Chapter

High Temperature Superconductors

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Abstract

One of the pioneers who introduced superconductivity of metal solids was Kamerlingh Onnes (1911). Researchers always struggled to make observations towards superconductivity at high temperatures for achieving goals of evaluating normal room temperature superconductors. The physical properties are based entirely on the behavior of conventional and metal superconductors as a result of high-temperature superconductors. Various synthetic approaches are employed to fabricate high-temperature superconductors, but solid-state thermochemical process which involves mixing, calcinating, and sintering is the easiest approach. Emerging novel high-temperature superconductors mainly engaged with technological applications such as power transmission, Bio-magnetism, and Tokamaks high magnetic field. Finally, in this chapter, we will discuss a brief outlook, future prospects, and finished with possible science fiction and some opportunities with high-temperature superconductors.

Keywords: cuprates, fabrication techniques, HTS films, coated conductors, BSCCO films, Wires and Tapes, applications

1. Introduction

Various metals exhibit modest electrical resistance owing to normal room temperatures, however, may be turned into superconductors by employing a frozen route towards absolute zero temperature. The very first metal presented in favor of superconductors was mercury that was discovered just after cryogenic refrigerator in 1908, attaining that temperature at which phase shift of helium may occur as liquid form showing 4.2 K = −452 °F. In addition, enveloping more than 60 years, further superconductor's discoveries continued and proved to be high-quality superconductors at such low temperatures. Furthermore, during 1960s, specific niobium alloys were also turned into superconductors, however, at the temperature range 11–24 K. Subsequently, theoretical studies also showed and proved that there is no existence of superconductors above 30 K. Superconductors being non-resistive, are considered fast driving current carriers without voltage or electricity [1–3].

Starting current continuously flows for "geological" periods subject to keeping cold the relevant superconductors. Over a long time, chilling requirements for extremely low temperatures showed greater effect towards confinement of superconductivity in the territory of literature laboratories [4, 5]. The running expenditure attributed to superconducting current loop is evaluated subject to refrigeration cost i.e., $7 per liter that is mostly considered as liquid helium purchasing cast accordingly. As far as electromagnets are concerned, their application as a current loop is very important. However, it is more expensive electromagnet that may be made by utilizing copper wires. Further by 1970s, it has become more cost-effective in numerous cases in the form of paying price for freezing a superconductor rather than bearing utility bills for electricity used against resistance [6, 7]. Industrial level setup was evolved so far, in which high-quality superconducting magnets were launched towards versatile applications. The most familiar application is now in hospitals in the form of Magnetic Resonance Imaging (MRI), proving as standard-diagnostic-tool to diagnose dead cells in the human body by scanning it successfully. This is a low-cost running device as compared with the cost of "exploratory surgery" [8, 9].

High-temperature superconductors (HTS) are strongly considered as defined materials behaving as superconductors at high temperatures (> 78 K) showing liquid nitrogen (boiling point), which is considered the simplest cryogenic- coolant [8, 10]. All types of superconductors are currently working nowadays at normal pressure but below ambient temperatures that require more cooling environment. However, most HTS behave such as ceramic type materials while metallic superconductors often work at temperature (< −200 °C), therefore referred to as LTS (low-temperature superconductors) [11, 12]. Furthermore, metals based superconductors are numerously identified as common superconductors owing to fine discovery as well as proper use before the introduction of high-temperature ones. Additionally, ceramic superconductors have also been proved to be suitable for practical application, rather they still show various fabricating issues since only very few examples of employment are on the screen up till now. Owing brittle nature of most ceramics they present behavior while fabricating wires from them for manufacturing superconductors [13, 14]. On the other hand, a major benefit belonging to high-temperature ceramic superconducting materials is their cooling through liquid-nitrogen on the contrary; metallic superconductors often need rare coolants that may be liquid helium [7, 15]. Unfortunately, a more common disadvantage is that no HTS may be refrigerated using dry ice, and none amongst those may work at room temperature as well as pressure. They can only work reasonably below the lowest-temperature measured on Earth's surface. Necessarily, HTS sufficiently requires some cooling system at every cast. Superior high-temperature superconductors belong to only particular class of copper oxides. Another class of HTS is practically classified as iron-based compounds [6, 7, 15]. Magnesium diboride is considered another HTS because of easy manufacturing, however, working conditions under −230 °C (lower than triple point temperature of nitrogen) make it unsuitable concerning cooling with liquid nitrogen (below nitrogen triple-point-temperature). Ideally, liquid-helium can be used to achieve extremely lower temperatures for proper application. Various ceramic superconductors may also depict superconducting behavior owing to second type. The very first HTS has been discovered by Bednorz and Müller in 1986 [11, 12, 16] and obtained Nobel Prize (1987) for the "discovery of superconductivity in ceramic materials". Various high-pressure super-hydride chemical species are often incorporated in the realm of HTS. Indeed, much literature work containing HTS has been found owing to gases with high-pressure, however, unfavorable for synergetic applications. Finally, the latest critical temperature (T_C) record holder is identified as carbon nature sulfur hydride, showing leading contribution leaving behind the previous record inherited in lanthanum deca-hydride (about 30 °C) [16–18].

