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MINI REVIEW

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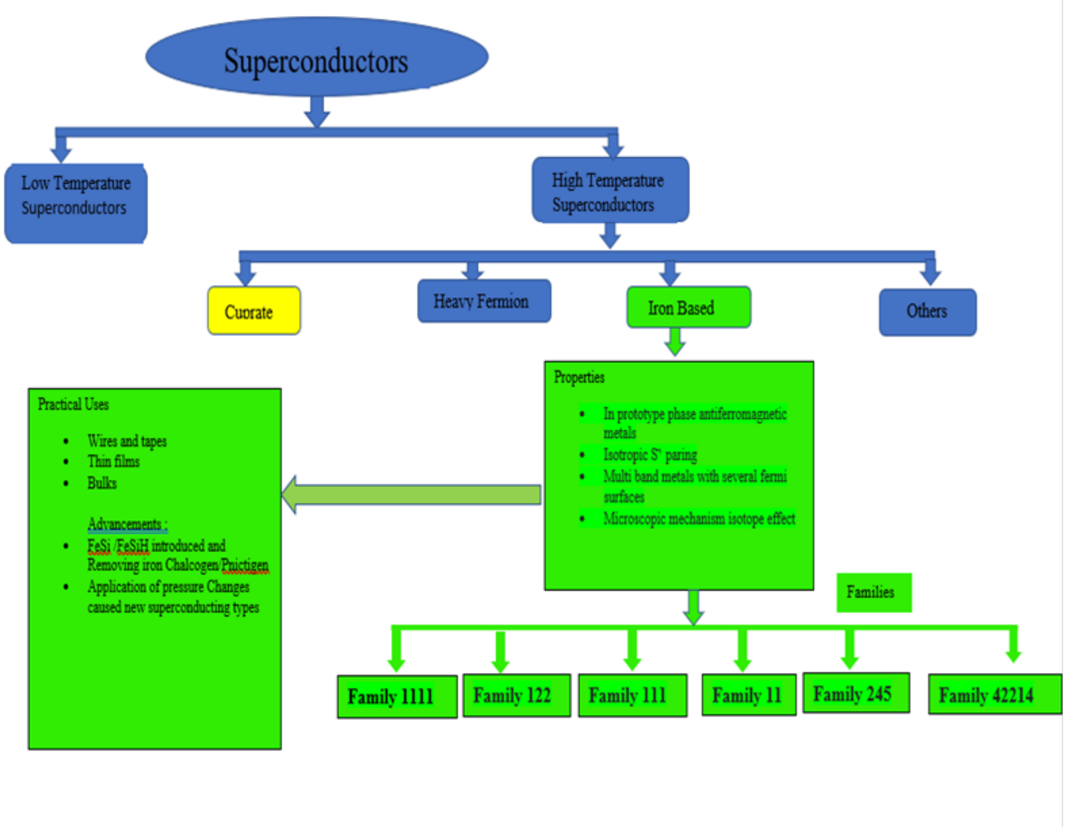

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MINI REVIEW

Potential of iron-based superconductors (IBS) in future applications

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Abstract: Due to the expansion of research studies in the family of new superconductors, there is a progress in the investigations of basic physical and chemical properties. The new findings certainly ended the cuprate monopoly in high temperature superconductor (*HTSC*) family with the introduction of iron based chemical structures. The possessed high values of superconductor temperatures (T_C) in iron-based superconductors (*IBS*) provide hints of novel approaches to futuristic applications while deepening the knowledge of high temperature superconductivity. Up-to-date, many theoretical and practical methods are being utilized to investigate new *IBS*.

