Ca-doping-induced enhancement of the critical currents of coated conductors grown by ion-beam-assisted deposition

A. Weber, G. Hammerl, A. Schmehl, C. W. Schneider, and J. Mannhart[a)]
Experimentalphysik VI, Center for Electronic Correlations and Magnetism, Institute of Physics, Augsburg University, 86135 Augsburg, Germany

B. Schey and M. Kuhn
AxynTeC Dünnschichttechnik, 86167 Augsburg, Germany

R. Nies, B. Utz, H.-W. Neumueller
Siemens AG, 91050 Erlangen, Germany

(Received 11 November 2002; accepted 13 December 2002)

One of the most promising technologies for the fabrication of high-T_c cables is the ion-beam-assisted deposition (IBAD) technique. The performance of the superconductors fabricated by IBAD, and the fabrication costs, are to a great extent determined by the critical current densities of the superconductors' grain boundaries. Since, in bicrystalline samples, overdoping has been found to improve the transport properties of grain boundaries in high-T_c superconductors, we have explored whether overdoping also enhances the critical currents of IBAD samples. The measurements show that, depending on the critical current density of the superconducting film, J_c (77 K) is increased by factors up to 2.2, also in applied magnetic fields of several tesla. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1543640]

The most promising approaches to the fabrication of competitive cables from high-T_c superconductors operating at 77 K[1,2] are the coated conductor technologies. These technologies aim to avoid the deleterious effects of large angle grain boundaries on the critical current density J_c[3,4] by aligning the grains to a few degrees along all major crystal axes. Large efforts have been undertaken to develop practical technologies for the fabrication of polycrystalline high-T_c superconductors with well aligned grains, of which the ion-beam-assisted deposition (IBAD),[5,6] the rolling assisted biaxially textured substrate process,[7] and the inclined substrate deposition technique[8,9] are the most advanced. By using these processes J_c values well above 10^6 A/cm^2 have been achieved for conductors up to several meters in length. The required precise alignment of the grains, however, is still a costly and time consuming procedure.[10]

We have shown recently that the critical current density of grain boundaries can be increased by appropriate doping, for example by doping $YBa_2Cu_3O_{7-\delta}$ with Ca.[11] The increase of J_c achieved by doping is maintained at temperatures up to T_c if the doping is performed by employing doping heterostructures.[12] These experiments suggest to use doping also to improve coated conductors.[13] To explore whether this is possible, we measured the effects of doping on the critical current densities of $YBa_2Cu_3O_{7-\delta}$ based IBAD samples.

For these experiments, we used YSZ polycrystalline substrates covered with a IBAD YSZ layer and a $\simeq$30-nm-thick Y_2O_3 buffer layer, fabricated by Siemens in a standard process.[14] To assess the quality of the substrates they were coated with $\simeq$700-nm-thick $YBa_2Cu_3O_{7-\delta}$ layers, of which J_c was measured. The $YBa_2Cu_3O_{7-\delta}$ layers were then removed by etching and the substrates were transferred to the University of Augsburg.

On the Y_2O_3 covered substrates $\simeq$160-nm-thick $YBa_2Cu_3O_{7-\delta}$ films were grown by pulsed laser deposition from $YBa_2Cu_3O_{7-\delta}$ targets. After deposition at $\simeq$760 °C the samples were cooled within one hour to $\simeq$400 °C in an oxygen atmosphere of 0.4 bar and, after holding this temperature for 20 min, further to room temperature.

The critical current densities of one group of the samples were then measured inductively. To dope the samples, $\simeq$20-nm-thick $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ cap layers were subsequently deposited on these samples by pulsed laser deposition under the conditions given earlier. After doping, J_c was measured again. The inductive J_c measurements were performed using the self-inductance method described in Ref. 15. In this technique, steadily increasing ac-screening currents are magnetically induced in the sample by a drive current I_d flowing through a coil placed on top of the sample. The magnetic fields generated by these currents are picked up with the same coil. The detection of the drive frequency's third harmonic signals that the density of the screening currents exceeds the critical current density of the superconducting film.

For control purposes another group of samples was characterized by transport measurements. These samples were patterned by photolithography and wet etching into standard four-point configurations with 30 μm wide and 200 μm long bridges. After measuring J_c, using a 1 μV criterion, the gold contacts were removed by ion etching. Subsequently a $\simeq$20-nm-thick $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ cap layer was grown on these samples too, before the samples were again patterned to regain the original bridges.

