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Current status of iron-based superconductors

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Abstract Current status of iron-based superconductors is summarized. Although short range magnetic ordering and magnetic phase separation of Fe are controversial, (long range) magnetic and electronic phase diagrams of iron based superconductors can be classified into two-type. Antiferromagnetic ordering of itinerant Fe does not coexist with superconducting phase of $SmFeAsO_{1-x}F_x$. The very large H_{c2} of iron-based superconductors attract us to attempts at applications.

Keywords Iron-based superconductors · Applications · ^{57}Fe Mössbauer effect · Critical magnetic field · Superconducting critical current density

1 Iron-based superconductors

Although iron and iron-based compounds are representative ferromagnetic and/or ferrimagnetic materials, a considerable number of iron-based compounds have been reported as exhibiting superconductivity. Figure 1 shows superconductors containing itinerant Fe 3d electrons which had been reported before 2005. Intermetallic compounds [U_6Fe, Th_7Fe, Zr_2Fe, $R_2Fe_3Si_5$ (R = Sc, Y, Lu, and Tm)] and rare-earth filled skutterudites [$LnFe_4P_{12}$ (Ln = La, Y)], whose superconducting transition temperatures ranged from 1.8 to 7 K, show Pauli paramagnetic behavior in the

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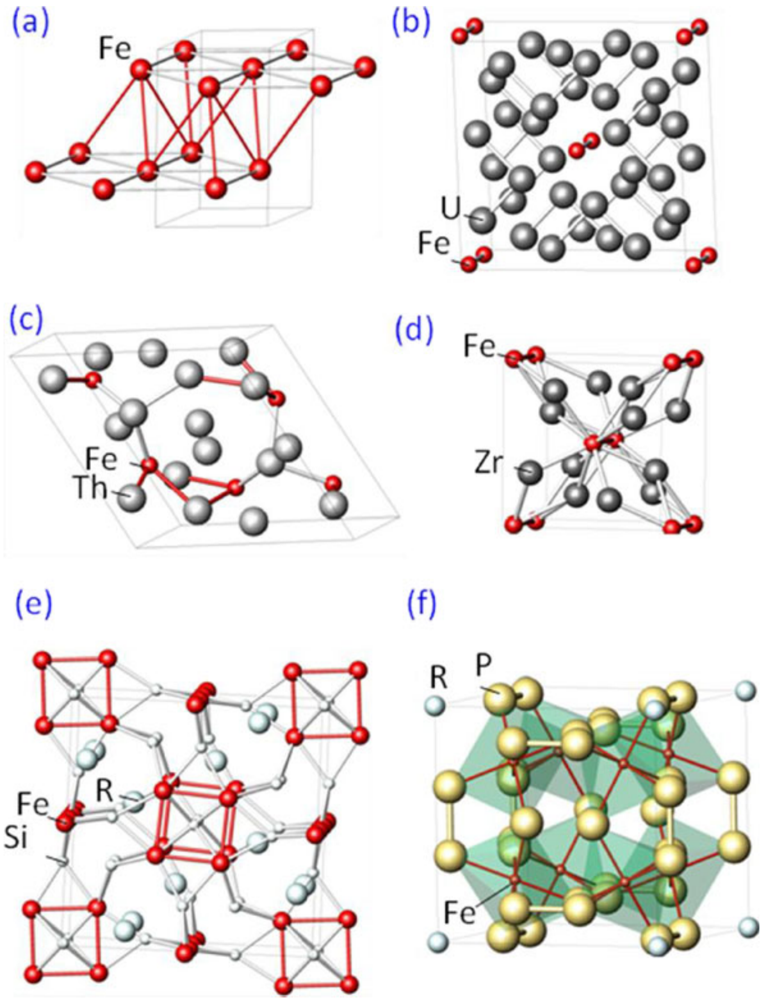

Fig. 1 Crystallographic structures of iron based superconductors. (**a**) ε-Fe [1], (**b**) U_6Fe [2], (**c**) Th_7Fe [3], (**d**) Zr_2Fe [4], (**e**) $R_2Fe_3Si_5$ (R = Sc, Y, Tm, and Lu) [5–9], (**f**) RFe_4P_{12} (R = La, Y) [10, 11]

normal conducting states, indicating that the magnetic moments of the iron are quenched. The quench of the magnetic moment is also observed in a high-pressure phase of elementary iron (ε-iron), which shows superconducting transition at ∼2 K [1].

Since the first discovery of an iron-based superconductor, $LnFePnO_{1-x}F_x$ (Ln: Rare earth ions, Pn: Pnicogen ions) [12, 13] many researchers focus on this material as a candidate for a new high-T_c superconductor. After the first report, series of iron-based superconducting materials have been reported. Figure 2 shows crystallographic phases of iron-based high-T_c superconducting materials. These superconducting materials contain iron: a typical Mössbauer nuclide. T_c of iron-based superconductors reached at 55 K in F-doped SmFeAsO [33].

