Superconducting $YBa_2Cu_3O_{7-\delta}$ Thin Film Detectors for Picosecond THz Pulses

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Abstract Ultra-fast THz detectors from superconducting $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films were developed to monitor picosecond THz pulses. YBCO thin films were optimized by the introduction of CeO_2 and PrBaCuO buffer layers. The transition temperature of 10 nm thick films reaches 79 K. A 15 nm thick YBCO microbridge (transition temperature—83 K, critical current density at 77 K—2.4 MA/cm^2) embedded in a planar log-spiral antenna was used to detect pulsed THz radiation of the ANKA storage ring. First time resolved measurements of the multi-bunch filling pattern are presented.

Keywords High-temperature superconductor · YBCO · Thin-film technology · Pulsed-laser deposition · THz detector · Picosecond synchrotron pulses

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1 Introduction

Synchrotron radiation in electron storage rings is emitted when accelerated electrons pass deflecting magnets. Due to the radio frequency (RF) system which is used to accelerate the electrons, they are grouped in bunches and the radiation is emitted in the form of short pulses. Coherent synchrotron radiation (CSR) is generated at wavelengths comparable or larger than the length of the electron bunch. Very short electron bunches, which were realized at the synchrotron source ANKA [1], enable pulses of THz CSR with the duration down to 1 ps. To analyze these very short pulses ultra-fast THz detectors are required.

Due to the requirement of ultimate speed, neither room-temperature THz detectors [2–4] nor cooled semiconducting composite bolometers are suitable for this application. Superconducting hot-electron bolometers (HEB) are promising candidates for fast direct detection of THz radiation [5–7]. YBCO microbridges have shown even faster photoresponse to THz radiation [8] as well as at optical through infrared wavelengths [9–12]. At optical wavelengths the relaxation time of the detector was found to be in the range of only a few picoseconds due to strong electron-phonon interaction [9, 12]. Another great advantage of high-transition-temperature YBCO detectors is the possibility to operate devices at temperatures above 77 K, thus low-cost cryocoolers can be used in applications.

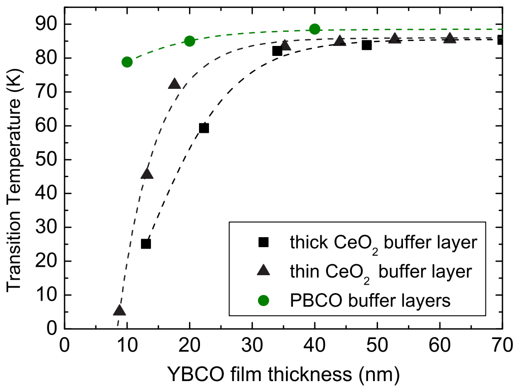
In this paper, we report on the technological challenges in the development of ultra-thin antenna-coupled YBCO microbridges of only a few unit-cells in thickness with critical temperatures above 77 K. We present the results of first measurements of THz pulses by a 15 nm YBCO detector operated at 77 K at the ANKA storage ring.

2 YBCO Thin-Film Microbridge Detector

The YBCO thin films were fabricated using the pulsed-laser deposition (PLD) technique. Pulses from a KrF excimer laser (wavelength 248 nm) with an energy density of 1 J/cm^2 were focused on a rotating stoichiometric YBCO target. The substrate holder was situated at a distance of 50 mm from the target in on-axis position and was heated up during film deposition.

The YBCO PLD process was optimized for the development of sensitive microbolometers. To improve the responsivity the volume of the microbolometer has to be minimized. Therefore, the deposition process was optimized in order to reduce the thickness of the YBCO films and to simultaneously keep the transition temperatures well above 77 K. To fabricate detectors for the THz frequency range with low dielectric losses, the YBCO films were grown on sapphire substrates. However, due to the crystalline mismatch between sapphire and YBCO and the diffusion of aluminum into the YBCO film at high deposition temperatures, it is not possible to grow high-quality superconducting YBCO films directly on sapphire. Buffer layers have to be used in the deposition process. A standard buffer material for YBCO on sapphire is cerium oxide (CeO_2). A CeO_2 buffer layer with a film thickness between 8 nm and 50 nm was deposited at a substrate temperature of 820°C and an oxygen pressure of

Fig. 1 (Color online) Dependence of the transition temperature on the YBCO film thickness for as-deposited films with different buffer layers: 50 nm thick CeO_2 buffer layer (*squares*), 8 nm CeO_2 layer (*triangles*), PBCO buffer layers (*circles*). The *dashed lines* are to guide the eye



$p_{O_2} = 0.9$ mbar. YBCO films with thicknesses between 10 and 100 nm were then deposited *in situ* on top of the CeO_2 layer at the same temperature with $p_{O_2} = 0.7$ mbar. After the YBCO deposition the oxygen pressure was increased to 900 mbar and the substrate temperature was ramped down to 550°C with a rate of 10°C/min. The temperature was kept constant at 550°C for ten minutes for annealing of the YBCO film. Afterwards the heater was ramped down to 400°C before switching off and cooling down exponentially to room temperature. The vacuum chamber was then evacuated and a 140 nm Au layer was grown *in situ* by PLD.

