

# Increasing the sensor performance using Au modified high temperature superconducting $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin films

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**Abstract.** We prepared planar, galvanically coupled gradiometers whereby the antenna structures of some of them were modified by incorporating Au nanoparticles. Gradiometers with gold modified antennas were compared with conventional ones to investigate the influence of gold induced pinning on the performance of superconducting sensor devices. We found that a local inclusion of gold nanoparticles offers the possibility of increasing the pinning of flux lines in the antenna regions, thus significantly reducing flux noise, especially in the low-frequency range. Since also the properties of grain boundary Josephson Junctions are strongly affected by Au particles, SQUID and antenna regions in gradiometric sensor devices can be separately optimized.

## 1. Introduction

Many superconducting thin film devices require a spatially resolved current carrying capability due to different boundary conditions. On the one hand, the critical current density and the pinning of flux lines, respectively, should be high to reduce flux noise in the antenna regions of gradiometers. On the other hand, the critical current density of the Josephson Junctions itself must not be too high to ensure a proper functionality. We show that adding thin gold layers during the preparation process of epitaxial  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (YBCO) thin films offers the possibility of creating such spatially varying flux pinning properties, allowing to separately optimizing SQUIDs and antennas.

## 2. Sample Preparation

Unfortunately, the grain boundary itself strongly influences the properties of grain boundary Josephson junctions and thus the performance of gradiometric sensor devices. To achieve comparable conditions we prepared gradiometers on the same  $\text{SrTiO}_3$  (STO) bicrystal substrate, thus using the same grain boundary. A patterned gold seed layer was deposited on the STO substrates to locally introduce modifications of the pinning only at the antenna areas of some of the gradiometers as can be seen in figure 1. The patterning of this Au seed layer was done using photolithography combined with dc-sputtering. After the gold seed layer had been deposited, the samples were heated to 780 °C to induce a dewetting of the Au layer, leading to a self-assembly of crystalline Au nanoparticles. As no



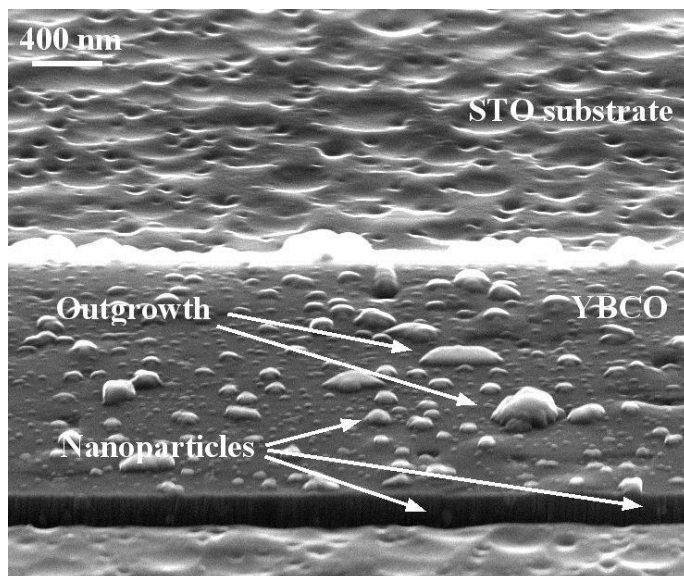
lateral diffusion of nanoparticles was observed, the usage of a prepatterned Au seed layer appears to be suitable for preparing nanoparticles at well-defined positions on the substrate - in our case only at the antenna regions. Using pulsed laser deposition in an oxygen atmosphere a YBCO thin film of 150 nm thickness was deposited on top of the nanoparticles. The gradiometer layouts subsequently were patterned utilizing ion beam etching and photolithography.



**Figure 1.** Layout of the four gradiometers on one and the same SrTiO<sub>3</sub> substrate. Black parts refer to pristine parts of the YBCO thin film, gold ones to YBCO with embedded Au nanoparticles.