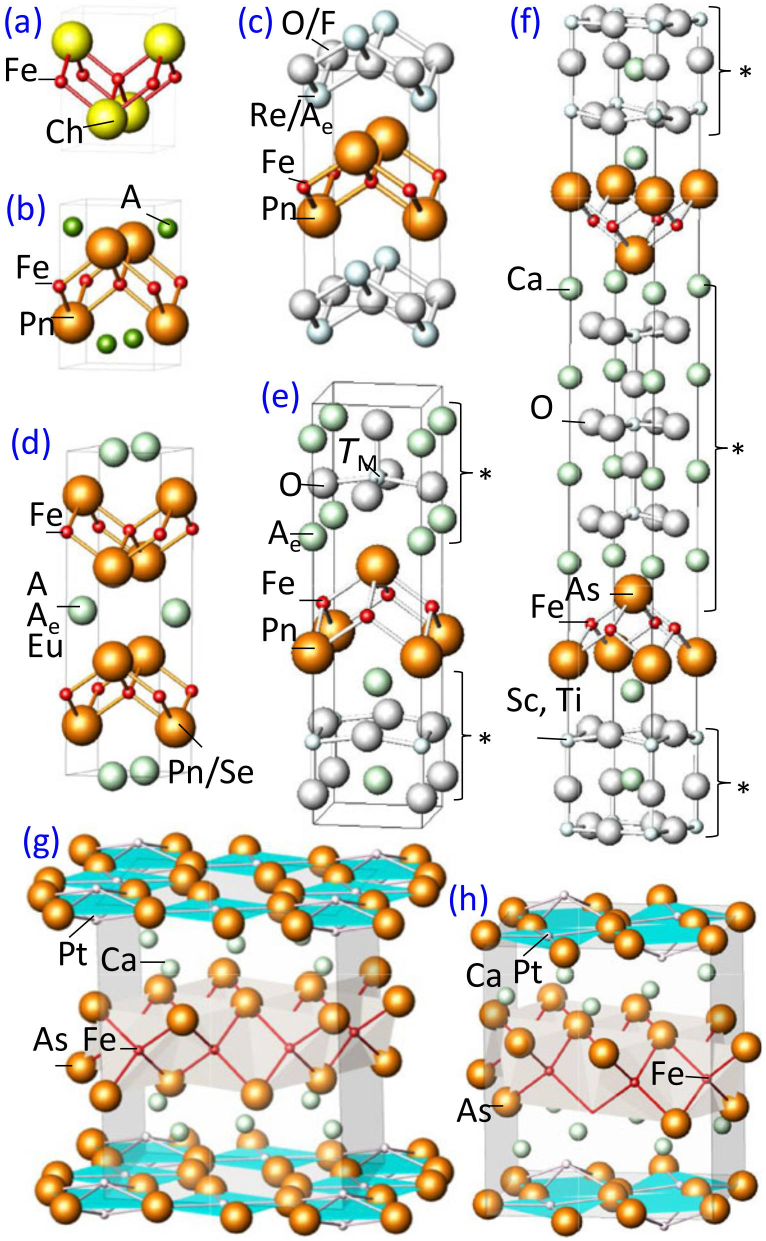

Fig. 2 Crystallographic structures of iron-based high T_c superconductors [14, 15]. (**a**) FeCh (Ch: S, Se, Te), 11-type [16], (**b**) AFePn (A: Li, Na, Pn = P, As), 111-type [17–19], (**c**) ReFePnO (Re: rare earth ions) / AeFePnF (Ae: Alkaline earth ion), 1111-type [12, 13, 20], (**d**) AFe_2Pn_2, $AeFe_2Pn_2$, $EuFe_2Pn_2$, AFe_2Se_2, 122-type [21–24], (**e**) $Ae_2TMFePnO_3$ (TM = Mg, Al, Ti, V), 21113-type [25–28], (**f**) $Ae_4TM_3Fe_2As_2O_8$ [29], * denotes homologus structures. (**g**) (**h**) Ce-Fe-Pt-As [30–32]

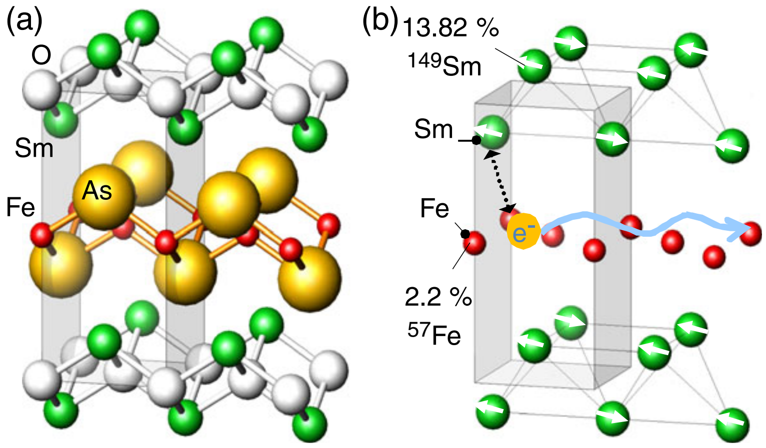

Fig. 3 Crystal structure (**a**) and schematic electrical conduction (**b**) of SmFeAsO

