Improving Coated Conductors

G. Hammerl, H. Bielefeldt, S. Leitenmeier, A. Schmehl, A. Weber, C. W. Schneider, and J. Mannhart

***Abstract*—Today's coated conductor techniques are aimed to minimize by grain alignment the grain boundary problem of high-T_c superconductors.**

We present a new approach to enhance the critical current density of coated conductors, which is based on a modified microstructure of the substrate, to utilize grains with large aspect ratios. Calculations clearly show that by using such substrates critical current densities close to the intragrain J_c are possible.

***Index Terms*—Coated conductors, critical current, grain boundaries.**

I. INTRODUCTION

THE COATED conductor technology is the most promising approach to the fabrication of competitive high-T_c cables [1], [2], [3]. Nevertheless coated conductors are still limited by the grain boundary problem, characterized by the strong dependence of the critical current density on the grain boundary angle [4]–[6]. State-of-the-art technologies such as the rolling assisted biaxially textured substrate (RABiTS) process, the ion beam assisted deposition (IBAD) or the inclined substrate deposition (ISD) use grain alignment to minimize the grain boundary problem. Substrates with grain misorientations less than 4° are achievable, but currently such tapes are produced only with great effort and in short lengths. Limitations on production speed and costs provide a major hurdle on the way to cost effective, large scale applications of high-T_c superconductors [7].

Here we propose a different approach to solve the grain boundary problem. Besides a) *grain alignment* [4], we suggest to use b) *doping* [8] and c) *large effective grain boundary areas* [10]–[12] to suppress the influence of grain boundaries. By this, enhancements of the critical current densities up to values close to the intragrain critical current density appear feasible.

II. COATED CONDUCTORS CONTAINING GRAINS WITH LARGE ASPECT RATIOS

The maximum supercurrent crossing a grain boundary is given by the product of the grain boundary area and the average critical current density J_c, which is a function of the grain boundary angle θ. Therefore critical currents of polycrystalline high-T_c superconductors can be increased by enhancing the critical current density of grain boundaries with grain alignment and doping, and by enlarging the effective grain boundary areas.

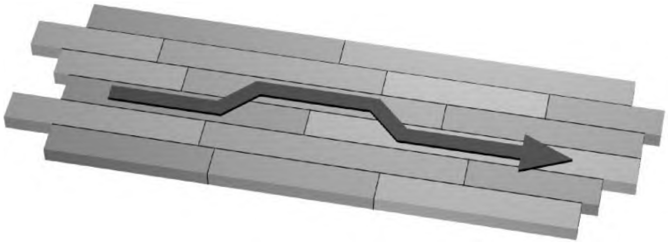

Fig. 1. Sketch of the current flow through a polycrystalline high-T_c superconductor containing grains with big aspect ratios. Large currents are supported by such a conductor, as the standard, small area grain boundaries can be bypassed (after [13]).

The utilization of grains with large grain boundary areas was conceived very early, when the use of meandering current paths as shown in Fig. 1 was proposed [13]. The success of the powder-in-tube technology employing many platelet-like superconducting grains stacked on top of each other is based on such meandering currents [6], [13]–[15].

To apply this principle to coated conductors, we have suggested modifying the microstructure of the substrates, so that the tapes primarily contain grains with big aspect ratios of, for example, grain length to grain width [10]–[12]. By this, substrates are obtained that can be used for the fabrication of coated conductors with very large critical currents.

To analyze the influence of highly aspected grains on the performance of the tapes, we calculated the critical current of such tapes at 77 K using an algorithm developed for this purpose [12]. This algorithm is based on Dijkstra's shortest path algorithm [16], which works on undirected graphs. A grain boundary network is interpreted as a graph with grains acting as edges and grain boundaries as vertices, weighted by their critical currents. In our case, the *shortest path* corresponds to the *path with the highest critical current*, therefore Dijkstra's original algorithm had to be adapted accordingly. In the calculations, self fields and phase effects were neglected.