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2. Milestone of high-temperature superconductivity

Kamerlingh Onnes was one of researcher who introduced superconductivity in metal solid (1911). Researchers always struggled to make observations towards superconductivity at high temperatures [10, 19] for achieving goals of evaluating normal room temperature superconductors [20, 21]. Besides, superconductivity has been detected in various metallic compounds such as Nb containing compounds, for example (Nb_3Ge, NbTi, and Nb_3Sn) at much higher- temperatures as compared with elemental-metals, exceeding −253.2 °C (late 1970s). Moreover, in 1986, IBM research lab (Zurich) provided an opportunity to Bednorz and Müller who were working on superconductivity research route for generating a new class of ceramics (maybe cuprates as well as copper oxides). Bednorz discovered a zero resistance copper oxide at 35.1 K = −238 °C [22]. However, collected results were soon supported by numerous thoughts, notably Paul Chu and Shoji Tanaka at Houston and Tokyo universities one after others [23, 24], all the story illustrated in **Figure 1** and **Table 1**. Very shortly after, Anderson worked at Princeton University and presented a new theoretical concept relating to these materials. The theoretical idea was based upon RVBT (resonating valence-bond theory) [43] however still, full exploring relevant to these materials is considered open-ended up-till now.

Above mentioned superconductors may possess identical d-wave pair. The very first suggestion in favor of high-temperature cuprate superconductors d-wave pair symmetry was offered by Scalettar, Scalapino, and Bickers [44], which was associated with theories presented in 1988 by famous researchers known as Hirschfeld, Doniach, Inui, and Ruckenstein [45], they used spin fluctuation theory. Additionally, Rice, Gros, Zhang, and Poilblan [46], and Kotliar, as well as Liu, identified pairing concept representing usual consequence based on RVBT [47]. On the other hand, d-wave shape attributing cuprate superconductors was observed by many experiments. Further, the involvement of d-wave nodes was observed directly during excitation-spectrum by employing Angle-Resolved Photoemission-Spectroscopy. Half-integer flux observation was indicated through tunneling experiments whereas indirect temperature-dependence related to penetration

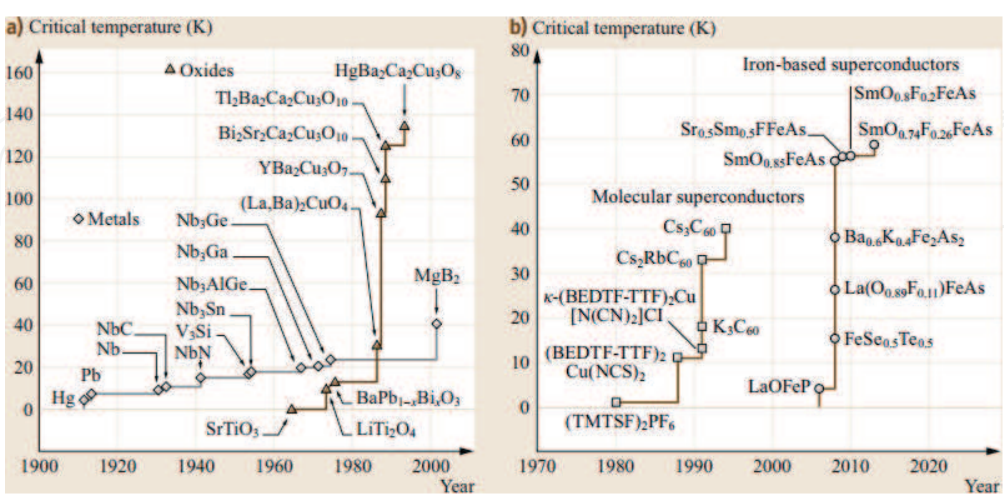

Figure 1.
(a) Maximum known Tc of molecular (TMTSF and BEDTF-TTF), iron-based, metallic, and oxide superconductors. Metallic superconductors' T_c increased from 4.2 K (Hg) to 23.2 K (Nb_3Ge) from 1911 and 1974. However, after unexpected discovery of superconductivity in MgB_2 in 2001, maximum T_c of 39 K was achieved. In 1986, highest T_c of oxides exceeded the boiling point of liquid nitrogen (77 K), after the discovery of high-Tc superconductivity in $(La, Ba)_2CuO_4$. (b) The first molecular superconductor was discovered in 1980 where high T_c of 40 K was discovered in Cs_3C_{60} fullerene. From 2006 to 2013, the maximum known T_c of iron-based superconductors gradually increased from around 4 K for LaOFeP to 58 K for $SmO_{0.74}F_{0.26}FeAs$. Reproduced from Ref. [25].