The as-deposited films were characterized by measuring the temperature dependence of the resistance. The transition temperature T_c was defined as the temperature at which the resistance decreases below 1% of the normal state resistance above the transition. The dependence of T_c on the YBCO film thickness for the 50 nm thick CeO_2 buffer layer is shown in Fig. 1. For YBCO film thicknesses above 30 nm T_c is nearly constant and well above 77 K. For films thinner than 30 nm T_c decreases significantly. This can be explained by the above-mentioned lattice mismatch leading to oxygen deficiency in the YBCO film, which results in a reduction of T_c [13] down to 25 K for 15 nm thick films. The T_c of films with $d < 30$ nm has been improved by a decrease of the CeO_2 layer thickness. Due to a shorter deposition time, the thinner CeO_2 films have less droplets leading to a smoother film surface. The YBCO films grow more homogenous on these surfaces which results in an improvement of the crystalline quality. The optimum was found at a CeO_2 film thickness of approximately 8 nm resulting in an increase of T_c up to 74 K for a 18 nm YBCO film (see Fig. 1).

The crystalline mismatch was further reduced by the introduction of an additional buffer layer made from $PrBa_2Cu_3O_{7-\delta}$ (PBCO). The lattice mismatch of approximately 1% between YBCO and PBCO allows for growing of very thin superconducting YBCO films with high crystalline quality. To protect the YBCO thin film during the patterning process, a PBCO protection layer was deposited on top of the YBCO film. The introduction of the 25 nm PBCO buffer layer combined with the PBCO protection layer of the same thickness resulted in $T_c = 79$ K of YBCO films with thickness of only 10 nm (see Fig. 1).

The multi-layers described above were patterned by several electron-beam lithography steps. The active, detecting area of the YBCO film was opened by removing

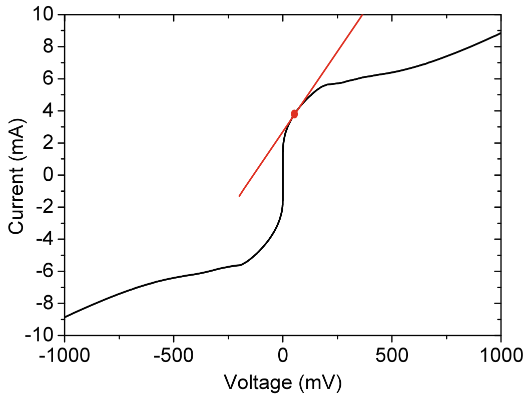


Fig. 2 (Color online) Current-voltage characteristic of a YBCO detector measured at 77 K in LN_2. The *straight line* is the tangent drawn through the working point where the differential resistance is 50 Ω

the Au layer by wet etching with an I_2-KI solution. Ion milling was used to pattern the Au antenna. To reduce oxygen loss in the YBCO layer during the ion milling, active sample cooling was employed. A broadband log-spiral antenna was used to cover the wide spectral band (0.2 through 2 THz) of ANKA [1]. The planar antenna was embedded into a coplanar readout line. The detectors were YBCO microbridges (4.5 µm wide, 1.5 µm long made from a 15 nm thick film) with a normal-state resistance of approximately 120 Ω that was measured right before the superconducting transition. The transition temperature of the microbridges reached 83 K which was almost the same as for non-structured films. A typical current-voltage characteristic (CVC) which was measured at 77 K in liquid nitrogen is shown in Fig. 2. The observed critical current $I_c = 1.6$ mA corresponds to a uniform critical current density of about $j_c = 2.4$ MA/cm^2. The s-shape of the CVC above 2 mA is caused by dissipative movement of magnetic vortices. Switching of the detector into the normal state around 6 mA occurs via formation of a normal domain across the whole YBCO microbridge.

3 Experimental Environment and Results

The YBCO detectors were mounted in a cryocooler allowing one to vary the operation temperature between 50 K and 300 K. The synchrotron radiation entered the cryocooler through a polyethylene window. The operating temperature was 77 K. The operating point was adjusted by current bias within the resistive transition between the normal and the superconducting state where the DC differential resistance was close to 50 Ω (Fig. 2). The bias was arranged via a room-temperature bias-tee. The signal was amplified with a room temperature amplifier and fed into a sampling oscilloscope.

