Unusually high critical current of clean P-doped BaFe$_2$As$_2$ single crystalline thin film

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Microstructurally clean, isovalently P-doped BaFe$_2$As$_2$ (Ba-122) single crystalline thin films have been prepared on MgO (001) substrates by molecular beam epitaxy. These films show a superconducting transition temperature ($T_c$) of over 30 K although P content is around 0.22, which is lower than the optimal one for single crystals (i.e. 0.33). The enhanced $T_c$ at this doping level is attributed to the in-plane tensile strain. The strained film shows high transport self-field critical current densities ($J_c$) of over 6 MA/cm$^2$ at 4.2 K, which are among the highest for Fe based superconductors (FeSCs). In-field $J_c$ exceeds 0.1 MA/cm$^2$ at $\mu_0H = 35$ T for $H || ab$ and $\mu_0H = 18$ T for $H || c$ at 4.2 K, respectively, in spite of moderate upper critical fields compared to other FeSCs with similar $T_c$. Structural investigations reveal no defects or misoriented grains pointing to strong pinning centers. We relate this unexpected high $J_c$ to a strong enhancement of the vortex core energy at optimal $T_c$, driven by in-plane strain and doping. These unusually high $J_c$ make P-doped Ba-122 very favorable for high-field magnet applications.

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Figure 1: Structural data of the P-doped Ba-122 thin film. (a) $\theta - 2\theta$ scan showing the c-axis oriented growth. (b) $\phi$-scan of the (103) reflection of the Ba-122 and the (220) reflection of the MgO substrate proving the cube-on-cube film growth. (c) Rocking curve of the (004) reflection (d) TEM image near the interface between the MgO substrate and the Ba-122 phase.

Figure 2: Field dependence of the resistive transition for the P-doped Ba-122 thin film for $H\|ab$ (top) and $H\|c$ direction (bottom). The field steps are 2.5 T. The inset shows the temperature dependence of the resistivity from 2 K up to 300 K in zero field.
tensile strain in the underdoped regime for P-doped Ba-122 enhances $T_c$. The normal state resistivity shows a linear temperature dependence below 100 K (inset of Fig. 2), which is a typical behavior for optimally P-doped Ba-122. Therefore, the tensile strain shifts the superconducting transition of our film to higher values compared to a $T_c$ of higher P concentrations without strain, a dependency which has been observed for Co-doped Ba-122 thin films as well.

In Fig. 3, the temperature dependence of the upper critical field $J_c$ for our P-doped Ba-122 film is compared to other $J_c$ results reported for FeSCs. It is seen that P-doped Ba-122 shows the highest self-field $J_c$ values among other FeSCs. Note, that even SmFeAs(O,F) (Sm-1111) with a much higher $T_c$ of 54 K shows smaller $J_c$ values. Our clean P-doped Ba-122 film presents a self-field $J_c$ of about 6.3 MA/cm$^2$ at 4.2 K, which is almost 7% of the depairing current density. We assume that this $J_c$ could be further increased by adding additional pinning centers. As can be seen in Fig. 3, the film prepared by the same method but with an excess of Fe content during the growth has twice the value of $J_c$. The field dependence of $J_c$ at various temperatures is summarized in Fig. 4a. The $J_c$ values for $H \parallel c$ ($J_{c,H \parallel c}$) are always lower than those for $H \parallel ab$, and no feature close to $H \parallel c$ is observed in Fig. 4a. These findings indicate the absence of $c$-axis correlated pinning and that the material anisotropy dominates the general $J_c$ trend. The pinning force density ($F_p$) calculated according to $F_p = H \times J_c$ at 4.2 K shows values up to 77 GN/m$^3$ (at 15 T) for $H \parallel ab$. The data for $H \parallel c$ show a maximum of around 35 GN/m$^3$ at around 10 T. Compared to the results presented by Miura et al. and Adachi et al., our film showed slightly higher values which might be due to the higher $T_c$. In particular, $J_c$ at 35 T $H \parallel c$ is as high as $J_{c,H \parallel c} = 1.1 \times 10^4$ A/cm$^2$. In general, $J_c$ of optimally P-doped films is quite robust against applied magnetic fields. The question arises why our microstructurally clean film exhibits such high $J_c$ values. Usually, a high density of defects is necessary to achieve high $J_c$. However, we did observe neither crystal structure defects nor impurity phases in our films (Fig. 1). Alternatively, it has been shown by Putzke et al. that the vortex core energy of the flux lines is enhanced close to the optimal doping. Therefore, we suppose that this high vortex core energy is a key factor responsible for the unusually high $J_c$ in optimally P-doped Ba-122. In this context, comparable $J_c$ values of the P-doped Ba-122 with $T_c$ around 25 K containing BaZrO$_3$ particles or strong pinning centers could be explained by the reduction of the vortex core energy due to non optimal $T_c$.