T_c boiling point		Material (HTS)	Comments
in K	**in °C**		
287	14	$H_2S + CH_4$ at 267 GPa	First room temperature superconductor [26]
250	−23	LaH_{10} at 170 GPa	Metallic superconductor with one of the highest known critical temperature [27]
203	−70	High-pressure phase of hydrogen sulfide at 100 GPa	Mechanism unclear, observable isotope effect [28]
138	−135	$Hg_{12}Tl_3Ba_{30}Ca_{30}Cu_{45}O_{127}$	High-temperature superconductors with Copper oxide with relatively high critical temperatures [25, 29–31]
110	−163	$Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO)	
92	−181	$YBa_2Cu_3O_7$ (YBCO)	
45	−228	$SmFeAsO_{0.85}F_{0.15}$	Low-temperature superconductors with relatively high critical temperatures [32, 33]
41	−232	CeOFeAs	
39	−234	MgB_2	Metallic superconductor with relatively high critical temperature at atmospheric pressure [34, 35]
30	−243	$La_{2-x}Ba_xCuO_4$	First high-temperature superconductor with copper oxide, discovered by Bednorz and Müller [36, 37]
18	−255	Nb_3Sn	Metallic low-temperature superconductors with technical relevance [38–40]
9.2	−264.0	NbTi	
4.15	−269.00	Hg	Metallic low-temperature superconductors [41, 42]
1.09	−272.06	Ga	

Table 1.
Collection of various superconductors and common cooling agents.

depth, and that of specific heat as well as thermal conductivity. Some superconductors possessing high transition- temperature but at ambient pressure, were declared as cuprate of elements such as mercury and calcium at around temperature (133 K) [48, 49]. Among superconductors some are, showing higher transition- temperatures like lanthanum super-hydride at around 250 K, whereas these may often occur at high-pressures [27, 50]. Resultantly, source of high-temperature- superconductivity of conductors is out of range. However, it seems to be conventional superconductivity in the form of an electron–phonon mechanism as well as by anti-ferromagnetic correlation mechanism. Again instead of conventional, pure s-wave pairing symmetry which is identified as exotic pairing symmetry is considered to be involved. Subsequently (2014), evidence relevant to fractional particles was presented in favor of the occurrence of quasi-2d magnetic-materials. EPFL scientists discovered these materials [51] which supported "Anderson's theory" based on HT superconductivity [51].

3. State-of-the-art superconductivity

As for physical properties, attributing to high-temperature superconductors are concerned, these are purely based upon behavior of conventional and metallic superconductors. In this literature, properties owing to superconducting state are widely described in the sense of detailed properties of simple and metallic superconductors. It was observed that below critical temperature (Tc), electrical resistance decreases to zero for SCs. However, T_c (critical temperature) is an important parameter for superconductors that are still in question mark. More apparently for pure metals, it was evaluated that zero-resistance-state may have reached in the range of a few mK as shown in **Figure 2a**. Moreover, for complex cuprate high critical temperature superconducting materials, transition state corresponding to superconducting state, observed is not sharp as compared with metallic SCs having low values of T_c. Transition-width possessing single-phase-cuprate SCs are critically identified as 1 K. Results indicate that critical temperature slightly belongs to the criteria that were used to specify (Tc). Various criteria support as suggested in **Figure 2b**. Whereas at observed transition temperature, resistance-drop has typically been searched corresponding to numerous orders of magnitude [25, 52].

Besides, it may be in the form of principle and not still possible to prove experimentally; that ideal resistance corresponding to superconducting state may become zero. t Subsequently, it was proved that the most effective technique determining the peak value of the resistance, is evaluated in detecting decay-state owing to magnetic fields, produced by those currents that were induced during an SC loop. Peak resistivity values occurred ranging from 2×10^{-18} [25, 53] to 7×10^{-23} Ωcm [54] were reported for $YBa_2Cu_3O_7$ that is identified as high (Tc) superconductor, and whereas 3.6×10^{-23} Ωcm value was found to be low (Tc) superconductors of type-I [25]. The aforementioned resistivity limits are considered to be several orders of magnitude indicating minute resistivity valuating 10×10^{-10} Ωcm (at 4.2 K), which was achievable at annealing state about pure metals. Therefore, it was strongly justified to make assure of zero-resistance, however, below (Tc) in all experimental work. While next extraordinary property belonging to superconducting state was diagnosed as perfect diamagnetism. More interestingly magnetic-behavior of superconductors may be understood through two variety of situations as shown in **Figure 3**. Firstly, the superconductor is made zero field-cooled below Tc. Secondly, superconductor is again cooled, however below Tc by applying magnetic field in this case. Both approaches are followed without incorporating magnetic flux in the interior of superconductor [20, 29].

