$YBa_2Cu_3O_7$ Nano-Bridge Junctions and dc SQUIDs made by Focused Ion Beam Milling

Dave H.A. Blank, Wilfred Booij, Hans Hilgenkamp, Bart Vulink, Dick Veldhuis, and Horst Rogalla
University of Twente, Applied Physics, Low Temperature Division, P.O.Box 217, 7500 AE Enschede, The Netherlands

***Abstract*-$YBa_2Cu_3O_7$ nano-bridges with widths ranging from 200 to 800nm were made using Focused Ion Beam milling. The IV-characteristics of the narrowest nano-bridges show, under microwave irradiation, pronounced Shapiro steps up to the transition temperature. An inductively shunted single layer SQUID, using these nano-bridges, has been realised by a combination of Focused Ion Beam milling and selective epitaxial growth. Flux to voltage modulation up to 82K was observed, with a maximum modulation depth of 3.7 μV at 78K.**

I. INTRODUCTION

Superconducting nano-bridges have received a lot of interest, because of their Josephson-like behaviour [1]. In view of their relative simple structure, they appear to be promising devices. However, the patterning techniques to produce nano-constrictions are very complex, often resulting in highly irreproducible results. The discovery of the High T_c Superconductors, renewed the interest in nano-bridges, because these nano-bridges can be realized using a single thin film.

In theory, only nano-bridges that have dimensions comparable with the coherence length ξ are expected to show true Josephson-like behaviour [2]. In practice, it is found that bridges with dimensions significant smaller than the effective magnetic field penetration depth λ_{eff} exhibit Josephson-like effects, like the occurrence of Shapiro steps under microwave irradiation [3]. The behaviour of these nano-bridges is governed by Abrikosov vortex motion. Consequently, these nano-bridges can be used in SQUID configurations, similar to conventional Josephson junctions.

In this article we present the characteristics of nano-bridge junctions as well as nano-bridge SQUIDs, made by Focused Ion Beam milling. To structure the contact leads, two different techniques have been used, of which one combines focused ion beam milling with selective epitaxial growth. Besides IV-characteristics, the response of the nano-bridges to microwave irradiation has been investigated. Furthermore, two of these nano-bridge junctions have been used in an inductively shunted dc SQUID. Here, the flux to voltage characteristics at 77K are presented.

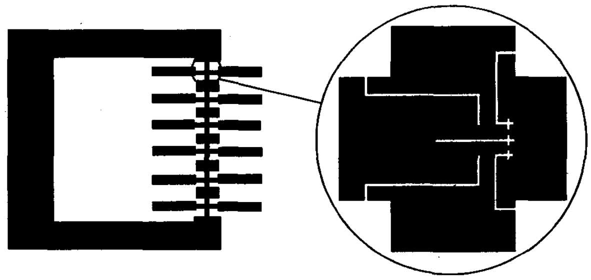
Manuscript received October 18, 1994.
This work was supported in part by the Dutch National Program on High Tc superconductivity (NOP-HTS).

II. EXPERIMENTAL

The nano-bridges presented in this paper were prepared by direct Focused Ion Beam (FIB) milling. With this technique trenches are etched in thin YBCO films (thickness ≤ 100nm), using a 25 kV Ga^+ beam with a diameter of 50 nm (FWHM). The FIB technique is used in combination with two different methods to structure the current and voltage leads. With the first method, the milling of the nano-structure was carried out before defining and patterning the current and voltage leads with standard photolithography and argon milling. In the second approach, first the contact leads were defined, using our Selective Epitaxial Growth (SEG) technique [4], and in the last step the nano-structure was defined using FIB-milling. In this case, the SEG was realised using Ti as the definition mask. The YBCO grown on top of the Ti-layer shows semiconducting behaviour. The major advantage of the SEG technique is that, apart from the nano-structure definition by FIB, no further etching procedures are necessary after the deposition of YBCO.

Besides the nano-bridges, also an inductively shunted single layer dc-SQUID [5], using these nano-bridges has been realised. The large SQUID loop, 8mm squared, including current and voltage leads were defined using SEG, see Fig. 1a. The nano-bridges (200nm long and 300nm wide) and the 200 nm wide and 100μm long slit, forming the small SQUID loop, were made using FIB-milling, see Fig. 1b. With this design six independent nano-SQUID structures, including contact leads, are coupled into one large SQUID loop.

All YBCO layers were prepared by the pulsed laser deposition technique, as described in ref [6].



