# Magnetic properties of $(Nd_{0.33}Eu_{0.33}Gd_{0.33})Ba_2Cu_3$-$O_y$ doped by additional Gd-211 particles

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**Abstract:** Magnetic hysteresis loops were measured on a series of $(Nd_{0.33}Eu_{0.33}Gd_{0.33})$-$Ba_2Cu_3O_y$ (NEG) samples melt-grown in a reduced oxygen atmosphere with additions of different concentrations of $Gd_2BaCuO_5$ (Gd-211) particles. Measurements were conducted by means of a SQUID magnetometer in fields up to 7 T, $5 \leq T \leq 92$ K. The hysteresis loops exhibit a strong peak effect in a wide range of temperatures. Scaling properties were studied and interpreted in terms of a phenomenological model for RE-123 materials. It is shown that a dispersion of fine Gd-211 particles is very effective in increasing the critical current density.

**Key words:** Current densities, pinning forces, scaling, $(Nd_{0.33}Eu_{0.33}Gd_{0.33})Ba_2Cu_3O_y$ superconductors

## INTRODUCTION

The embedding of small normal-conducting particles into melt-textured superconductors is way to increase the flux pinning strength. Depending on the size of the particles, this pinning is mainly effective at low temperatures/low fields. The newly developed NEG superconductors were found to exhibit a strongly developed peak (fishtail) effect [1]. To increase the critical current density, $J_c$, even further, we added (Nd,Eu,Gd)-211 particles with the same ratio as in the NEG-123 matrix. By TEM analysis, it was found that we indeed obtain submicron-sized 211 particles, but the particles consist mainly of Gd in the rare earth site [2]. Therefore, we attempt the addition of various amounts of Gd-211 to the starting composition.

## EXPERIMENTAL

Powders of $Nd_2O_3$, $Eu_2O_3$, $Gd_2O_3$, $BaCO_3$ and CuO were weighed to have a nominal composition of $(Nd_{0.33}Eu_{0.33}Gd_{0.33})Ba_2Cu_3O_y$ (NEG). These powders were ground thoroughly and calcinated at 880 °C for 24 h with intermediate grinding, which was repeated three times, and were then pressed into pellets and sintered at 1020 °C for 48 h. NEG bulk samples with a volume fraction of 10 (A), 20 (B), 30 (C) and 40 mol% (D) of Gd-211 secondary phase were prepared using a mixture of sintered NEG and commercial Gd-211 powders. Since the Pt addition is known to be effective in refining the size of Y-211 in the YBCO system, we added 0.5 mol% Pt to the starting powders. More details of the sample preparation can be found in Refs. [3, 4] Finally, the samples are cut into a cubic shape with dimensions 1 × 1.5 × 0.3 mm$^3$. $T_{c,onset}$ of all the samples is around 93.5 K. Magnetization loops are obtained using a Quantum Design MPMS-7 SQUID magnetometer equipped with a 7 T superconducting magnet; $H_a \parallel c$. The homogeneity of all samples was checked by magneto-optic imaging [5].

## RESULTS AND DISCUSSION

The field dependence of the critical current density, $J_c(B)$ for samples A, B, C, and D, is presented in Fig. 1, measured at $T = 77$ K. All samples show a pronounced fishtail (peak) effect. The position of the fishtail peak is always found at ≈ 2.5 T. Only sample D shows