A typical result of the inductive J_c measurements is shown in Fig. 1, in which the amplitude of the third har-

[a)]Electronic mail: jochen.mannhart@physik.uni-augsburg.de

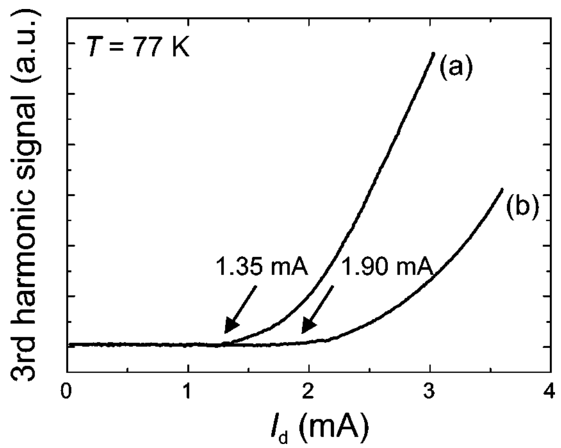

FIG. 1. Inductively measured critical currents of an IBAD sample (a) without and (b) with a Ca-doped cap layer.

monic signal is plotted as a function of I_d for a standard IBAD sample. As illustrated by this figure the critical current density of this sample was enhanced by doping by a factor of 1.4. This increase of J_c by doping is characteristic for the behavior of the whole set of samples we have studied. The samples furthermore revealed a characteristic trend: the J_c values of the samples with small critical current densities were increased by larger factors than the critical current densities of the samples which already had high J_c values before doping. This is illustrated by Fig. 2, in which for all inductively investigated samples the doping induced enhancement of J_c is plotted as a function of the critical current density measured prior to the doping on the 700-nm-thick $YBa_2Cu_3O_{7-\delta}$ films. Whereas no increase was observed on the substrate with the best texture, enhancement factors in the range of 1.4–2.2 were obtained on all other samples.

The doping induced enhancement of the IBAD samples' critical current densities was confirmed by the transport measurements. Figure 3 shows as an example the temperature dependence of the critical current density of one bridge of an IBAD sample before and after doping. Clearly, J_c is enhanced in the whole temperature range up to T_c, at 77 K by

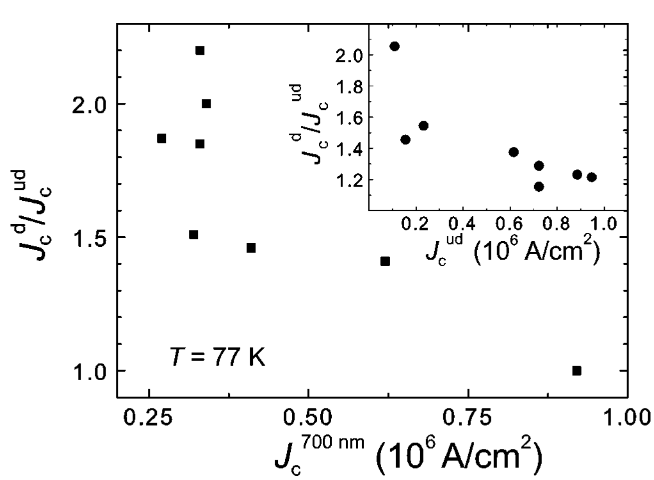

FIG. 2. Doping induced enhancements of the inductively measured critical current of the IBAD samples ($J_c^{doped}/J_c^{undoped}$) at 77 K. The critical current density is plotted as a function of the critical current density of the 700-nm-thick $YBa_2Cu_3O_{7-\delta}$ film prior to the doping ($J_c^{700\,nm}$), which reflects the substrate quality. The inset shows the doping induced J_c enhancements observed in transport experiments (77 K).

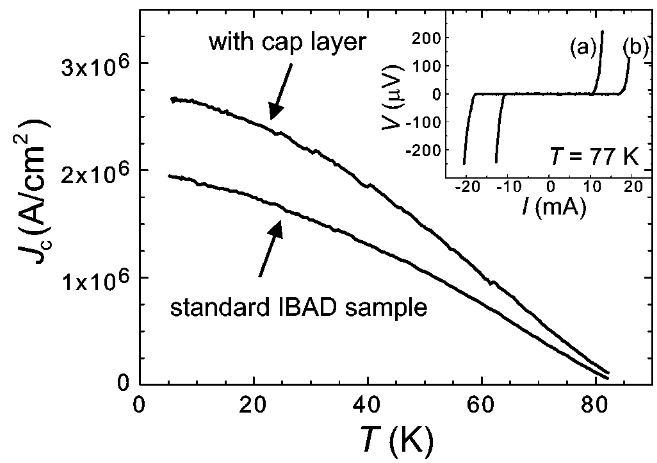

FIG. 3. Temperature dependence of the critical current density of an IBAD sample before and after Ca doping, as obtained by transport measurements. The inset shows the $I-V$ curves of (a) the undoped and (b) the doped bridge at 77 K.

a factor of 1.5, as also illustrated by the inset of Fig. 3, which depicts the $I-V$ curves of a bridge before and after doping. Doping also increased the n value of the sample, as obtained from the $I-V$ characteristics in the range of 10–100 μV. It equalled $\simeq 15$ and $\simeq 25$ for the undoped and doped sample, respectively. Like the inductive measurements, the transport experiments revealed the largest J_c enhancements for the samples with small critical current densities (see inset of Fig. 2). This behavior is consistent with earlier measurements which showed that the doping induced J_c enhancement increases with increasing grain boundary angle, i.e., with decreasing critical current density of the samples.[4]