On the other hand, screening-currents induced through surface-layer of superconductor will produce magnetic flux but in opposite direction to the applied field. In this case, magnetic flux density becomes zero throughout the superconductor. Whereas outside the superconducting-sphere, magnetic field increases caused by

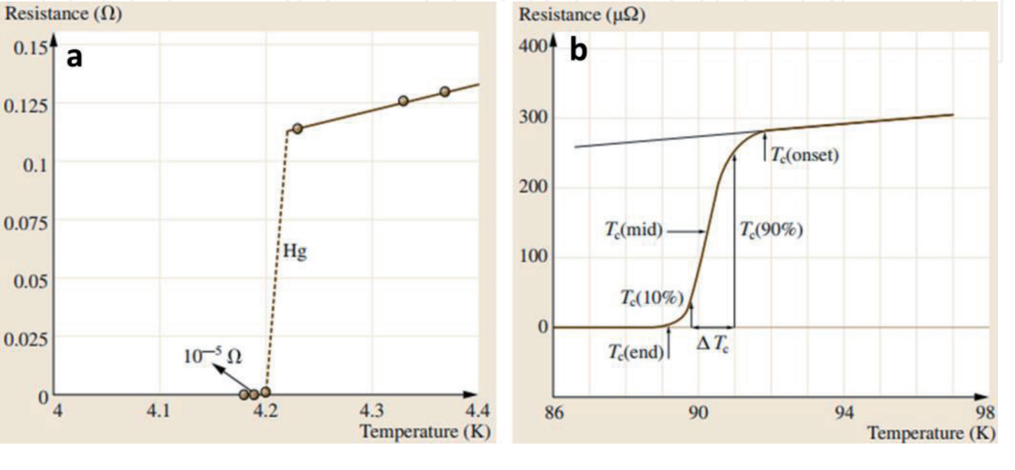

Figure 2.
(a) Plot of resistance as a function of temperature for mercury generated by Heike Kammerlingh Onnes. (b) Resistance-temperature plot for a multicore wire of $Bi_2Sr_2CaCu_2O_8$/Ag labeled with T_c referring to different definitions of transition temperature. The width of the transition ΔTc = Tc(90%)-Tc(10%) is ≈ 1.2 k Reproduced from Ref. [25].

superposition of flux generated due to applied field as well as of screening currents. However, in both states, superconductor is observed to be un-magnetized whenever a magnetic field accidentally vanishes. Resultantly when superconductor is cooled without applying magnetic field, its behavior may be identified only in the form of screening effect but still caused by perfect-conductivity. While contrary to screening effect magnetic flux expulsion arising out from the Meissner effect has not still been explained (perfect conductivity) [55, 56]. Additionally, varied behaviors attributed to field-cooled perfect- conductor have also been illustrated in **Figure 3a**-**c**. Relative magnetic-permeability found by different repeated experiments was evaluated close to unity comparatively owing to non-ferromagnetic metals. Resultantly, magnetic flux that was observed within the metal is.

analogous to an external magnetic field. Since dB/dt is zero in this case, and therefore no screening currents arise eventually. Consequently, no magnetic flux is extracted within perfect conductor's interior region at low kelvin temperatures. When magnetic field i.e., dB/dt becomes non-zero, then magnetization has occurred relevant to perfect conductor. The superconductivity may be diminished by applying large amount of magnetic field. The B-field at which superconductivity of the material is lost is termed as B_c (critical field) under consideration [57, 58]. Temperature-dependent critical-magnetic-field is mathematically described by the well-known Eq. (1).

$$B_c(T) = B_c 0\left[1 - \left(\frac{T}{T_c}\right)^2\right] \tag{1}$$

Where Tc and B_c0 are critical temperatures as well as critical field at T = 0, respectively. B_c is considered as temperature-dependent function as depicted in **Figure 4** corresponding to different metallic SCs. The $B_c(T)$ graphs differentiate the normal and superconducting state of Scs. Furthermore, the Meissner effect