### 3. Results

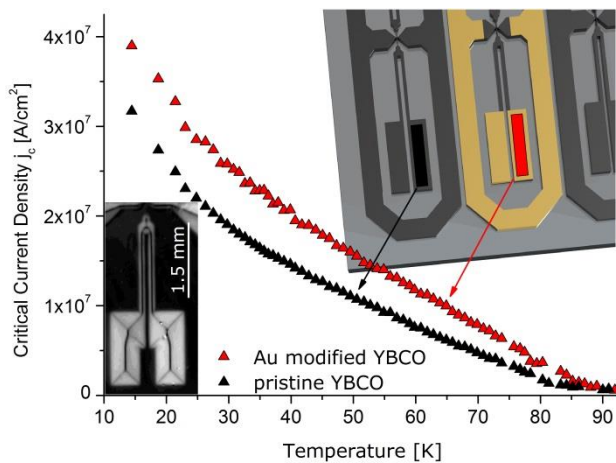
In contrast to what was reported by Mikheenko et al. [1] the nanoparticles cannot only be found at the substrate/YBCO thin film interface. As we confirmed by transmission electron microscopy (TEM) and scanning electron microscopy (SEM – see figure 2), some of the particles are overgrown by the YBCO matrix but some of them also can be found on top of the YBCO layer or within the superconducting layer itself. Interestingly, in TEM images we do not find any additional defects or disturbances in the epitaxial growth of the YBCO thin film in vicinity of Au nanoparticles. Instead, there only appears to be a local bending of lattice planes around the nanoparticles [2].



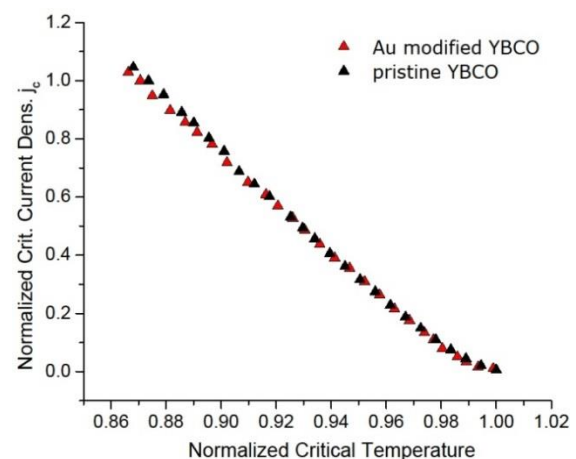
**Figure 2.** SEM image of a patterned YBCO layer. Note that the sample surface does not only show nanoparticles but also some additional outgrowths which are typical for YBCO thin films. Some nanoparticles can be found within the YBCO layer as it is visible in the cross section.

To characterize the critical current density in our samples we employed magneto-optical Faraday microscopy. Thus, in contrast to transport measurements the local critical current density could be calculated out of the obtained flux density distribution via an inversion of the Biot-Savart law [3]. Using this method, in principle it is possible to achieve a very high spatial resolution in the local  $j_c$  measurements. In our case this resolution was restricted to about  $5\mu\text{m}$ . As can be seen in figure 3, the critical current density  $j_c$  was significantly increased over the whole temperature range in the Au modified areas (at a temperature of 77 K the enhancement is approximately 70 %). Although the absolute value of  $5\cdot 10^6\text{ A/cm}^2$  is not a record in the field of artificial pinning centres, the reported method still appears to be advantageous compared to conventional ones. The most intriguing argument is that the incorporation of self-assembled Au nanoparticles allows modifying the properties of the grain boundary Josephson junctions at the same time [4]. More specifically, in contrast to the increasing current density of thin films, the critical current density of grain boundary Josephson junctions is decreased, allowing to reduce the noise due to fluctuations of  $I_c$ . At the same time the normal state resistance of the junction is increased, compensating the decreasing critical current [4]. Thus, the characteristic  $I_c R_N$  product of the junctions remains the same, enabling high transfer functions of the SQUID [5].

It should be noted that the curve progression of the temperature dependency of the critical current density remains the same, indicating that the same pinning mechanism as in pristine YBCO films is responsible for the increasing current density. I.e. individual pinning of flux lines at the gold nanoparticles can be neglected. These findings are in excellent agreement with transport measurements performed on different samples (see figure 4).