To analyze whether doping also improves the critical current density of IBAD samples in magnetic fields H, the $J_c(H)$ characteristics of three samples were measured at 77 K by transport in magnetic fields up to 8 T applied parallel to the tape normal. The samples showed a similar behavior, and the result of one sample is plotted in Fig. 4. As shown, the J_c enhancement is found in the whole magnetic field range, and even increases considerably in fields exceeding 6 T. This effect is attributed to a shift of the irreversibility line due to a slight enhancement of T_c after doping. A comparable large doping induced J_c enhancement at 8 T was observed by Yao *et al.*[16] on 5-μm-thick $YBa_2Cu_3O_{7-\delta}$ films. In our case, the

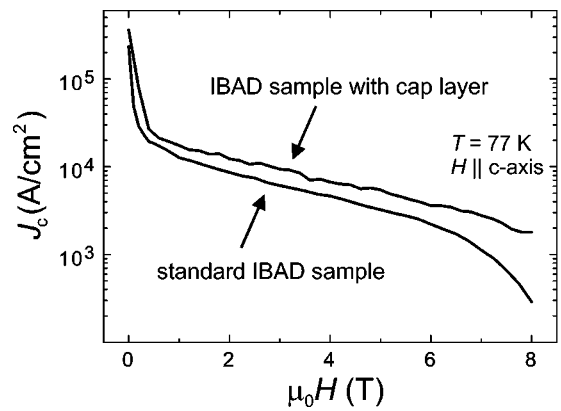

FIG. 4. Magnetic field dependence of the critical current density of a bridge of an IBAD sample before and after Ca doping (transport measurement, 77 K).

samples that had retained their T_c after doping did not show the very large enhancement in high magnetic fields, but an almost constant J_c increase over the whole field range.

In summary, the use of doping heterostructures was found to enhance the critical current density of conventional coated conductors. By doping, the critical current density of the investigated IBAD tapes was enhanced by factors as large as 2.2, at all temperatures up to T_c. At 77 K, the J_c enhancement persists in magnetic fields of at least 8 T.

The authors thank J. R. Thompson for fruitful discussions, as well as A. Herrnberger and K. Wiedenmann for their support. This work was supported by the Bundesministerium für Bildung und Forschung (Project No. 13N6918).

[1] J. G. Bednorz and K. A. Müller, Z. Phys. B: Condens. Matter **65**, 189 (1986).
[2] M. K. Wu, J. R. Ashburn, C. J. Torng, P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang, and C. W. Chu, Phys. Rev. Lett. **58**, 908 (1987).
[3] D. Dimos, P. Chaudhari, J. Mannhart, and F. K. LeGoues, Phys. Rev. Lett. **61**, 219 (1988).
[4] H. Hilgenkamp and J. Mannhart, Rev. Mod. Phys. **74**, 485 (2002).
[5] Y. Iijima, N. Tanabe, O. Kohno, and Y. Ikeno, Appl. Phys. Lett. **60**, 769 (1992).
[6] X. D. Wu, S. R. Foltyn, P. N. Arendt, J. Townsend, C. Adams, I. H. Campbell, P. Tiwari, Y. Coulter, and D. E. Peterson, Appl. Phys. Lett. **65**, 1961 (1994).
[7] D. P. Norton, A. Goyal, J. D. Budai, D. K. Christen, D. M. Kroeger, E. D. Specht, Q. He, B. Saffian, M. Paranthaman, C. E. Klabunde, D. F. Lee, B. C. Sales, and F. A. List, Science **274**, 755 (1996).
[8] K. Hasegawa, N. Yoshida, K. Fujino, H. Mukai, K. Hayashi, K. Sato, T. Ohkuma, S. Honjyo, H. Ishii, and T. Hara, *Proceedings of the International Cryogenic Engineering Conference (ICEC16), Kitakyushu, Japan, 1996* (Elsevier Science, Oxford, 1997), p. 1413.
[9] M. Bauer, R. Semerad, and H. Kinder, IEEE Trans. Appl. Supercond. **9**, 1502 (1999).
[10] R. F. Service, Science **295**, 787 (2002).
[11] A. Schmehl, B. Goetz, R. R. Schulz, C. W. Schneider, H. Bielefeldt, H. Hilgenkamp, and J. Mannhart, Europhys. Lett. **47**, 110 (1999).
[12] G. Hammerl, A. Schmehl, R. R. Schulz, B. Goetz, H. Bielefeldt, C. W. Schneider, H. Hilgenkamp, and J. Mannhart, Nature (London) **407**, 162 (2000).
[13] G. Hammerl, A. Herrnberger, A. Schmehl, A. Weber, K. Wiedenmann, C. W. Schneider, and J. Mannhart, Appl. Phys. Lett. **81**, 3209 (2002).
[14] R. Nies, W. Schmidt, B. Seebacher, B. Utz, and H.-W. Neumueller, Inst. Phys. Conf. Ser. **167**, 1025 (1999).
[15] J. H. Claassen, M. E. Reeves, and R. J. Soulen, Jr., Rev. Sci. Instrum. **62**, 996 (1991).
[16] X. Yao, D. X. Huang, K. Nomura, Y. Nakamura, T. Izumi, and Y. Shiohara, Physica C **378–381**, 107 (2002).