As in other calculations (see, e.g., [17], [18]), the algorithm initially generates a grain boundary network with a given geometry determined by the aspect ratio ρ of the grains and the distribution of the grain boundary angles σ, which is chosen to be Gaussian. In order to get a consistent grain boundary angle network, each grain is assigned a grain angle relative to one edge of the tape. Obviously, the grain boundary angle between two grains is found as the difference of the involved grain angles.

After initializing, the algorithm proceeds in steps, in each step i in Dijkstra's sense the shortest path through the network is found, which carries a current I_i. This current is either limited by a grain or by a grain boundary in the path, which then is removed from the network model. The critical currents of the remaining grains and grain boundaries of this particular path are then reduced by I_i. After all possible paths have been obtained

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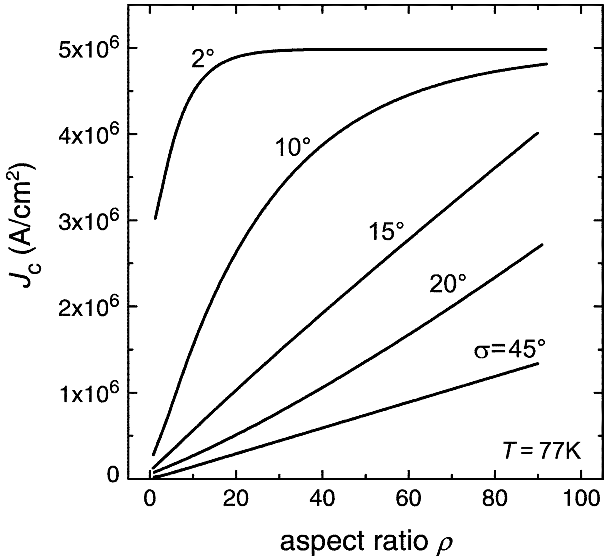

Fig. 2. Calculated dependence of the critical current density J_c of RABiTS tapes as a function of the grain aspect ratio ρ for various spreads of misorientation angles σ.

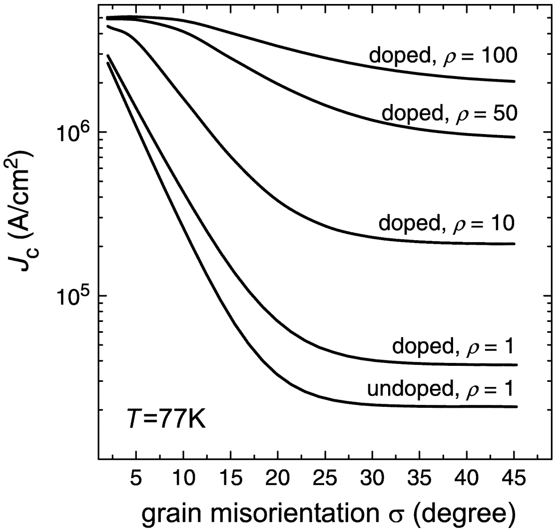

Fig. 3. Calculated dependence of the critical current density as a function of the average grain misorientation σ and doping for several aspect ratios ρ (from [12]).

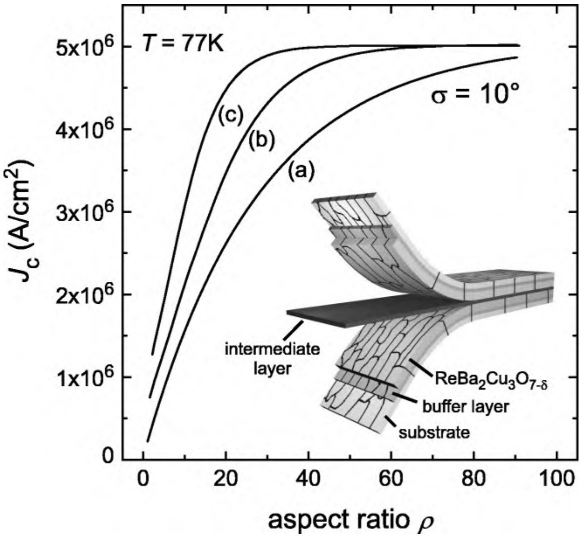

Fig. 4. Calculated dependence of the critical current density as a function of the aspect ratio ρ of two RABiTS tapes with misorientation $\sigma = 10°$ stacked on top of each other with coupling factors: (a) $f_c = 0$, (b) 10^{-4}, and (c) 10^{-3}. The inset shows a sketch of such a tape, the intermediate layer is used to weld the two tapes together (from [12]).

this way, the overall critical current I_c of the tape is determined by adding all I_i. These calculations are repeated at least 20 times on different networks with identical input parameters, but randomly chosen grain lengths and grain angles within the given distributions. By averaging the intermediate results, the value of the critical current is obtained with a statistical accuracy better than 5%.