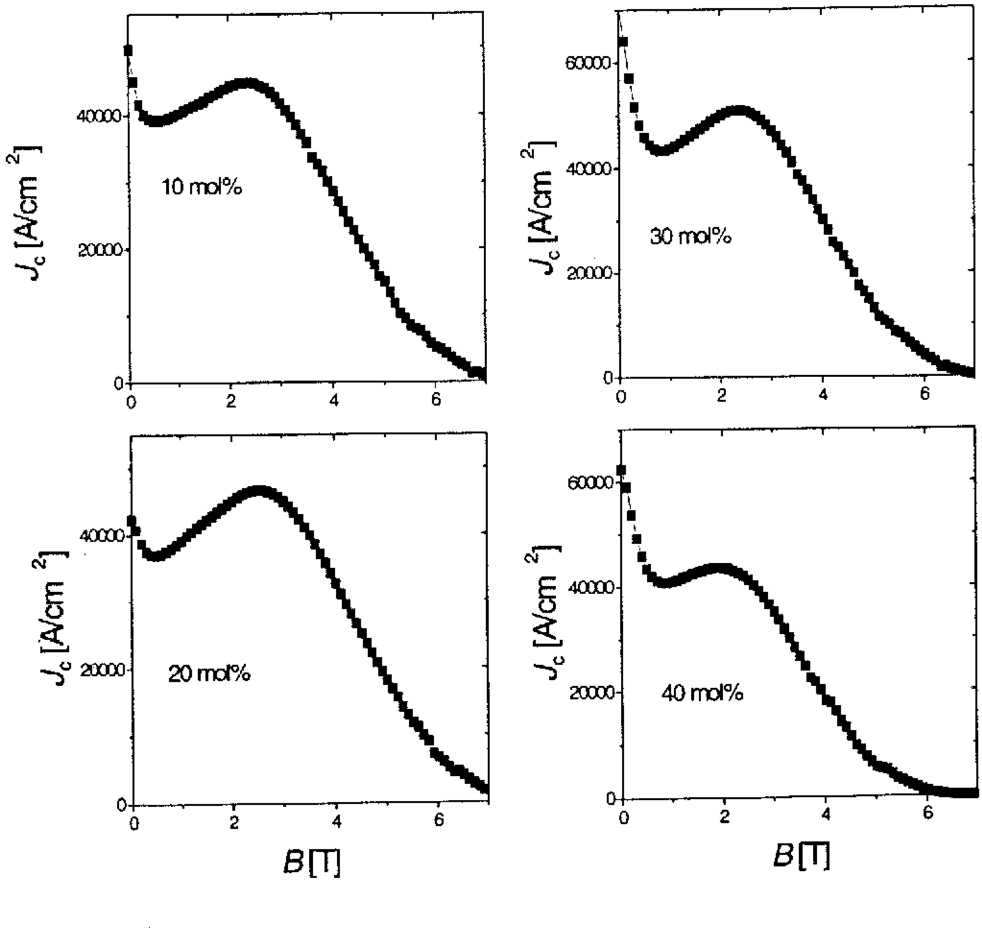


Fig. 1. $J_c(B)$ of all samples A – D with different Gd-211 content, measured at $T = 77$ K.

a somewhat reduced peak field. The current density, $J_c(0)$, is increasing on increasing Gd-211 content. This demonstrates that the submicron-sized Gd-211 particles [2] are effective to increase the pinning at low fields, but an addition of a too high amount of Gd-211 particles as in the case of sample D clearly affects the properties of the superconducting NEG matrix. Note that $J_c$ is largest for sample C. Therefore, an addition of 30 mol% Gd-211 particles seems to be the optimum, as shown in Ref. [2].

To analyze the pinning properties of superconductors, the scaling of the current densities, $J_c$, or volume pinning forces, $F_p = J_c \times B$, plays an important role [6, 7, 8]. In Ref. [9], an empirical formula was developed

$$f(b_{\mathrm{f}}) = b_{\mathrm{f}}^{m+1} \exp\left[\frac{m+1}{n}(1 - b_{\mathrm{f}}^{n})\right] \quad , \tag{1}$$