***Keywords*:** superconductivity; superconductor temperatures; iron-based superconductors; Families of Iron Based Superconductors; Applications of iron-based superconductors

INTRODUCTION

For the past decades, superconductivity has attracted many researchers around the globe as one of the widely studied and researched phenomena in the world of Physics. In practical applications, critical temperature ($_c$) plays a major role. Even though high T_c was only observed in the High Temperature Superconductor (*HTSC*) family of cuprates (Bednorz *et al*., 1987) in early cases, a new family was discovered in 2008 with layered compounds based on iron. It was the superconductivity observation in fluorine-doped *LaFeAsO* with the primitive tetragonal *ZrCuSiAs*-type (Family *1111* / *1111*-type crystal structure) structure at *26 K* (Kamihara *et al*., 2008). Afterwards, an enhancement of Critical temperature ($_c$) was carried above *50 K* in $PrFeAsO_{1-x}F_x$, $SmFeAsO_{1-x}F_x$, $CeFeAsO_{1-x}F_x$ and $NdFeAsO_{1-x}F_x$ (Ren *et al*., 2008 ; Chen *et al*. 2008; Chen *et al*., 2008; Ren *et al*., 2018) by the modulation of structural parameters and replacement of Lanthanum atoms with other rare earth elements. Up to date many theoretical and practical methods are being utilized to investigate the new Iron Based Superconductors (IBS).

If a structural comparison of superconductivity in IBS and in cuprate superconductors are being carried out, both are known to be layered systems. Except the fact that Fe atoms are in a square planar lattice structure in *FeAs* superconductive layer of the crystal structure of iron-based compounds. This is a similar characteristic of CuO_2 layer in cuprates. Moreover, the isotope effect in IBS has indicated that the superconductivity is much different from cuprate superconductors (Cheng *et al*., 2014). Hence, the present review aims to provide an insight into the IBS with a detailed description about their properties and an open discussion about their potential in future applications to promote further investigations.

IRON BASED SUPERCONDUCTORS (IBS)

Replacing cuprates, IBS are taking monarch of HTSC family and it marked the beginning of a new era. Unlike cuprates, IBS have some important characteristics such as high upper critical field, low anisotropy, large current density values etc. (Pallecchi *et al*., 2015) that provide the potential in real-world applications very easily. These superconductors can coexist with magnetism which is a unique feature that is being applied into applications such as spintronics (Kordyuk, 2012). There are few differences between cuprate superconductors and IBS (Table 1).

Table 1: Differences between cuprate superconductors and *IBS* (Sadovskii, 2008).

Cuprate Superconductors	Iron Based Superconductors
One band metal with a single Fermi surface	Multi-band metals with several Fermi surfaces
Have anisotropic d wave pairing	Isotropic S^{+} paring
In prototype phase antiferromagnetic insulators	In prototype phase antiferromagnetic metals
Microscopic mechanism spin fluctuations	Microscopic mechanism isotope effect

According to their crystal structure, *IBS* are categorized into families.

Family *1111*: This family is available in single crystals that are very small and they are different from bulk electronic structure. Due to that, this family is hard to study (Kordyuk, 2012). In this family, there are two

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parameters which affect its superconductivity. Namely, they are Pnictogen height (h_p) and doping. Maximum $_c$ is given by $h_p=1.38\ Å$, and in doping it gives more efficient results as Oxygen sites are replaced by Fluorine, Hydrogen or by Oxygen (Katrych *et al*., 2014).

Family *122*: Members in this family can dope both holes and electrons (Kordyuk, 2012). This family members have a structure of AFe_2As_2 (A-Alkaline Earth Metal/Fe-Iron/As-Arsenic) with the least anisotropic, relatively large $_c$ values and they exhibit large critical current densities. But this family has toxic Arsenic and highly reactive alkaline earth metals which cause difficulties in manufacturing large scale (Pallecchi *et al*., 2015)

Family *111*: This family has *LnFeAsO* as stoichiometric formula (Ln-Lanthanides/O-Oxygen). It also contains toxic Arsenic and volatile compounds (Pallecchi *et al*., 2015). Its high volatility exposure to air affects its T_c. In this case, iron can be replaced by Cobalt or Nickel to increase superconductivity (Kordyuk, 2012).

Family *11*: This family contains Chalcogens and its typical structure is *FeCh* (Ch-Chalcogens). This family is not toxic. But it has lower temperatures such as *16K* (Pallecchi *et al*., 2015).

Family *42214*: Stoichiometric formula for this family is $RE_4Fe_2As_2Te_{1-x}O_4$(RE-Rare earth materials/Te-Tellurium and x-native Tellurium vacancies). This family also has Fe-As plane like the Family *1111*. It can show intrinsic Josephson junctions as a considerable development (Bucci *et al*., 2016)

Family *245*: Typical formula in this family (parent compound) is $A_2Fe_4Se_5$ (A- alkali metal/Se-Selenium) (Bao,2015). One of the interesting phenomena of this family type is the antiferromagnetic semiconductor behaviour (Kordyuk, 2012).