The experiments were performed at ANKA, the synchrotron light source at KIT which was operated at 1.3 GeV electron energy with a dedicated magnetic optics for short bunches (“low-alpha mode”). Short CSR pulses down to 1 ps with a frequency bandwidth of $f = 0.1$–2 THz [1] are achieved at ANKA by this low alpha mode. The time-delay between two adjacent electron bunches is 2 ns corresponding to the 500 MHz frequency of the RF system. The typical filling pattern of the ANKA

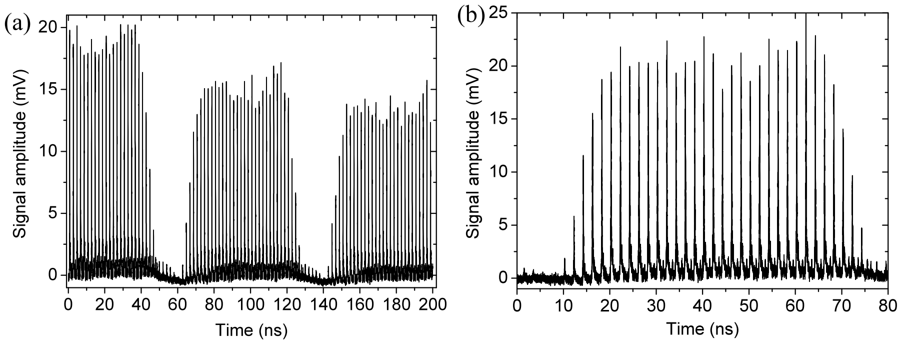


Fig. 3 (**a**) Measured detector signal of a 15 nm YBCO THz detector over time. The distance between two trains is 20 ns (50 MHz). In (**b**) one train with 33 bunches is depicted in detail

storage ring consists of 3 trains separated by a 20 ns gap. Each train consists of 33 bunches. The revolution frequency of the whole pattern is 2.7 MHz. Figure 3a shows the YBCO detector response to the radiation produced by these three trains. In Fig. 3b the response to only one train is depicted in detail that demonstrates the successful detection of all 33 bunches.

We have developed a technology process for antenna-coupled superconducting ultra-thin YBCO microbridges. A YBCO microbridge detector with only 15 nm film thickness and a critical temperature above 77 K was successfully tested at ANKA. The multi-bunch filling pattern of the storage ring was resolved in time via its synchrotron radiation. The measurements have demonstrated the successful use of the YBCO microbridge detector for monitoring THz radiation at a synchrotron source and—in combination with advanced readout techniques—the potential for picosecond time-resolution of THz synchrotron pulses.

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References

1. A. Plech, S. Casalbuoni, B. Gasharova, E. Huttel, Y.-L. Mathis, A.-S. Müller, K. Sonnad, A. Bartels, R. Weigel, in *Proceedings of PAC09*, vol. TU5RFP026 (2009), p. 1
2. E.R. Brown, Solid-State Electron. **48**(10–11), 2051 (2004)
3. D B. Rutledge, D.P. Neikirk, D. Kasilingam, in *Infrared and Millimeter Waves*. Millimeter Components and Techniques, Part II, vol. 11 (1984)
4. D.P. Neikirk, W.W. Lam, D.B. Rutledge, Int. J. Infrared Millim. Waves **5**(3), 245 (1984)
5. A D. Semenov, G.N. Gol'tsman, R. Sobolewski, Supercond. Sci. Technol. **15**, R1 (2002)
6. H.-W. Hübers, A. Semenov, K. Holldack, U. Schade, G. Wüstefeld, G. Gol'tsman, Appl. Phys. Lett. **87**, 184103 (2005)
7. A D. Semenov, H.-W. Hübers, K.S. Ilin, M. Siegel, V. Judin, A.-S. Müller, in *Proceedings of 34th International Conference on Infrared, Millimeter, and Terahertz Waves, 2009 (IRMMW-THz 2009)* (2009), p. 1
8. P. Probst, A. Scheuring, M. Hofherr, D. Rall, S. Wünsch, K. Il'in, M. Siegel, A. Semenov, A. Pohl, H.-W. Hübers, V. Judin, A.-S. Müller, A. Hoehl, R. Müller, G. Ulm, Appl. Phys. Lett. **98**, 043504 (2011)

9. M. Lindgren, M. Currie, C.A. Williams, T.Y. Hsiang, P.M. Fauchet, R. Sobolewski, S. Moffat, R. Hughes, J.S. Preston, F. Hegmann, IEEE J. Sel. Top. Quantum Electron. **2**(3), 668 (1996)
10. M. Danerud, D. Winkler, M. Lindgren, M. Zorin, V. Trifonov, B. Karasik, G.N. Gol'tsman, E. Gershenzon, J. Appl. Phys. **76**(3), 1902 (1994)
11. A D. Semenov, I.G. Goghidze, G.N. Gol'tsman, A.V. Sergeev, E.M. Gershenzon, Appl. Phys. Lett. **63**(5), 681 (1993)
12. A D. Semenov, R.S. Nebosis, Y.P. Gousev, M.A. Heusinger, K.F. Renk, Phys. Rev. B, Condens. Matter Mater. Phys. **52**(1), 581 (1995)
13. K.S. Il'in, M. Siegel, J. Appl. Phys. **92**, 361 (2002)