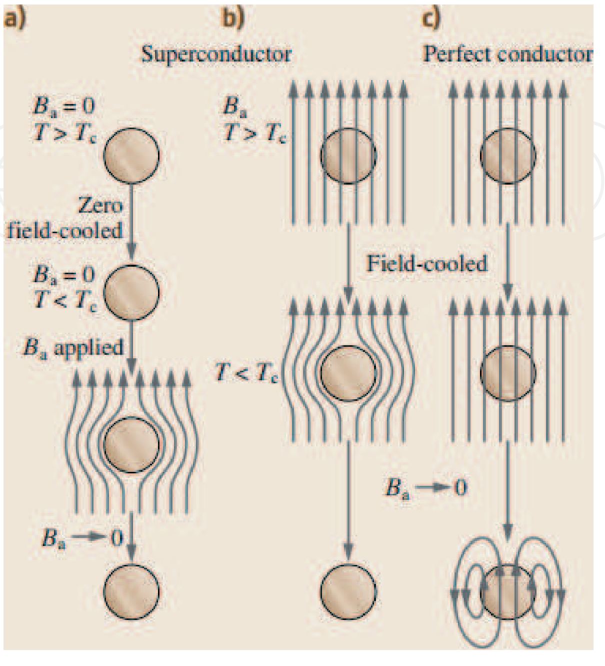

Figure 3.
(a) The magnetic flux is excluded from the interior of a superconductor, (b) in the presence and absence of field-cooling, (c) In contrast, a field-cooled perfect conductor shows presence of interior magnetic flux. Reproduced from Ref. [25].

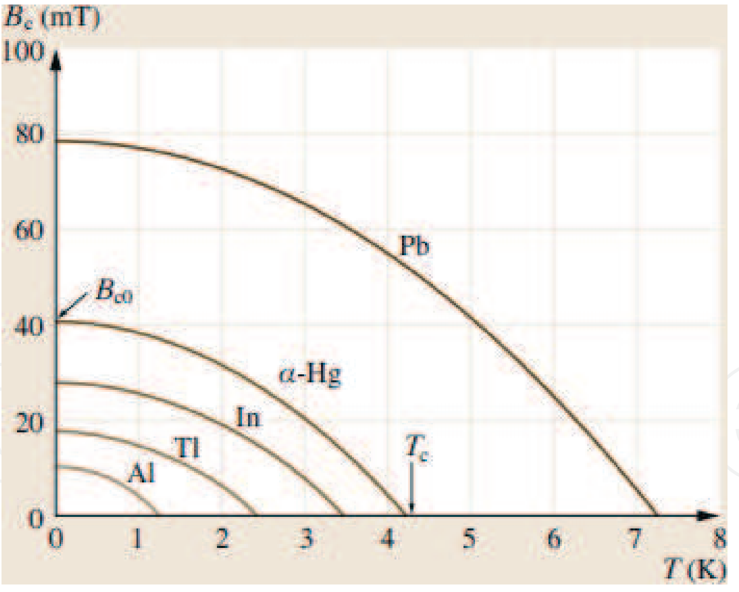

Figure 4.
Critical field as a function of temperature plots for selected metallic superconductors. The B_c0 values vary from ≈10 − ≈ 80 mT. Reproduced from Ref. [25].

confirms arising properties that are observed during superconducting state, and also proved independent order of the final conditions reached to applied-magnetic-field as well as temperature [25].

4. Cuprates

Layered material cuprates consisting of copper-oxide superconducting-layers (**Figure 5**), which are separated by spacer-layers is an interesting field of research also. The crystal structure of cuprates is closely related to the structure of two-dimensional materials. The superconductivity of these materials is evaluated by electrons randomly moving within intercalated layers of copper oxide (CuO_2) that are weakly coupled in nature. However, other layers containing metal and non-metal ions (lanthanum, strontium, and barium atoms) perform an active role to stabilize the structure through doping process of electrons/holes upon copper oxide layers.

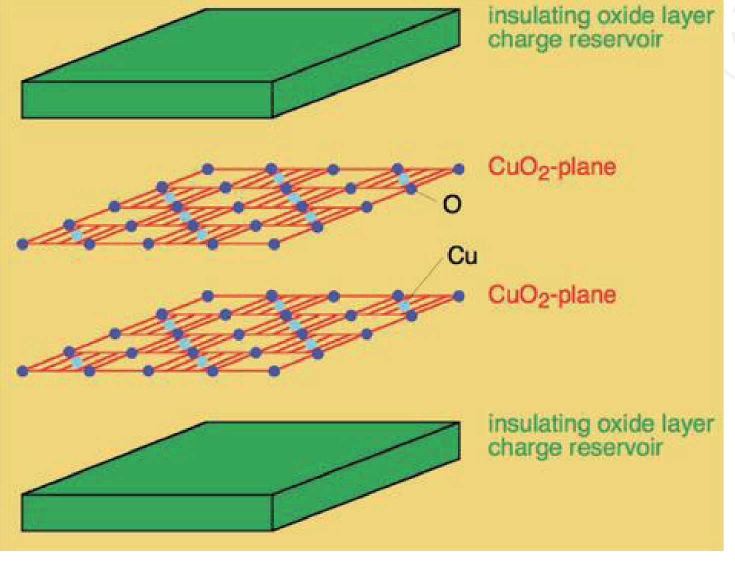

Figure 5.
Schematic geometry of a cuprate HTS superconductor. Reproduced from Ref. [59].