Considering the crystal structure of these IBS, they can contain layered *FeAs* or *FeSe* which are stacked in its crystal form. Also, in IBS, the critical temperature depends on the angles between *FeAs/FeSe* bonds and the height of tetrahedranes. The shape of these layers is formed as tetrahedranes as this electron structure is anisotropic (Zhang etal., 2011.). These Fe_2X_2 layers (x-Pnictogen or chalcogen) are anti-fluorite type (Jiang *et al*., 2016). Families of *11,111*and *1111* have a non-symmorphic space group of P4/nmm but family *122* is a symmorphic space group I4/mmm (Eschrig and Koepernik, 2009).

Evidence obtained by x-ray analysis revealed that the Coulomb repulsion energy (*U*) between Fe *3d* electrons is strongly solute in both doped and undoped pnictides. The crystal structures of these kinds of superconductors have Fe^{2+} in the middle with orbital degenerate state and it is surrounded by Arsenic, Tellurium, or Selenium which are exceptionally polarizable anions (Yin *et al*., 2010). This can be explained as a tetrahedral coordination of chalcogenide ions or picnitide ions with a square lattice of Fe^{2+} ions. Iron plays a key role in superconductivity because it has five 3d-orbitals which dominate the Fermi level of each parent molecule (Hosono et al., 2015). All five of Fe's *3d* electron shells participate in the Fermi surfaces, forming numerous Fermi pockets, usually those of hole bands around the zone center (point) and electron bands around the region edge (M point) in momentum space. This is one characteristic of *IBSCs* (Isoyama *et al*., 2021). Tetragonal symmetry characterizes these substances in the Pauli para metals in the superconducting phase change from their normal condition to either orthorhombic or monoclinic anti-ferromagnetism at low temperatures A suitable carrier doping or structural alteration can cause superconductivity in the majority of the constituent materials which are antiferromagnetic metals. Even if certain parent phases exhibit superconductivity without doping, the link between magnetic ordering in the parent phase and resultant *Tc* is likely close. The Curie temperature of metallic ferrous with bcc structure is *1043 K*, making it a ferro-magnetic. However, high pressure phases with hexagonal structures lose their ferromagnetism and display superconductivity with a *Tc* of *0.4 K* under *15–30GPa*. This may infer that high c IBSCs are produced by carrier doping rather than applying a field to remove long - distance spin ordering in multilayer iron pnictides (Hosono, 2015).

As a summary of *IBS*, *3d* band of *Fe* involved as band type of superconducting and 5 bands join the process. For the superconducting process there are two suggested mechanisms, such as spin fluctuation and orbital fluctuation. Pairing symmetry of this is S type and the undoped electronic state is antiferromagnetic metal (Tanabe and Hosono, 2012) and also electrons in *3d* orbital of *Fe* plays a huge part of iron-based superconductivity (Fujitsu *et al*., 2012)

MODERN ADVANCEMENTS AND APPLICATIONS OF IBS

Applications of superconducting materials can be categorized as three major types, such as wires and tapes, thin films and bulks (Durrell *et al.*, 2018). In 2009, $Sr_{0.8}K_{0.4}Fe_2As_2$ (K-Pottasium) wires and tapes fabricated inside of Silver (*Ag*) tube. This gave a successful measuring of current transport in *122* - type wires (Yanwei, 2012). *Fe (Se, Te*) superconducting wire was created utilizing a unique technique. Fe sheath serves as both a sheath and the starting point for the creation of superconducting phases. As anticipated, the sheath evenly distributed Fe to the superconducting phases. The critical current in the *I-V* measurements for the generated *Fe(Se, Te*) wire have been observed. By enhancing grain connectivity, adding pinning centers, and creating multi-core wire, the Current Density (*Jc*) can be improved (Mizuguchi *et al*., 2009).

IBS has good mechanical strength, simple tape and wire preparation methods, upper critical field, smaller anisotropy and low cost. Due to all of the above reasons, applications of IBS are more popular in industrial levels.