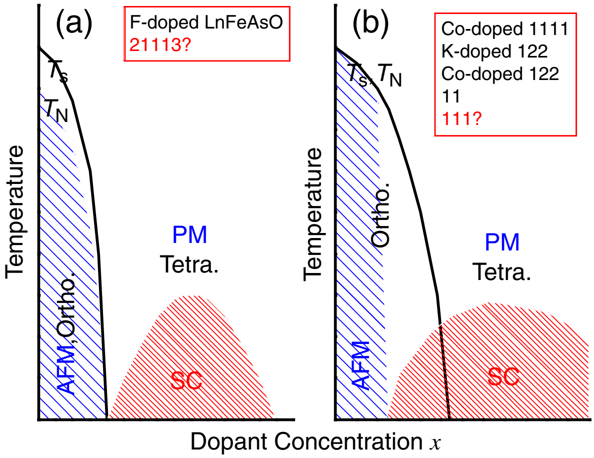

Fig. 4 Magnetic and electronic phase diagrams for Iron-based high-T_c superconductors

2 Magnetic and electronic phase diagram for iron-based high-T_c superconductors

Details for coexistence or not-coexistence of magnetic and superconducting phases were important issues for iron-based superconductors in 2008–2010 [34, 35]. In general, it is very difficult to measure element-specific magnetic moments in a compound containing plural magnetic element using DC magnetization measurement, heat capacity, and μ-SR measurement. In contrast, Mössbauer spectroscopy (MS) and nuclear resonant forward-scattering (NRFS) provide us information on the magnetic hyperfine field at nuclei position. MS and NRFS are also effective to distinguish main phase's magnetic ordering from impurity's magnetic ordering using isomer shift values like Knight shifts values in nuclear magnetic resonance (NMR). MS and NRFS are very good element-specific magnetic measurement methods. Indeed, magnetic properties of $SmFeAsO_{1-x}F_x$ are demonstrated by using ^{57}Fe MS and ^{149}Sm NRFS [36].

Table 1 Superconducting transition temperatures (T_c), superconducting transport-, intergrain-, intragrain-critical current densities (J_c), and upper superconducting critical fields (H_{c2}) for iron-based high-T_c superconductors

Chemical composition	Shape	T_c (K)	J_c (A/cm^2) Transport	Intergrain	Intragrain	$\mu_0 H_{c2}$ (T)	Remarks	Refs.
LaFePO	Poly	2–5.4	–	–	–	0.01–0.1	–	[12, 43]
$LaFePO_{0.94}F_{0.06}$	Poly	6.1	–	1.3×10^4	1.3×10^4	~1	1.83 K	[44]
LaFePO	Single	6.6	–	–	–	4	2 K, H‖*ab*	[45]
$LaFePO_{1-d}$	Single	7.8	–	–	–	–	–	[45]
$LaFeAsO_{1-x}F_x$	Poly	26	–	–	–	–	–	[13]
	Poly	25	–	–	–	$60 \perp ab$, $40 // ab$	0 K	[46]
	Single	11.5	–	–	–	–	–	[47]
	Wire	20	–	–	1.0×10^3	–	5 K	[48]
	Film(Poly)	24	1.0×10^3	–	–	120	2 K	[49]
$NdFeAsO_{1-x}F_x$	Film	45	–	–	–	–	PLD	[50]
	Single	37	–	–	1.0×10^5	–	5 K	[51]
	Single	46	–	–	–	200–300	0 K	[52]
	Poly	47	–	2.1×10^3	6.7×10^6	–	5 K	[53]
$SmFeAsO_{1-x}F_x$	Film	56.2	1.0×10^6	–	–	–	MBE	[54]
	Single	54	2.0×10^6	–	–	200–300	0 K	[55]
	Poly	52	–	–	1.1×10^5	–	5 K	[56]
	Wire	43	4.0×10^3	–	–	–	4.2 K	[57]
	Tape	43	2.7×10^3	–	–	–	4.2 K	[58]
$SmFeAsO_{1-d}$	Poly	53	–	4.0×10^3	7.3×10^6	–	2 K	[53]
$Ba_{1-x}K_xFe_2As_2$	Film	36.9	–	–	–	–	MBE	[59]
	Single	37	–	–	2.5×10^6	–	5 K	[60]
	Single	35.9	–	–	4.7×10^6	–	2 K	[61]
	Single	28.2	–	–	–	70	0 K	[62]
	Poly	35	–	2.0×10^4	2.0×10^6	–	5 K	[63]
	Wire	35	1.0×10^4	–	–	–	4.2 K	[64]