On the other hand, the undoped materials such as mott insulators are identified as of long-range order of magnitudes of antiferromagnetic atoms at relatively low temperatures. However, single-band-models describe electronic properties other than unique behavior [47, 60–62]. The hole-doped HTS presenting a region of antiferromagnetic behavior ordering at low *p* and superconductivity at a higher doping ratio [63].

Furthermore, cuprates superconductors possess unique perovskite structures. Copper oxide planes indicate checkerboard lattices in square shape oxide (O^{2-} ions) as well as cupric (Cu^{2+} ions) residing at centers of squares. Unit cells are rotated through 45° angles from these squares. Chemical formulae corresponding to each superconductor possess fractional numbers to represent required doping necessary for sufficient superconductivity. Cuprate superconductors have been classified into several families with respect to containing elements as well as the number of layers of copper-oxide attributed to every superconducting block. As an example, YBCO may be referred to as Y123 and BSCCO as Bi2201/Bi2212/Bi2223 alternatively which depends on contribution of each layer to every superconducting block (n). Optimum T_c was evaluated against optimum doping of p = 0.16 whereas optimal layers were n = 3 corresponding to each superconducting block [62, 64, 65].

Superconductivity related to cuprates is still a continuously researchable subject and considerable debate obviously for further research. Considerable aspects common to superconducting materials are to be diagnosed. Common characteristics of antiferromagnetic materials indicate low-temperature state containing undoped material whereas superconducting state has emerged upon doped material. Primarily Cu^{2+} ions ($d_{x^2-y^2}$ orbital-state) diagnosed that electron–electron interactions were significantly dominant as compared with electron–phonon interactions in case of cuprate superconducting materials, thereby indicating unconventional superconductivity. Recently, Fermi surface work suggested occurrence of nesting caused by four points appearing in Brillouin zone of antiferromagnetic materials, and at those points, spin waves may lie due to which superconducting energy-gap may appear larger enough at those points. Minute isotope-effect was also observed for numerous cuprates relatively conventional-superconductor described deeply by BCS theory [25, 62, 66]. The cuprate process is based on the spectral distance and/or sharp peak appearance or absence. The above suggests the presence of well-defined quasi-particle excitations, e.g. as in the overdoped region of the more conventional metallic state (**Figure 6**).

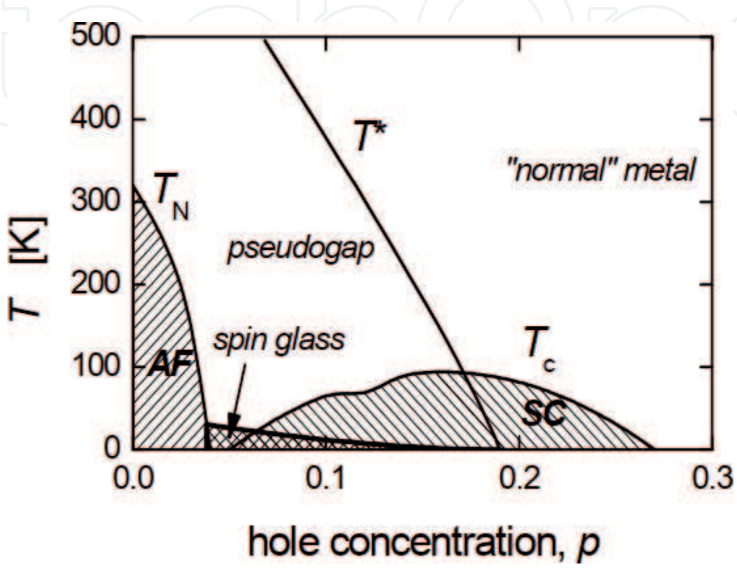

Figure 6.
Region of antiferromagnetic (AF) ordering at low p and superconductivity (SC) at higher doping observed in the universal phase diagram for hole-doped HTS superconductors. Reproduced from Ref. [63].