1a 1b

Fig. 1: SQUID loop including current and voltage leads (1a) and nano-bridges and SQUID hole by focused ion beam milling (1b).

1051-8223/95$04.00

The depth profiles and dimensions of nano-bridges were determined using Scanning Force Microscopy (SFM). The length of the bridges (200nm) is defined by the spot size of the FIB system.

The depth of the milled lines is approximately 140 nm, the film thickness was designed to be 100nm. The edges of the nano-bridges have generally a Gaussian shape, due to the shape of the beam profile. Consequently, the width of the bridges is in most cases 100nm less than designed. The electrical isolation of the milled trenches was determined by an "open bridge". The resistance of this structure was > 40 MΩ, so we conclude that the electrodes of the nano-bridges were electrically isolated.

III. Results and Discussion

In the first method (FIB milling with subsequent argon milling) a number of process steps are needed after the FIB milling. Nano-bridges made by this method showed irreproducible results. Usually, a room temperature resistance in the order of several MΩ was found and no superconducting transition (or at very low temperatures) could be observed. We attribute this to poisoning of the HTS material by the gallium left behind after the milling step. This occurs in the next processes during which the sample is heated up several times to a temperature of approximately 90°C, causing the gallium to diffuse into the superconductor and destroying the superconducting properties.

The transition curves of the samples that had their contact leads patterned using SEG, show similar behaviour as the as-grown films. The resistance versus temperature levels off at higher temperatures, because the semiconducting YBCO on top of the titanium layer shunts the nano-bridges. At low temperatures this layer leads to much higher resistances leading to a negligible influence on the IV-characteristics of the nano-bridges. The critical temperature of the bridges range from 88K for bridges wider than 500 nm to 86K for the 250nm wide bridges.

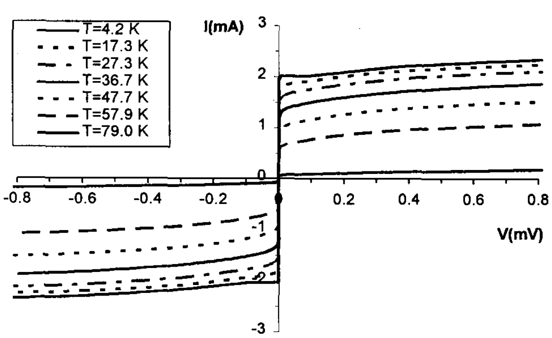


Fig. 2: IV-characteristics of a nano-bridge (w=238nm, l=220nm) at different temperatures.

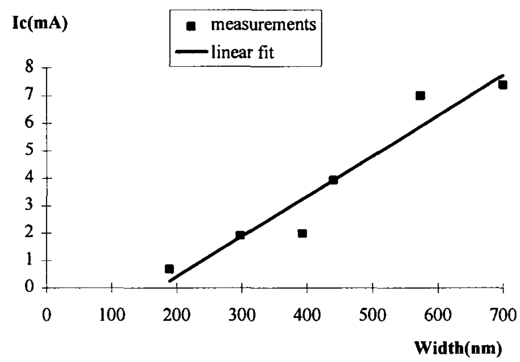


Fig. 3: Critical current of different nano-bridges as function of their width.

The IV-characteristics of a nano-bridge with a width of 238nm and length of 220nm is given in Fig. 2. Only the low-voltage range to approximately 20μV is measured, to prevent structural damage due to strong heating effects. At 4.2K, a sharp transition to the resistive state appears. This small jump in the IV-characteristic completely disappears at higher temperatures. The critical current of the nano-bridges, using a 1μV criterion, scales very well with the dimensions of the bridges determined by SFM, see Fig. 3. From the figure it can be seen that the minimum width of the FIB-structured nano-bridge is approximately 170nm.

The Josephson-like performance of the nano-bridges has been verified with microwave irradiation. Fig. 4 shows the IV-characteristic of a 240nm wide nano-bridge under 9.35GHz microwave irradiation at 36.4K, with different microwave power levels. The IV-characteristic shows up to 20 Shapiro steps at integral multiples of a constant voltage of 19.4μV. Shapiro steps were observed up to the transition temperature. Due to the high dielectric constant of the used $SrTiO_3$ substrate, high power levels were needed to obtain Shapiro steps.

