Smooth NdBa$_2$Cu$_3$O$_{7-\delta}$ thin films and ramp Josephson junctions

M. Sjöstrand$^1$, P. Komissinski$^{1,2}$ and D. Winkler$^1$

$^1$ Department of Microtechnology and Nanoscience, Chalmers University of Technology, Göteborg, Sweden
$^2$ Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Moscow, Russia

E-mail: mikael.sjostrand@mc2.chalmers.se

Abstract. We report on c-axis oriented NdBa$_2$Cu$_3$O$_{7-\delta}$ (NBCO) superconducting thin films grown on SrTiO$_3$ substrates using pulsed laser deposition. The transition temperature of these NBCO films was around 89.5 K and the root mean square (RMS) surface roughness for 150 nm thick films was 0.75 nm. Insulating layers of PrBa$_2$Cu$_3$O$_{7-\delta}$/SrTiO$_3$/PrBa$_2$Cu$_3$O$_{7-\delta}$ grown on top of the NBCO superconducting films result in superconductor/insulator multilayers of about 400 nm in total thickness and an RMS surface roughness of 2.4 nm. Smooth ramps with angles of about 20° are patterned in the multilayers using a photore sist reflow process and Ar ion milling. 15-25 nm thick Ga-doped PrBa$_2$Cu$_3$O$_{7-\delta}$ barriers and NBCO counter electrodes are deposited on the ramp forming Josephson junctions. Current-voltage ($I-V$) curves of the obtained ramp Josephson junctions were studied at 4.2 K. Multiple Shapiro steps were observed when the junctions were irradiated at frequencies around 10 GHz. The amplitudes of these steps oscillate with microwave power in agreement with the resistively shunted Josephson junction (RSJ) model.

1. Introduction

When fabricating Josephson junctions, one of the most crucial parameters is the roughness of the superconducting thin films. The most commonly used high temperature superconductor (HTS) is YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO). But according to [1] the HTS material NdBa$_2$Cu$_3$O$_{7-\delta}$ (NBCO) should be smoother than YBCO. It also has some other favorable features such as the highest critical temperature ($T_c$) in the rare earth–BCO family, about 98 K for bulk material [2]. However, for thin films $T_c$ is considerably lower, about 93 K for the best films [3]. Furthermore, NBCO has high critical current density ($J_c$) in an intermediate magnetic field [4]. It has also been reported that NBCO has high surface stability because one believes that NBCO is terminated with a CuO-plane, which is less reactive to the ambient than the Ba-based layers [1]. The drawback of NBCO is that the parameter space for growing high quality films is narrower than for YBCO. This is closely connected to that Nd$^{3+}$ substitutes for Ba$^{2+}$ in the lattice [5] and this introduces strain and rearrangement of charges which reduce the critical temperature. One can try to adjust the composition of the target in order to compensate for this effect. However, in this paper we have chosen to use a commercial stoichiometric target for fabricating NBCO thin films. These films are then used for ramp Josephson junctions.
2. Fabrication

2.1. Growth of NBCO thin films

We have managed to grow high quality superconducting NBCO films by pulsed laser deposition (PLD). The substrate we use is (001) SrTiO$_3$ (STO). After an optimization of the parameters we use a deposition temperature of 830 °C and an oxygen pressure of 0.8 mbar. The laser energy density is 1.2 J/cm$^2$ and the target-to-substrate distance is 55 mm resulting in a deposition rate of 0.7 Å/pulse. Furthermore, we use a pulse repetition rate of 10 Hz. The base pressure in the deposition chamber is typically 4 · 10$^{-6}$ mbar. Directly after the deposition we let in 0.9 bar of O$_2$ and cool down the substrate at 10 °C/min.

With these parameters we get a critical temperature of 89.5 K and a transition width of 1.4 K.

The surface morphology of the films has been studied in atomic force microscope (AFM) and the films are very smooth. For a 150 nm thick film the RMS surface roughness across a 5 × 5 μm$^2$ large area is 0.75 nm and the peak-to-valley distance along a 7 μm long scan is less than 4 nm, see Figure 1.

Furthermore, the films are highly $c$-axis oriented, as is confirmed with X-ray diffraction (XRD), see Figure 2. We calculate the $c$-axis parameter to be 11.73 Å, c.f. the tabulated value of 11.74 Å[6].

![Figure 1. An AFM picture of a 150 nm thick NBCO film. The scan is 5 × 5 μm$^2$. The inset shows a surface profile along the line.](image1)

![Figure 2. A 2θ XRD measurement on an NBCO film showing (00n) reflections of NBCO and STO (N = NBCO, S = STO).](image2)

2.2. Fabrication of NBCO ramp Josephson junctions

The ramp Josephson junctions have a 150 nm thick NBCO bottom electrode and an insulator stack of 70 nm PrBa$_2$Cu$_3$O$_{7-δ}$ (PBCO), 70 nm STO and 70 nm PBCO (see Figure 3). The reason for this type of mixed structure is that STO is a good insulator, however lossy in high frequency applications. PBCO is introduced as an additional insulator because it grows epitaxially on NBCO due to matching lattice parameters. A multilayer as the one described above has an RMS surface roughness of 2.4 nm across a 5 × 5 μm$^2$ large area.