Electronic structure, indicating not isotropic nature of superconducting cuprates is illustrated in **Figure 1** that is highly anisotropic such as of YBCO/BSCCO. Hence, HTS fermi-surface is observed near to multi-planes of CuO_2 (doped) in the form of multi-layer structured cuprates which may appear over 2D momentum space corresponding to CuO_2 lattice space. Moreover, It might be extracted from measurements of band structure as well as from ARPES (angle-resolved photo-emission spectroscopy) analysis. **Figure 7** presents BSCCO Fermi surface, which is evaluated through ARPES. Consequently, results were obtained corresponding to in-plane anisotropic nature correspond to electronic properties relevant to HTS.

Contrast properties of hole-doped cuprates as compared with electron-doped cuprate superconductors are:

- Pseudogap phase existence upto optimal doping is observed.
- Different behaviors attributing to Uemura plot transition-temperature towards superfluid-density. London penetration depth inverse square effect appears proportional to be an as critical temperature that is for cuprate superconductors during doping process; however, proportionality constant is different for hole-doped as well as electron-doped cuprate superconductors. Linear trends strongly indicate material physics, which is logically 2d.
- Neutron diffraction (inelastic) is used to evaluate universal hourglass quality during spin excitations of cuprates.
- "Nernst effect" is evident with superconductivity as well as pseudogap phases [68–70].

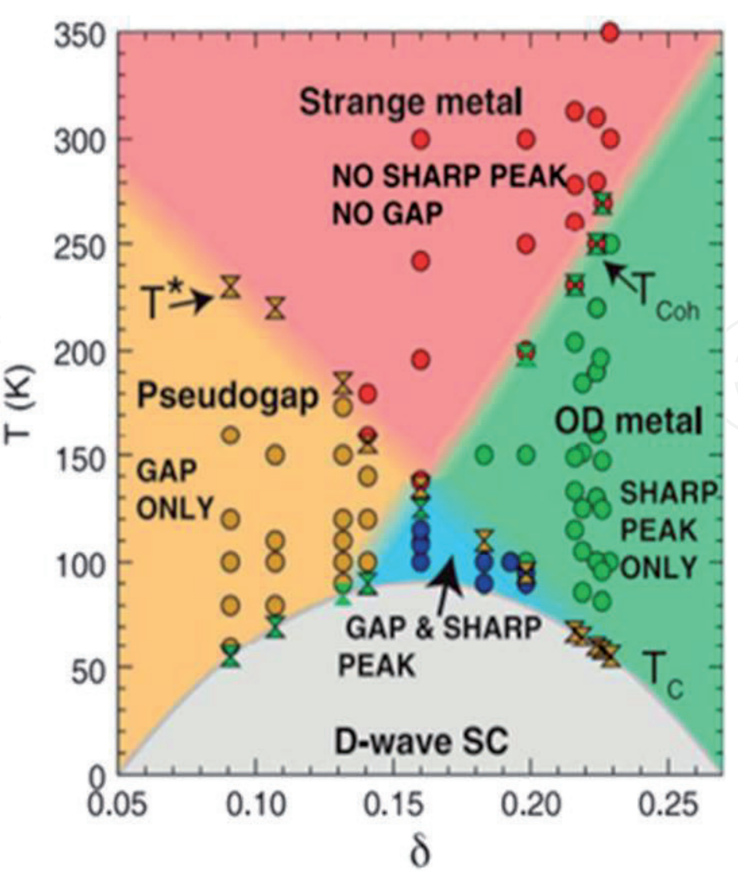

Figure 7.
The phase diagram of cuprate based on either the presence or absence of sharp peak and/or spectral gap. The latter represents the presence of well-defined quasi-particulate excitations. Reproduced from Ref. [67].

5. Preparation and fabrications routes

For the fabrication of high T_c-superconducting materials, the easiest approach which involves mixing sintering is thermochemical (solid-state) reaction. Precursors, generally oxides and carbonates, in stoichiometric ratios are mixed and ground in fine powder through a Ball mill. Alternative methods to achieve a homogeneous mixture include coprecipitation, freeze-drying [71], and sol–gel techniques. The resulted in a homogeneous mixture is then subjected to an elevated temperature of about 800–950 °C for various hours and cooled down till room temperature, reground, and put to calcination again. To ensure homogeneity of extract repeat this process several times and afterward, powder is transformed into compact pellets for sintering. The key factor to synthesize better quality superconductors is sintering conditions such as annealing temperature, time, and rate of cooling [71–73].