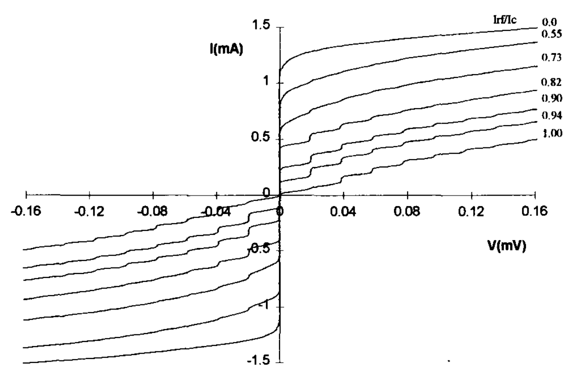


Fig. 4: IV-characteristic of a 240nm wide nano-bridge with different levels of microwave power. The values shown with each curve are the normalized microwave current amplitude I_{mw}.

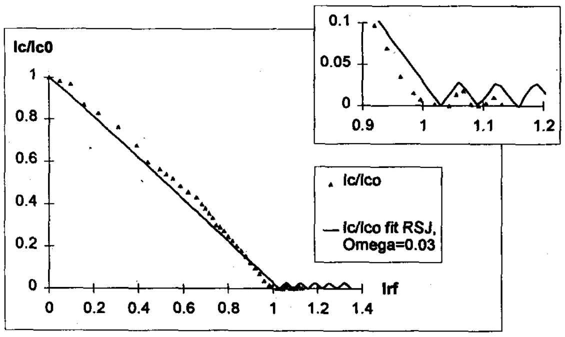


Fig. 5: Critical current versus the amplitude of microwave injected current for a 238nm wide nano-bridge, under microwave irradiation (I_{mw}) at a T=36.6K.. I_{mw} is normalized to the value where the injected microwave current completely suppresses the critical current for the first time. The RSJ-fit is indicated by a solid line

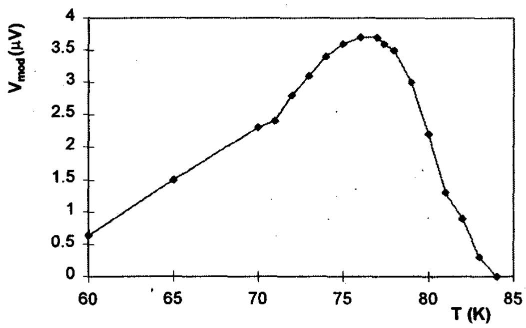


Fig. 7: Modulation depth as function of the temperature with a maximum of 3.7 μV at 78K

We modeled the behaviour of the nano-bridge by the RSJ-model. The capacitance of the nano-bridge is negligible, so that the junction can be modeled by an ideal Josephson junction (J) that is shunted by a resistance (R).

In Fig. 5, the critical current of the nano-bridge is shown as a function of microwave current I_{mw}. We assume that the amplitude of the current is proportional to $(P_{mw})^{1/2}$, with P_{mw} being the incident microwave power. The critical current reappears at higher microwave power levels. This behaviour is fitted with the results of the RSJ-model, shown as a solid line in Fig. 5. The fit is best for a parameter $\Omega=\varpi_{mw}/\varpi_c=0.03$, with $\varpi_c=2e\ IcRn/\hbar$ being the angular frequency of the junction at a voltage given by the IcRn product. This fit leads to a value of the IcRn product of the nano-bridge of 650μV at 36.6K. This is in reasonable accordance with the value obtained from the IV-characteristics (940μV).

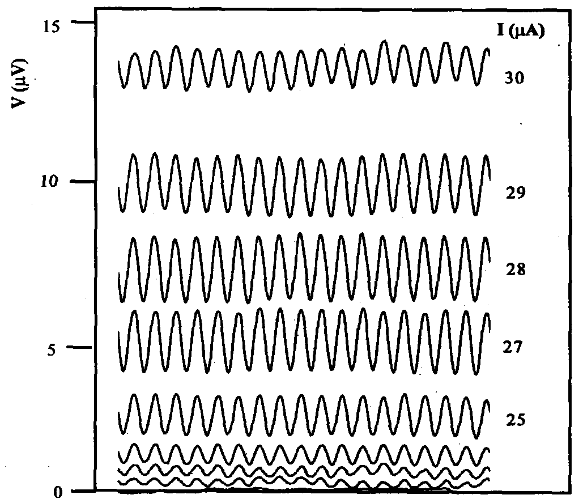


Fig. 6: the flux to voltage modulation of the single layer inductively shunted SQUID at 80K, for various values of the bias current.