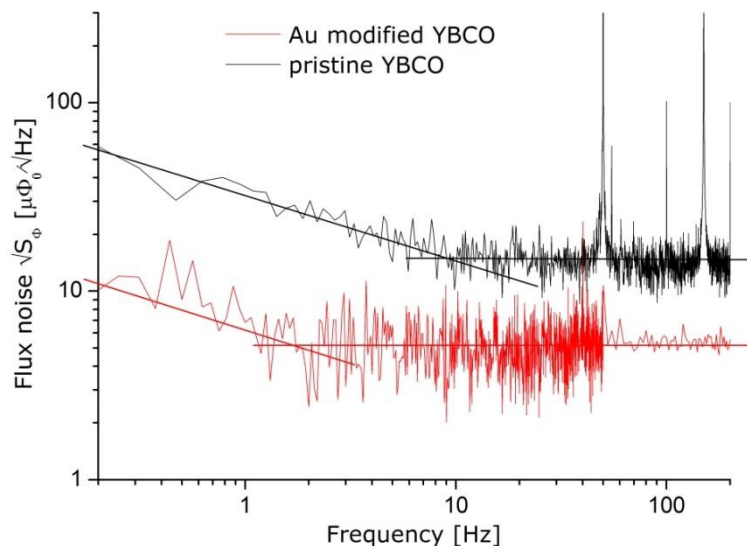
**Figure 3.** Temperature dependence of the critical current density obtained using magneto-optical imaging.



**Figure 4.** Normalized temperature dependence of the critical current density obtained using transport measurements on different samples.

Any additional pinning of flux vortices should not only increase  $j_c$  but also influence the flux noise of the gradiometers. Because the optimization of high temperature superconducting SQUID gradiometers is dependent on various parameters, e.g. the ambient magnetic field, we carried out noise measurements in a locally shielded environment ( $\mu$ -metal shield) at  $T = 77\text{K}$ . The measurements were performed in flux locked loop mode with an ac-bias reversal technique. Comparing a gradiometer which had an Au modified antenna structure with a gradiometer already used in biomagnetic measurements, one finds the white noise level to be drastically decreased (see figure 5). We achieved white noise levels between  $5\mu\Phi_0/\sqrt{Hz}$  and  $6\mu\Phi_0/\sqrt{Hz}$  with gold modified gradiometers. Compared to the conventional SQUID gradiometer this value is very low, as it is even comparable to the best values achieved for single SQUIDs without an antenna structure [6]. Furthermore, the corner

frequency was shifted to lower values, significantly enhancing the performance in the low-frequency range. This is far more interesting, as it was possible to increase the field gradient resolution at 1 Hz from  $700 \text{ fT}/(\text{cm}\sqrt{\text{Hz}})$  to  $600 \text{ fT}/(\text{cm}\sqrt{\text{Hz}})$  for the gradiometer with a gold modified antenna structure.



**Figure 5.** Noise measurements of gradiometers with and without embedded gold nanoparticles in the antenna regions. The corner frequencies are about 2 Hz with Au particles and 10 Hz without Au, respectively.

#### 4. Conclusion

A local inclusion of gold nanoparticles offers the possibility of increasing the pinning of flux lines in the antenna regions, thus significantly reducing flux noise. Since also the properties of grain boundary Josephson junctions are strongly affected by Au particles (lowering the critical current while increasing the normal state resistance), SQUID and antenna regions in gradiometric sensor devices can be separately influenced. Thus, a patterning of the Au seed layer using lithographic techniques seems to be highly suitable for preparing ideal templates for the production of superconducting sensor devices with optimized performance.

#### Acknowledgement

C. Katzer would like to thank the Landesgraduiertenförderung Thüringen for financial support.

#### References

- [1] Mikheenko P, Abell K S, Sarkar A, Dang V S, Awang Kechik M M, Tanner J L, Paturi P, Huhtinen H, Hari Babu N, Cardwell D A and Crisan A 2010 *J. Phys. Conf. Ser.* **234** 022022
- [2] Grosse V, Engmann S, Schmidl F, Undisz A, Rettenmayr M and Seidel P 2010 *Phys. Status Solidi RRL* **4** 97
- [3] Jooss C, Albrecht J, Kuhn H, Leonhart S and Kronmüller H 2002 *Rep. Prog. Phys.* **65** 651
- [4] Michalowski P, Schmidt M, Schmidl F, Grosse V, Kuhwald D, Katzer C, Hübner U and Seidel P 2011 *Phys. Status Solidi RRL* **5** 268
- [5] Wu C H, Sou U C, Chen J C, Chen K L, Yang H C, Hsu M H, Lai T S, Jeng J T, Tsai Y S and Horng H E 2006 *Appl. Phys. Lett.* **88** 102504
- [6] Wunderlich S, Schmidl F, Dörrer L, Schneidewind H and Seidel P 1999 *IEEE Trans. Appl. Supercond.* **9** 71