In addition, IBS can perform well in high magnetic field's influence (Qian *et al*., 2021). During the searches on high-temperature superconductors, there are lot of ongoing experiments that use these technologies for real-world applications. Major application can be seen in the manufacture of electric conducting wires to transfer electric current without resistance or minimum resistance.

First iron-based wire types of *Sm-1111* and *Sr 122* wires have considerably $_{c}$ values of approximately *4000 A/cm²* at 5K. This value is relatively larger than cupartes which has J_c value of *100 A/cm²*(Yanwei, 2012). To manufacture these type of wires Power In Tube (PIT) method is widely used and there is ongoing work to design long-length (kilometers) superconducting wires fabricated using *F-La 1111* group and *F-Sm 1111* group (Biswal and Mohanta, 2021). In 2017, *100 m* long *Ba122* IBS wire was manufactured using PIT method in China (Qian *et al*., 2021).

The PIT (powder in tube) process is highly appealing since it takes the use of affordable costs and straightforward deformation processes. In $LaFeAsO_{1-x}F_x$ and $SmFeAsO_{1-x}F_x$ wires of type *1111 IBS* ($LaFeAsO_{1-x}F_x$ and *SmFeAsO* $_{1-}$*xFx*) were made using the in-situ PIT method for the first time in 2008, shortly after IBS was discovered. This method begins by placing powders of unreacted precursor materials inside a metallic tube in a high purity *Ar* atmosphere. Then, in 2009, reports of PIT wires of the *122*- and *11*-type ($_{1-x\ x\ 22}$ and *Fe (Se,Te)*) were also made. However, during the wire sintering procedure, these wires experienced composition segregation and porosity caused by volatile elements like *As*, *F*, and *K*. A high *c* performance meeting the needs of practical applications is crucial for superconducting wires and tapes. Recently, using a variety of techniques including metal addition (*Ag, Pb, Sn, Zn*, and *In*), flat rolling induced texture, intermediate annealing during deformation process cold or hot uniaxial press, and hot isostatic press, the transport *c* of *122-IBS* (primarily $Sr_{1-x}F_xFe_2As_2\ Ba_{1-x}K_xFe_2As_2$) wires and tapes was effectively manufactured (Yao and Ma, 2019). This PIT process benefits from cheap material costs and straightforward deformation procedures. There are 2 PIT techniques. One involves the use of a powder mixture of *122* phase precursor as a precursor material for an in-situ technique. The other is an ex-situ technique that makes use of *122* phase powder. Currently, the so-called ex-situ PIT method was the most effective method for creating pnictide wires (Ma, 2015). The manufacture of *1111, 11* (*FeSe*), and *122*-type superconducting wires and tapes utilizing a variety of sheath materials, including *Fe, Ag, Nb*, and *Ta*, is the application for which the powder-in-tube (*PIT*) method is most commonly utilized.(Ma, 2015.).

There is another method which can be used to manufacture IBSC. In that method manufacture of *1111, 11* (*FeSe*), and *122*-type superconducting wires and tapes are utilized by a variety of sheath materials, including *Fe, Ag, Nb*, and *Ta* but the application of the powder-in-tube (*PIT*) method is most commonly utilized.(Ma, 2015.).

Recently by using the electrochemical technique, superconducting *FeSe* films were successfully created. Tetragonal *FeSe* films electrodeposited at p^H *2.3* and *-1.75 V* showed a c *3.5 K* superconducting transition. The findings provided a novel synthesis technique to create superconducting coated conductors, such as films, wires, tapes, and other materials(Satoshi Demura et al., n.d.). Scientists were able to create a single, *30*-mm-diameter *7*-filament *Ba122/Ag/AgMn* (Mn-Manganese) pancake coil. Using the wind-and-react method, this Single Pancake Coil (SPC) was created utilizing stainless steel tape and non-insulating *Ba122/Ag/AgMn* tape. First, a *24 T* external magnetic field and liquid helium were used to examine the transport characteristics of *Ba122* SPC. Similar to the straight Ba122 short tape, the SPC transport current was unaffected by the background magnetic field and remained substantial in high magnetic fields. The transport current (*Ic*) value of the SPC, for instance, was still *26 A* at *24 T* background field, which is around *40%* of what it was with zero external magnetic field. These findings imply that high-field magnet applications for iron-based superconductors are quite promising (Wang *et al*., 2019).