In Fig. 3, the angular dependence of $J_c$ ($J_c(\theta)$) measured at 4.2 K and various fields up to 35 T. $J_c$ has a broad maximum positioned at $\theta = 0^\circ$ ($H \parallel ab$) and no prominent $J_c$ peaks at $\theta = 90^\circ$ ($H \parallel c$). Low $J_c(H)$-anisotropy values ($\gamma_{J_c} = J_{c,H \parallel ab}/J_{c,H \parallel c}$) of around 2 approaches to 15 T at 4.2 K are observed, increasing for higher fields. Noteworthy is the observation of a small shoulder near the $ab$-peak, marked with arrows. It shifts to lower angles when the magnetic field is increased. Such shoulders are known from cuprates and exist usually due to strong correlated defects, such as in double-perovskite-doped YBa$_2$Cu$_3$O$_7$ (YBCO) thin films, or due to uncorrelated defects, as shown in Fig. 4c: these findings indicate the absence of $c$-axis correlated pinning and that the material anisotropy dominates the general $J_c$ trend. The pinning force density ($F_p$) calculated according to $F_p = H \times J_c$ at 4.2 K shows values up to 77 GN/m$^3$ (at 15 T) for $H \parallel ab$. The data for $H \parallel ab$ show a maximum of around 35 GN/m$^3$ at around 10 T. Compared to the results presented by Miura et al. and Adachi et al., our film showed slightly higher values which might be due to the higher $T_c$. In particular, $J_c$ at 35 T $H \parallel c$ is as high as $J_{c,H \parallel c} = 1.1 \times 10^4$ A/cm$^2$. In general, $J_c$ of optimally P-doped films is quite robust against applied magnetic fields. The question arises why our microstructurally clean film exhibits such high $J_c$ values. Usually, a high density of defects is necessary to achieve high $J_c$. However, we did observe neither crystal structure defects nor impurity phases in our films (Fig. 1). Alternatively, it has been shown by Putzke et al. that the vortex core energy of the flux lines is enhanced close to the optimal doping. Therefore, we suppose that this high vortex core energy is a key factor responsible for the unusually high $J_c$ in optimally P-doped Ba-122. In this context, comparable $J_c$ values of the P-doped Ba-122 with $T_c$ around 25 K containing BaZrO$_3$ particles or strong pinning centers could be explained by the reduction of the vortex core energy due to non optimal $T_c$.

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by extended structural defects and often also by a strong c-axis peak in a certain magnetic field range. For our films, we did not observe any extended or correlated defects in TEM images nor any sign of off-axis peak by XRD. Therefore, the reason for these shoulders may lie in a possible variation of the P-content. For example, nanoscale regions of non-optimal P-content (not observable in TEM) of size slightly larger than the coherence lengths might act as uncorrelated strong pinning centers due to the unusually strong P-content dependence of the vortex core energy. These possible P-inhomogeneities in combination with the inequality of λ and ξ anisotropy as in the FeSCs can lead to such shoulders, as was shown by van der Beek et al. The presence of the pinning centers is further evidenced by the \( J_c(T) \) dependence at intermediate and high temperatures (Fig. 4b). Additional artificial disorder in the form of Fe impurities enhances the strong pinning resulting in a \( J_c(T) \) dependence consistent with the \( \delta \) pinning scenario in the whole temperature range. Thus, we believe pinning driven by differences in the vortex core energy enhances \( J_c \) values of the optimally P-doped Ba-122 well above all other FeSCs.

There is still room for further increase in \( J_c \) of the P-doped Ba-122 thin films, like doping with pinning-promoting particles the way it was done by Miura et al. in combination with optimal growth, and high crystalline quality. Additionally, a high concentration of a secondary phase like Fe can be incorporated into the superconducting matrix as artificial pinning centers for \( J_c \) increase without detrimental decrease in \( T_c \). This implies that the \( J_c \) anisotropy can be reduced while maintaining high \( T_c \) as well as \( J_c \). The unusually high critical currents makes the P-doped Ba-122 one of the most promising materials among FeSCs for the study of the superconducting pairing mechanisms and high field applications.

To conclude, using MBE we have fabricated P-doped Ba-122 thin film directly on MgO achieving epitaxy and phase purity with a high \( T_c \) of 30.7 K. We measured the field and the angle dependence of \( J_c \) up to 35 T. A very high self field \( J_c \) of 6.3 MA/cm² at 4.2 K was observed even though no structural defects were found in TEM and XRD. This observation suggests that in the optimally doped P-doped Ba-122 compound rather weak structural...
inhomogeneities result in strong pinning centers. This unusual pinning enhancement is explained by a sharp maximum in the vortex core energy near to the optimal doping.

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