Furthermore, it proved to be impossible to obtain Shapiro steps under temperatures of approximately 20K.

Microwave measurements were also carried out at higher temperatures, showing pronounced but more rounded steps up to 80K.

The fact that the nano-bridges can well be described by the RSJ-model is also found in other experiments, for example for Nb_3Ge nano-bridges [7]. They found that when an induction is included in the RSJ-model, their fit is even better. This seems not the case for the HT_c nano-bridges.

A single layer inductively shunted dc SQUID was constructed based on nano-bridges of 300nm width, see Fig. 1. The SQUID hole consists of a 200 nm wide and 100 μm long slit, defined by focused ion beam milling. The slit inductance is estimated to be 40 pH.

Fig. 6 shows the flux to voltage modulation of this device at 80K, for various values of the bias current. A nice periodic behaviour is observed, even when a large amount of flux (over 100 ϕ_0) is coupled to the SQUID loop. This can be explained by the fact that relatively high fields, of the order of Bc2, are needed to suppress the critical current of the nano-bridges. Fig. 7 shows the maximum peak to peak modulation voltage as a function of temperature. Contrary to SQUIDs based on grain boundary junctions, we observe a maximum in the modulation depth, here 3.7 μV at 78K. We attribute this maximum to a stronger flux-pinning behaviour at low temperatures (higher dI/dV in the resistive state, leading to smaller modulation depth) on one hand and a decrease of critical current at the transition temperature of the nano-bridge on the other hand.

IV. Conclusions

Using direct Focused Ion Beam milling of YBCO, nano-bridges with high critical current density and critical temperature were fabricated. The sequence of the process steps is very important in the fabrication process of nano-bridges. Heating the samples to moderate temperatures after the nano-bridges are structured, proved to be fatal to the superconducting properties of these samples. The reason for this seems to be that the gallium implanted alongside the milled trenches poisons the YBCO and destroys superconductivity. Using SEG to define the current and voltage leads, a method was developed to structure the nano-bridges as the final step in the fabrication process.

The IV-characteristics of the most narrow nano-bridges (200-300nm) showed a sharp transition to the voltage state at low temperatures. Under microwave irradiation a 238nm wide nano-bridge featured pronounced Shapiro steps. The height of the Shapiro steps as a function of the microwave power amplitude could be fitted with the RSJ-model, leading to very reasonable values of the IcRn product (650μV), compared with the values derived from the IV-characteristic (940μV).

A single layer inductively shunted dc SQUID showed flux to voltage modulation up to 84K, with a maximum modulation depth of 3.7 μV at 78K.

The results obtained for the nano-bridges in combination with the simplicity of the fabrication technique indicate that these devices can be used in more complicated structures like dc SQUIDs.

References

[1] P.W. Anderson and A.H. Dayem, "Radio-frequency effects in superconducting thin film bridges", *Phys. Rev. Lett.*, vol. 13, pp. 195-197, 1964.

[2] K.K. Likharev, "Superconducting weak links", *Rev. Mod. Phys.*, vol. 51, pp. 101-159, 1979, and K.K. Likharev, "Vortex motion and Josephson effect in superconducting thin bridges", *Sov. Phys.-JETP*, vol. 34, pp. 906-912, 1972.

[3] M.J.M.E. de Nivelle, "Transport properties of nano-bridges in high-Tc superconducting YBCO films", *PhD-thesis University of Twente*, The Netherlands, 1993.

[4] D.H.A. Blank, C.A.J. Damen, and H. Rogalla, "Selective Epitaxial Growth of YBCO by metal definition masks", *Applied Superconductivity 1993*, vol. 1, ed. H.C. Freyhardt, DGM Verlag, Oberursel, pp. 675-678, 1993.

[5] E.P. Houwman, D. Veldhuis, J. Flokstra, and H. Rogalla, "Comparison of shunted dc SQUIDs with large β ", Physica B, vol. 165&166, pp. 81-82, 1990.

[6] D.H.A. Blank, D.J. Adelerhof, J. Flokstra, and H. Rogalla, "Preparation of YBCO thin films on various substrates by laser ablation", *Physica C*, vol. 167, pp. 423-432, 1990.

[7] H. Rogalla, "High-Tc Josephson contacts preparation and properties", *Habilitationsschrift*, University of Giessen, Germany, 1986.