Several lengthy iron-based superconducting tapes are connected together for use on a broader scale. Hence, a superconducting joint is crucial for sustained current operation and reducing the overall heating generation. The joints between the coils must be superconducting even in the presence of a strong magnetic field in order for the magnet to function in the persistent mode. As a result, one of the most crucial technologies now involves the connection of two superconducting wires or tapes. The first method for creating superconducting junctions amongst Sr-122 IBS tapes has been established. Each sample's Ag sheath was pulled off of one side. The two tapes' exposed superconducting sections were connected together, and then again wrapped with Ag foil. By using the hot press technique in an environment of argon, the iron-based superconducting joint's diffusion bonding was accomplished (Yao and Ma, 2019).

In the current state of *122*-type iron-based superconductor-based round wire development, gradually various techniques are being introduced, such as high-pressure sintering, controlling the drawing and sintering conditions, and promoting the reaction of raw materials by densification. By the introduction of dyes during the drawing process, has improved the texturing inside the wire core, where in turn the transport c has been improved. The current transport c records for round wires treated at *175* MPa have accomplished with values at *4.2* K under self-field and *100* kilo Oersted(kOe) being 2.0×10^5 A/cm² and 3.8×10^4 A/cm², respectively. HIP tapes manufactured under the same circumstances also showed good performance, with transport c values of 2.8×10^5 A/cm² and 3.8×10^4 A/cm² at self-field and *100* kOe, respectively (Tamegai *et al*., 2017).

Another application of IBS is in a testing state, which is in building race tracks. This test was carried under two different background fields such as *7.5* T and *10* T. The results of the test revels that IBS strength is less dependent on background field intensity regarding other types of superconductivity (Zhang *et al*., 2021).

The proposed *FeSi* as a new component for superconductivity based on iron, opening us a new avenue for understanding the complex physics of high-temperature superconductors. This silicide hydride has magnetic, electrical, and structural characteristics that are comparable to those of previously known iron-based superconductors. Hence, a *FeSiH* illustrates the potential for iron-based superconductivity in a chalcogen- and pnictogen-free manner.(Bernardini *et al*., 2018)

Considering modern advancements of IBS, there was specific research which was conducted to check whether superconductivity is dependent on pressure or not. In that work, the results showed that by the application of pressure shows a new kind of superconducting phase. The reason for that is the pressure deforms lattice parameters, bond angle and bond length. Due to that, the band structure and charge transfer is changing accordingly. In IBS, the cooper pairs will form hole-band interbond interaction. During old days it was believed that the superconducting paring state in IBS is S wave but based on new data it can be due to d wave paring too (Sang *et al.*, 2021). Even there was a modelling method used to predict superconducting lattice parameters and pressure relations using Gaussian Process regression (GPR) model (Zhang and Xu, 2021), using that in the future prediction of superconducting materials can be easily predict.

CONCLUSION

Considering IBS, there are few obstacles to overcome. Many of them contain Arsenic (As) which is toxic to humans. Doping another material without Arsenic can be the problem solver, and also in family *11* it doesn't contain any toxic elements, but the critical temperature should be needed to increase. Also, IBS are categorized as unconventional superconductors, and their microscopic behaviour and chemistry must be studied further. Studying vortexes inside of this kind will be helpful to understand how they behave in magnetic fields as well.

IBS can tolerate magnetic fields in a certain amount rather than other types of high temperature superconductors. It can perform well in relatively high pressure. With these kinds of properties, IBS can be used to deep space exploration projects and deep oceanic rovers. Usage of Sc can help to use limited power with full efficiency hence without losing it due to resistivity. In moons like titan contains vast oceans. So, the observation rovers can use IBS wires in power supply mechanisms. Monorail systems can also be an application IBS, because they can be used to improve to tolerate earth's magnetic field and any external magnetic fields. By the usage of IBS to monorail systems will give a partial solution for modern power crisis. Many applications of IBS are limited due to small critical temperature values. Thus, there is new research arena with a wide scope that a researcher can enter into by increasing the investigations on critical temperature in IBS. Even IBS can be modified to work in normal room temperature.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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