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Upper critical fields and critical current densities of Fe-based superconductors as compared to those of other technical superconductors

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ABSTRACT

Three years since the discovery by the Hosono's group of Fe-based superconductors, an enormous number of compounds, belonging to several different families have been discovered and fundamental properties have been deeply investigated in order to clarify the interplay between magnetisms and superconductivity in these compounds. Indeed, the actual potential of these compounds for practical applications remains still unclear.

Fe-based superconductors are midway between high temperature superconductors (HTSCs) and MgB_2. In Fe-based superconductors the critical current is rather independent of the field, similarly to HTSCs, as a consequence of the exceptionally high upper critical field and strong pinning associated with nm-scale local modulations of the order parameter. They exhibit low anisotropy of the critical current with respect to the crystalline directions, as in the case of MgB_2, which allows current flow along the *c*-axis. However, Fe-based superconductor polycrystalline materials currently available still exhibit electromagnetic granularity, like the HTSCs, which suppresses superconducting current flow over long length. Whether the nature of such granularity is extrinsic, as due to spurious phases or cracks between grains or intrinsic, as related to misalignment of adjacent grains, is under debate. These aspects will be reviewed in the light of the recent literature.

1. Introduction

The modern age of superconductivity started in 1986 with the discovery by Bednorz and Müller of high-temperature superconductors (HTSCs), where an exotic coupling mechanism yields a critical temperature, T_c, above liquid nitrogen temperature (77 K). Till now many of the promises of these materials have not been kept: in fact, on the one hand we are still far from a full understanding of the coupling mechanisms and, on the other hand, due to the structural complexity, anisotropy, and bad metallicity of these compounds, only a few niche applications have been realized.

The new century has started with the discovery of MgB_2 [1]. In this case it was soon understood that conventional electron–phonon coupling in a complex multiband framework determines superconductivity at $T_c = 40$ K. This simple, metallic, cheap, light compound has just proved to be suitable for cryogen-free applications.

Finally, in February 2008, the discovery of a Fe-based superconductor (FeSC), $LaFeAs(O_{1-x}F_x)$ with T_c of 26 K, was announced by the group of Hosono [2]. This event prompted an army of physicists and chemists to discover other different families (the most studied are called "1111" for REFeAsO, "122" for AFe_2As_2, "111" for AFeAs, "11" for Fe(Te, Se)) with critical temperatures, in the optimally doped compounds, ranging from 55 K [3] to 19 K and incredibly high upper critical fields.

Two years after Hosono's discovery two crucial questions arise: the first is, will FeSC be instrumental in deciphering the 22-year-old mystery behind high-T_c superconductivity? The second is, will FeSCs be simpler and more suitable materials for applications than the HTSCs? In this paper we will try to address the latter issue, reviewing the most recent results on the critical current density of single crystals, films, polycrystals wires and tapes of FeSCs, also in comparison with data on high-T_c cuprates and technical superconductors. At the present stage, no conclusive answer can be given yet on the actual application potential of these compounds and further studies are clearly needed, on all FeSC families.

2. Basic properties of Fe-based superconductors

FeSCs share several characteristics with HTSCs, such as the layered structure, the coexistence of different orderings, the

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occurrence of superconductivity upon doping, the small coherence length, and non-conventional pairing. Some of these aspects have shown to be unsuitable for practical application. On the other hand FeSCs exhibit several advantages with respect to HTSCs; namely, they are metallic in the parent compounds, the anisotropy is generally smaller and not strongly dependent on the level of doping, the supposed order parameter symmetry seems to be different, and in principle not so detrimental to current transmission across grain boundaries (GBs), impurities do not significantly affect T_c.

FeSCs share characteristics also with the more conventional MgB_2. The most remarkable one is the multiband nature that has offered unprecedented tools in MgB_2 to tune and improve the superconducting properties and needs to be carefully investigated also in FeSC.

Moreover, FeSCs appear to be extremely versatile in terms of chemical composition, as they belong to a comprehensive class of materials, where many chemical substitutions are possible and their layered structure allows designing new FeSC with composite structures or even artificial multilayers. This versatility could enable the superconducting properties to be tailored for commercial technologies.

We will now review the most relevant properties for applications.

3. Upper critical fields

Since the earliest stages of the research on FeSCs, it has been apparent that they are characterized by very high *upper critical field* values (H_{c2}), which is one of the main requirements for having a good in-field behaviour of the critical current density. The first magnetotransport measurements in high fields have been carried out on the 1111 phase [4–6]. The shape of the 1111 resistive transition is significantly broadened by the magnetic field [5,4], but to a smaller extent than in the high-T_c cuprates. The extracted upper critical field curves exhibit a distinctive upward curvature, reminiscent of the MgB_2 behaviour [7], which is a signature of the multiband character. H_{c2} values of up to 60 T and H_{c2}-slopes close to T_c between −10 T/K and −15 T/K have been measured [5,8]. The H_{c2} anisotropy is between 5 and 9 close to T_c [5,8] and its slight temperature dependence is again indicative of multiband behaviour. On the other hand, as a consequence of the broadening of the transition, the irreversibility field H_{irr} (defined as the field where the resistivity becomes zero) is much smaller than H_{c2} (defined at the onset of the transition). This feature, which is an obvious drawback for applications, is very common in HTSC cuprates and strongly related to their anisotropic nature, the nearly 2D-character of these compounds and a signature of the weakness of flux pinning and/or the significance of thermal fluctuations.