Table 1 (continued)

Chemical composition	Shape	T_c (K)	J_c (A/cm^2)			$\mu_0 H_{c2}$ (T)	Remarks	Refs.
			Transport	Intergrain	Intragrain			
$Sr_{0.6}K_{0.4}Fe_2As_2$	Wire	35	2.5×10^4	–	–	–	4.2 K	[65]
$BaFe_{2-x}Co_xAs_2$	Single	22	–	–	2.6×10^5	–	5 K	[66, 67]
	Single	22	–	–	–	$50 \perp ab$, $55 // ab$	0 K	[68]
	Film	22.15	4.5×10^6	–	–	–	4.2 K	[69]
	Film	22	4.0×10^6	–	–	–	4 K	[70]
	Film on tape	21.3	3.5×10^6	–	–	–	2 K	[71]
$SrFe_{2-x}Co_xAs_2$	Film	17.1	–	–	–	47	0 K	[72]
	Film	17.6	5.0×10^5	–	–	–	4.5 K	[73]
$FeSe_{1+x}$	Poly	9	–	–	–	~16.3	0 K	[16]
	Single	9.8	–	–	2.2×10^4	–	1.8 K	[74]
	Film	6	–	–	–	–	–	[75]
	Wire	11	3.8×10^2	–	–	–	–	[76]
$FeSe_{0.25}Te_{0.75}$	Poly	13.7	–	–	–	40–50	1.4 K	[77]
$FeSe_{0.5}Te_{0.5}$	Film	16	5.9×10^4	–	–	–	4.5 K, 10 T	[78]
	Film	20.2	–	–	–	–	–	[79]
	Wire	10.5	2.3×10^2	–	–	–	4.2 K	[80]

Poly: polycrystalline sample, Single: single crystals, Wire: superconducting wires, Film: poly- and/or single crystalline thin film, Tape: superconducting tape, Film on tape: epitaxial thin film on a metallic tape, Transport J_c: J_c measured from voltage drop measuring method, Intergrain J_c: J_c between grain boundary, Intragrain J_c: J_c in grain boundary. T_cs in this table are onset of the magnetic shielding effects or T_c middle read from figures in cited references. When J_c, H_{c2} are extrapolated values, “0 K” are shown in remarks. MBE: Molecular beam epitaxy

Figure 3 shows crystallographic structure of SmFeAsO. Polycrystalline $SmFeAsO_{1-x}F_x$ samples were synthesized using two-step solid state reaction described elsewhere [36]. Purity of samples was checked by X-ray diffraction patterns using Cu K-α radiation. Resistivity and magnetization measurements, as well as by ^{57}Fe MS and ^{149}Sm NRFS spectroscopy, at various temperatures were performed to define superconducting, magnetic ordering temperatures. A magnetic phase diagram we have proposed is closer to that by Hess et al. [34] (Fig. 4a); that is long-range AF ordering of Fe (a static magnetism) does not persist in the superconducting regime. Such a relation between spin dynamics and SC is a common feature among $LnFeAsO_{1-x}F_x$ (Ln = La, Ce, Pr, Nd, and Sm). Our results indicate that the relation between the long range magnetic ordering and T_c of $LnFeAsO_{1-x}F_x$ shows similar topology to that of copper-based high-T_c superconductors. If short range magnetic ordering [37, 38] and magnetic phase separation [39, 40] of Fe are excluded, macroscopic magnetic and electronic phase diagrams of iron based superconductors can be classified into two-type demonstrated in Fig. 4. Present issues are microscopic, short-range-ordered, magnetic properties on a nanometer-range in iron-based high-T_c superconductors [41, 42].

3 Researches for applications of iron-based superconductors

Iron-based high T_c superconductors demonstrate very large upper critical magnetic fields (H_{c2}) which reach same extent compared with copper-based superconductors [81]. These attractive characteristics of iron-based superconductors triggered research into new iron-based superconductors as well as several attempts at applications. Table 1 shows transport critical current densities (J_c), and H_{c2} for several iron-based high-T_c superconductors.

4 Summary

Considerable number of iron-based high-T_c superconductors has been reported. If short range magnetic ordering and magnetic phase separation of Fe are excluded, magnetic and electronic phase diagrams of iron based superconductors can be classified into two-type. Present issues between magnetism and superconductivity of iron-based superconductors are microscopic, short-range ordered, magnetic properties on a nanometer range. The very large H_{c2} of iron-based superconductors triggered research into several attempts at applications.

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