} to 10^{-6} mbar	sputter deposition Ar pressure 2.10^{-2} mbar power 500 W target Ø 20 cm self bias 1350 V
thickness	100 nm	100 nm
annealing conditions	1 bar O_2 400°C 1 hour	1 bar O_2 500°C 1 hour
etch cleaning	not possible	power 150 W self bias 350 V
adhesion layers	Cr, ~ 10 nm	Ti, 3-10 nm

To peal off the top layers of the damaged YBCO film and produce a new, fresh surface, soft Ar ion etching was used prior to metal deposition. In our case this was only possible in the Au deposition process. Using this cleaning procedure gave a bad, semiconducting contact. Only after additional annealing, R_c was lowered by two orders of magnitude compared to the 'as deposited' contacts. (Hahn et al. [13] suggested that more improvement could be obtained using a sputter gas containing 20% oxygen.) We also observed a significant improvement of the adhesion of Au to the substrate. Further studies will be directed, therefore, to the optimization of the cleaning parameters and the composition of the sputtergas.

Thin Cr and Ti films were used to improve the adhesion properties of Ag and Au, respectively. They were deposited in situ, immediately followed by deposition of the Ag/Au layers. Both in the Au/Ti and in the Ag/Cr case this gave a large improvement of the adhesion to the substrate. Since Cr and Ti chemically react with YBCO, however, causing a strong degradation of the superconducting properties, direct contact of these materials to YBCO has to be avoided. Therefore, when an adhesion layer (AL) is involved, a bilayer technique is used. The first layer of Ag/Au (M) is deposited directly on top of the YBCO, and structured into the same shape as the junction leads. A thin Cr/Ti layer is then deposited, directly followed by the second layer of Au/Ag. The result of this process is a M/AL/M structure on YBCO, giving a good electrical contact, and a AL/M structure on the substrate, giving good adhesion there.

This qualitative study suggests that good contacts may be obtained with evaporated Ag, using a bilayer technique as described above with Cr as adhesion layer. Prior to deposition of the Cr and second Ag layer, the contact can be annealed (at temperatures below 370°C), to improve R_c. Most promising results, however, have been obtained with sputtered Au, after soft Ar ion sputter cleaning of the YBCO surface, followed by an anneal treatment. This gives the lowest R_c values and good adhesion to the substrate, even without using a bilayer design with Ti as sticking material. A quantitative study is being performed at this time, using a suitable structure for measuring contact resistivities. All cleaning, etching, deposition and annealing parameters of the two processes described will be optimized.

3. Summary and Outlook

Summarizing, we have described the design and fabrication of a device for highly sensitive detection of (sub-) millimeter waves. This device is a combination of an YBCO/PBCO/YBCO ramp type Josephson junction with a barrier thickness of 10-20 nm and a log-periodic antenna made of noble metal. These devices will meet the requirements for an efficient high-Tc high-frequency detector, concerning the values of critical current, normal state resistance and I_cR_n products as well as efficient coupling to incoming radiation.

The deposition temperature of the isolating PBCO layer was lowered to prevent shunting of the junction by outgrowths in the base YBCO electrode.

A soft Ar ion sputter clean treatment prior to Au sputter deposition, to repair the damaged YBCO surface, was found to be the most promising procedure for obtaining low ohmic contacts of noble metal to the YBCO junction leads, as well as good adhesion of the metal to the substrate.

It is clear that much work is needed to meet all requirements for optimal properties of the described device. For example, the substrate should be changed from YSZ to a more suitable material like $LaAlO_3$ or $NdGaO_3$. This is likely to be the next step in the evolution process. Nevertheless, first junction-antenna combinations that were tested recently, show promising results. No degradation of junction properties due to the antenna patterning was observed. The devices showed good sensitivity to millimeter wave radiation: multiple Shapiro steps were observed at a frequency of 100 GHz up to 75 K, making operation possible in the submillimeter range. These results will be presented in a separate paper.

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