The ramp is then formed in a separate vacuum chamber by argon ion milling during approximately 150 min with an ion energy of 300 eV and a current density of 0.1 mA/cm$^2$. A reflowed resist mask for etching, created by baking the resist after exposure in 130 °C for 30 min, is used to produce a low angle ramp. The sample is mounted on a rotating water cooled...
stage. When the stage is tilted 45° against the beam, the resulting ramp angle becomes around 20° after etching.

After creation of the ramp, the sample is brought back to the PLD chamber and the ramp is cleaned in-situ with argon and oxygen ions using an ion energy of 300 eV during 5-10 min and then lowered to 100 eV during the final 3-5 min. A 15 to 25 nm thick PrBa$_2$Cu$_{2.9}$Ga$_{0.1}$O$_{7-δ}$ (PBCGO) barrier is then deposited. Finally, a 150 nm thick NBCO top electrode is deposited in-situ.

Gold for the contact pads is dc-sputtered and the patterning of the junctions is then done by a standard photolithography process.

3. Characterization of the NBCO ramp Josephson junctions

An $I-V$ curve of a 4 μm wide junction with a 21 nm thick barrier measured at 4.2 K is shown in Figure 4 and at a larger voltage scale in Figure 5. The critical current of the junction is 55 μA and the normal resistance ($R_n$) measured at 8 mV is 140 Ω. This implies that $AR_n = 2.5 \mu$Ωcm$^2$, where $A$ is the area of the ramp. The critical voltage is $I_cR_n = 7.7$ mV and $J_c = I_c/A$ is about 3.1 kA/cm$^2$. Large excess current is seen in Figure 4 and 5, probably due to microshorts in the barrier. We also notice the hysteretic behavior and estimate the Steward-McCumber parameter ($\beta_c$) to be 1.8 [7]. The reason for this could be a high capacitance caused by a too thin insulator layer and a too large overlapping area between the top and bottom electrodes.

![Figure 3. Schematic picture showing the different layers in a ramp Josephson junction. $I$ denotes the current through the junction.](image)

Despite the large excess current, some of the junctions have sharp Shapiro steps when irradiated by microwaves, see Figure 6. At a frequency of $\nu = 9.7$ GHz, Shapiro steps appear at multiples of the voltage [8] $V = h\nu/2e = 20.1 \mu$V, as is clearly seen in Figure 6 ($h$ is Planck’s constant and $e$ is the elementary charge). We see up to 17 Shapiro steps at this frequency corresponding to a characteristic frequency of 166 GHz.

Furthermore, the height of the Shapiro steps is modulated by the applied microwave power as illustrated in Figure 7, where $I_c$, the first Shapiro step ($I_1$) and the second Shapiro step ($I_2$) are plotted as a function of the applied microwave power.

![Figure 4. $I-V$ curve for a 4 μm wide junction measured at 4.2 K.](image)

![Figure 5. $I-V$ curve of the same junction as in Figure 4 but measured at a larger voltage scale.](image)
In order to find out a more true value of $I_c R_n$ taking into account the large excess current, from Figure 7 we can calculate the parameter $\kappa_n = \sqrt{P_{n,2}/P_{n,1}} - 1$. $P_{n,k}$ is the applied microwave signal power when the $n^{th}$ Shapiro step has its $k^{th}$ zero. We get $\kappa_0 = 0.29$, $\kappa_1 = 0.26$ and $\kappa_2 = 0.22$. Furthermore, from [9] (assuming the RSJ model) $\kappa$ is numerically related to the parameter $\omega_c = 2eV_c/\hbar$, where $V_c = I_c R_n$. From [9] and using our values of $\kappa$ we get a critical voltage of about 0.13 mV. Using our value $R_n = 140 \Omega$ we see that the critical current should be 0.9 $\mu$A, compared to the measured value of 55 $\mu$A. Thus, most of the critical current consists of excess current.

4. Conclusion
We have been able to grow high quality superconducting NBCO films. They have a critical temperature of 89.5 K and a transition width of 1.4 K. Furthermore, the films are extremely smooth with an RMS surface roughness for a 150 nm thick film of only 0.75 nm. Ramp Josephson junctions have been fabricated and measured. They show sharp Shapiro steps when irradiated with microwaves. Up to 17 steps can be seen. The junctions suffer from a large excess current and have a flux-flow-like dependence.

References
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