with $b_{\mathrm{f}} = B_{\mathrm{a}}/B_{\mathrm{fp}}$ and $f = F_{\mathrm{p}}/F_{\mathrm{p,max}}$ are the applied field and the pininning force density normalized with respect to the coordinates of the fishtail maximum ($B_{\mathrm{fp}}$, $F_{\mathrm{p,max}}$). Jirsa and Půst [9] showed that eq. (1) is capable to describe the scaling of various 123 superconductors found in literature with $m = 1$ and leaving $n$ as the only free parameter. For a fixed position of the fishtail peak $n$ can be interpreted as a measure of the width of the normalized fishtail curve. Alternatively, $n$ represents a measure of the mutual position of $B_{\mathrm{p}}$ and $B_{\mathrm{irr}}$, where $B_{\mathrm{irr}}$ denotes the irreversibility field. The higher $n$, the lower the ratio $B_{\mathrm{irr}}/B_{\mathrm{p}}$, i.e. a high $n$ indicates that the fishtail peak lies close to irreversibility field. It is now important to relate the parameters $m$ and $n$ with microstructural features. In fig. 2, we present the scaling of samples A and D, where we expect to observe differences as revealed from the current density measurements (fig. 1).

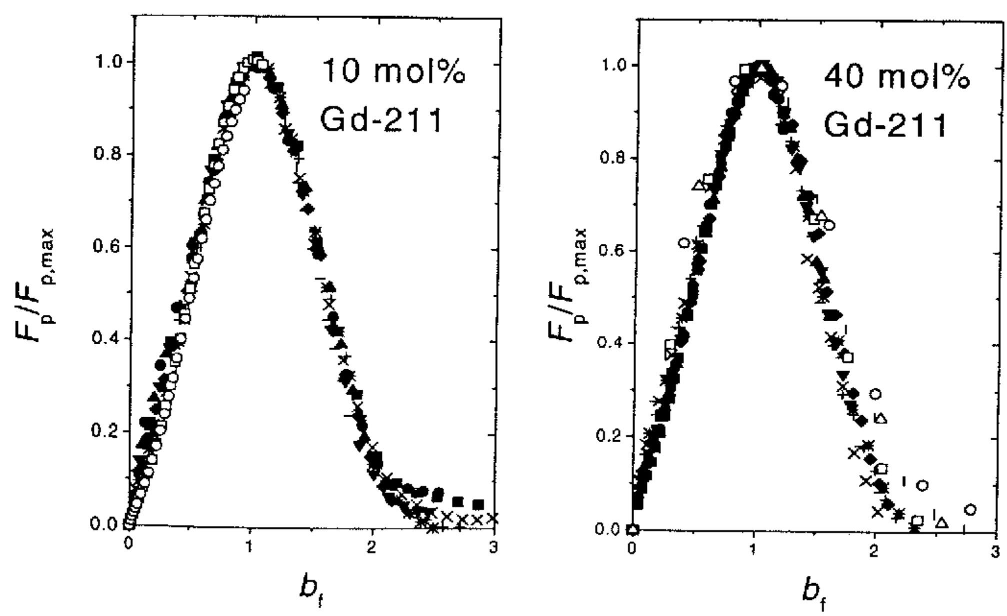


Fig. 2. $F_{\mathrm{p}}$-scaling of sample A and D at temperatures between 60 K and 90 K. The scaling is found to be excellent; in sample D some deviations from the ideal behaviour occur.

The scaling was performed using data between 60 K and 90 K, where all necessary parameters are directly accessible to experiment. The scaling of both samples is excellent; the parameter $n$ is determined to 2.34 (sample A) and 2.13 (sample D). However, the fitting of sample D reveals some important differences: The data at low $b_f$ increase faster than the best fit to eq. (1). This indicates that at low fields, there is a strong contribution to the pinning by the normal conducting particles. The data taken at temperatures above 84 K also show a deviation at the low field side. As discussed in Ref. [1], the main source of pinning in the NEG compounds is of the $\delta T_c$-type. These pinning sites may become normal at elevated temperatures. The shape change of the $j_c(B)$ curves and the deviation in the scaling of sample D may therefore indicate that the dominant pinning mechanism changes from $\delta T_c$ to $\delta l$-type (i.e. pinning at normal-conducting particles).

## CONCLUSIONS

The addition of Gd-211 particles is effective to increase the pinning strength at low fields: the optimum content is found to be 30 mol%. The scaling of the volume pinning forces is found to be excellent, with $n$ ranging between 2.13 and 2.34.

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