With this algorithm the critical current density of realistic model tapes was calculated. For this, the intragrain critical current density $J_{c,\mathrm{grain}}$ (77 K) was taken to be $5 \cdot 10^6$ A/cm^2. The size of the model tapes was 2 mm by 3 cm, and the tapes contained between 500 and 10 000 grains. Control calculations on larger tape sizes provided the same results.

In Fig. 2 the calculated influence of the average grain aspect ratio ρ on the critical current density is plotted for a series of grain misorientation spreads σ. The plot clearly shows that the critical current density of RABiTS tapes increases significantly with increasing grain aspect ratio ρ. For example, with $\rho = 20$ and misorientation angles of $\approx 10°$ the same J_c values are achieved as for state-of-the-art tapes $(\rho \approx 1)$ with today's best textures of about 2°. Using an aspect ratio of $\rho = 20$, for tapes with misorientations of 2° the critical current density is nominally equal to the intragrain J_c.

We recently have shown that preferential doping of the grain boundaries significantly enhances the transport properties of high-T_c superconductors [8], even in high magnetic fields [9]. To study the influence of doping superconductors with highly aspected grains, the grain boundaries critical current densities have to be increased. Therefore in the calculations the $J_c(\theta)$ dependence was modified to describe doped grain boundaries. The $J_c(\theta)$ characteristic used for this is based on the experimental data, which show that in the range of $24° < \theta < 36°$ the critical current density can be doubled by doping [8]. For lower and higher angles, J_c is taken to be reduced exponentially to the undoped values. With this modification our algorithm is able to simulate grain boundary doping. The effect of preferential doping and elongation of the grains on the critical current density is illustrated in Fig. 3. As compared to standard, undoped RABiTS tapes $(\rho = 1)$, doping enhances J_c for all misorientations σ. For $\sigma > 15°$, the J_c values are doubled, in agreement with experimental results. By further increasing the aspect ratio ρ, J_c is significantly enhanced. The calculations predict that untextured tapes with $\sigma = 45°$ and $\rho = 50$ support the same J_c values as conventional, state-of-the-art RABiTS tapes aligned to 6°. For aspect ratios $\rho \gtrsim 50$, the exponential drop of $J_c(\sigma)$, i.e., the core of the grain boundary problem, has almost disappeared.

Further, we considered utilizing large effective grain boundary areas by stacking two RABiTS tapes on top of each other, taking into account that the coupling between the two layers is reduced due to the interface and small c-axis critical current densities. For this, a coupling factor $f_c < 1$ for critical currents flowing between the two tapes was introduced. The lateral mismatch of the grains in the top and bottom layer was chosen to be 30% of the grain width.

The results of the calculations performed for two undoped RABiTS tapes stacked on top of each other is presented in Fig. 4. Assuming a coupling strength of $f_c = 10^{-3}$, J_c is enhanced by a factor of 5 for conventional RABiTS tapes with a given grain alignment of 10°. With increasing aspect ratio ρ however, the enhancement in J_c achievable by stacking two tapes is reduced. Stacking tapes on top of each other only provides large advantages for tapes with $\rho \lesssim 10$.

III. SUMMARY

We suggested and have shown by model calculations that the critical current density of coated conductors can be improved significantly by using preferential doping and grain architectures characterized by grains with large aspect ratios. By this, a possible solution of the grain boundary problem has been found. For tapes with aspect ratios $\rho \cong 20$ to 50, moderate texturing $(\sigma \approx 10^\circ)$ and doping is found to be sufficient to achieve critical current densities of $4 \cdot 10^6$ A/cm^2 at 77 K, values close to the intragrain J_c.

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