A strikingly different H_{c2} behaviour has been observed in the 122 phase. The in-field 122 resistive transition exhibits no broadening [9], much like the behaviour of low-T_c superconductors [10], where the effect of the magnetic field is an almost rigid shift of the transition to lower temperatures. Consequently, the H_{irr} curve closely follows the H_{c2} curve. The H_{c2} anisotropy is 1.5–2 close to T_c and rapidly approaches unity with decreasing temperature [11,12]. This behaviour of the anisotropy is a consequence of approaching the paramagnetic limit, responsible for the downward curvature of H_{c2} for H parallel to the Fe planes. On the whole, the H_{c2} values of this family are smaller than those of the 1111 family, with H_{c2} slopes close to T_c around −5 T/K [9,11,12].

The magnetoresistance behaviour of the 11 family is midway between the fan-shaped one of the 1111 phase and the rigidly shifted one of the 122 phase [8,13]. The H_{c2} slopes close to T_c are the largest among FeSCs, ranging from −10 T/K to −30 T/K [14,15,13,8]. Very recently, huge values of H_{c2} slopes as large as −500 T/K have been measured in thin films [16]. Such values indicate an almost complete suppression of the orbital pair-breaking, possibly as a consequence of the inhomogeneous Fulde–Ferrel–Larkin–Ovchinnikov (FFLO) state which forms below 5–6 K by applied strain. This finding is of crucial importance in driving future experimental investigations on H_{c2}, as it may suggest that the H_{c2} enhancement can be better tuned by doping and strain than by the conventional disorder tuning. The H_{c2} anisotropy in the 11 family quickly decreases to unity with decreasing temperature and even becomes smaller than unity at the lowest temperatures [15] as a consequence of approaching the paramagnetic limit, which bends the H_{c2} curves to downward curvatures for both field directions.

In Fig. 1, typical H_{c2} curves of the 1111, 122 and 11 families for field parallel and perpendicular to Fe planes are shown.

As can be seen in Table 1, FeSCs show the largest H_{c2} slopes close to T_c in comparison with all other HTSC. This is a point of strength of FeSCs making them suitable for high field applications.

On the whole, the *anisotropy* of FeSCs is smaller than that of the $YBa_2Cu_3O_{7-\delta}$ (YBCO) family, where values from 4 to 14 have been reported [18] and much smaller than that of the $Bi_2Sr_2CaCu_2O_x$ (BSCCO) family, where it is typically in the range 50–60 [24]. This is a very important point because the anisotropic, nearly two-dimensional nature of high-T_c cuprates is the main reason for the weakness of the pinning and the significance of thermal fluctuations, which cause the broadening of the transition.

The different behaviour of the broadening of the transitions in these superconductors is understood if the *coherence lengths* ξ are considered. Rough estimates of ξ obtained from the H_{c2} slopes at T_c are reported in Table 1 (2.1, 2.9 and 1.5 nm along the Fe planes, for the 1111, 122 and 11 families, respectively) [8]. These values must be compared with the distance d between the Fe–As planes, in order to establish the two-dimensional or three-dimensional character of superconductivity and consequently the degree of dissipation in a magnetic field. The values of d are around 0.86, 0.65 and 0.6 nm in the 1111, 122 and 11 families, respectively. Therefore, the 122 family appears to be the most promising for applications in this respect, with the largest ξd ratio among the FeSCs.

Broadening of the transition in zero field is caused by *thermal fluctuations*, which can be parameterized by the Ginzburg number $Gi = (\pi\lambda_0^2 k_B T_c \mu_0 / 2\xi_c \Phi_0^2)^2$ where λ_0 is the London penetration depth at zero temperature, k_B the Boltzmann constant, Φ_0 the magnetic flux quantum. Typical values of $Gi \approx 4 \times 10^{-4}$, 1.5×10^{-5}, 1×10^{-3} for the 1111, 122 and 11 families [8] should be compared to $Gi \approx 5 \times 10^{-4}$ for $YBa_2Cu_3O_{7-\delta}$ and 10^{-5} for MgB_2. Again the 122 family seems to be the most promising for applications, as its slightly lower T_c and lower anisotropy yield reduced thermal fluctuations.

4. J_c in single crystals and thin films

Measurements of the critical current density J_c in *single crystal samples* of FeSCs have revealed a promising combination of high and nearly isotropic critical current densities along all crystal directions. Moreover, J_c is rather independent of the field at low temperatures, similarly to observations in $YBa_2Cu_3O_{7-\delta}$ [25]. Such a behaviour is consistent with the nm-scale coherence lengths, the exceptionally high H_{c2} values and the pinning associated with atomic-scale defects, resulting from chemical doping or nm-scale local modulations of the order parameter [26]. For the 1111 family, a high in-plane J_c of 2×10^6 A cm^{-2} at 5 K in a $SmFeAsO_{1-x}F_x$ crystal, almost field-independent up to 7 T at 5 K, has been reported [27,28]. Many single crystal results have been reported for the 122 system, since larger crystals can easily be grown. Significant fishtail peak effects and large current carrying capability up to 5×10^6 A cm^{-2} at 4.2 K have been found in a K-doped $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystal [29]. Fishtail effect and currents in