A quaternary compound with composition $YBa_2Cu_3O_{7-x}$; was synthesized by calcination and sintering of precursor metal oxides Y_2O_3, CuO, and carbonate $BaCO_3$ mixed and milled in an appropriate molar ratio. The reaction was carried out at 900–950 °C and sintered in an oxygen environment (950 °C). Appropriate stoichiometry of oxygen is essential to fabricate this superconducting $YBa_2Cu_3O_{7-x}$ compound. During sintering, a semiconducting tetragonal phase of $YBa_2Cu_3O_6$ is formed which converts into superconducting $YBa_2Cu_3O_{7-x}$ material on gradual cooling in an oxygen atmosphere. The addition and removal of oxygen in $YBa_2Cu_3O_{7-x}$ compound is a reversible process as a result both oxygenated orthorhombic $YBa_2Cu_3O_{7-x}$ and deoxygenated tetragonal $YBa_2Cu_3O_6$ phases are interchangeable at 700 °C [71, 74, 75]. Bi, Tl, and Hg-based HTS are difficult to prepare as compared to the synthesis of YBCO system. This hassle is attributed to the formation of similar layered structures in different phases of these compounds which results in the introduction of intergrowth (syntactic) and faults produced during synthesis which make isolation of single superconducting phase impossible. In case of Bi–Sr–Ca–Cu–O system, Bi-2212 ($T_c \approx 85$ K) is easier to form as compared to Bi-2223 single-phase ($T_c \approx 110$ K). Sintering for few hours at 860–870 °C is sufficient to prepare Bi-2212 phase while the formation of Bi-2223 phase requires extensive heating at 870 °C for more than one week [76]. It has been proposed that Pb substitution in Bi–Sr–Ca–Cu–O composites enhance growth of high-T_c phase, [77] but extended sintering for long-duration continues to be required.

5.1 HTS films and coated conductors

Films of HTS can be synthesized both via in-situ and ex-situ methods. During in-situ techniques, direct epitaxial crystallization takes place under applied conditions. In case of ex-situ synthesis, initially, low temperature is used to deposit films but this low temperature is not suitable for the required crystalline phase, thus deposited films are subjected to sintering under an oxygen environment to secure the necessary crystalline structure. Various physical means to deposit films inclusive evaporation and scattering are discussed here [71]:

5.1.1 Vacuum co-evaporation

As layers of HTS are precipitated they are evaporated by various sources like electron beam guns or resistive evaporators. This method applies to two-step synthesis [71].

5.1.2 Laser evaporation

This is an efficient technique for HTS thin film deposition. The main benefit of this method is same rate of evaporation for all chemicals present in a compound [78, 79]. Likewise, there are some disadvantages too such as (a) small portions of stoichiometric film are deposited (b) non-uniform film thickness, and (c) surface irregularity.

5.1.3 Magnetron scattering

Magnetron Scattering is used for one-stage HTS (YBCO films) deposition with the advantages of having a smooth surface and homogeneous thickness. In this method plasma with high energy electron and ions is generated which compensates the high-temperature requirement and helps to attain one-stage HTS films [80, 81].

5.1.4 Chemical precipitation

In this technique from the stream of volatile metal–organic compounds, metallic components are mixed with gaseous oxidizer in a reactor. This stream of volatile mixture is transported further and oxide film precipitates on the substrate. This method has following advantages over the previous ones:

a. More chance to get a homogeneous film with a large surface area of unplanned conformation

b. enhanced rate of condensation with better quality

c. flexibility at initial stage of technical system [82].

Other most widely used techniques are as follow:

- 2D texture film via ion-beam assisted-deposition [82, 83].
- Electro-phoretic deposition [84].
- MOCVD (Metal–organic chemical vapor deposition) [85].
- Coated conductors synthesis via MOD (metal–organic deposition) [86].
- Buffer layer can be prepared by surface oxidation epitaxy (SOE) [87, 88], electron beam evaporation, laser ablation, [89–91], ion beam sputtering [92, 93], and Rf-sputtering [94, 95].

5.2 BSCCO films, Tapes, and Wires

Melt-processing, electrophoretic deposition, dip-coating, doctor-bladed, and organic precursor film are some techniques helpful in synthesizing Bi-2212 thick films over Ag and MgO substrates. In doctor-bladed practice, before heat treatment, a plane film is formed over the surface of glass slab. For this purpose slurry of powder blend is poured over the glass plate and is spread with the help of a straight-edge blade attached to the plate to form a smooth film. In dip-coating method, Ag foil is dipped in mixture, and film is set down over it. To prepare organic precursor films, organometallic compounds (Bi, Ca, Sr., and Cu) solutions are deposited on Ag foil. An extra solvent is evaporated through burning and process is repeated until the desired thickness is achieved [71, 96, 97].

6. Applications

Unique properties of HTS make them very attractive from an application point of view due to continuous enhancement in their properties (**Figure 8**). Semiconductor sciences have been consistently depriving of novel applications of superconducting materials for quite a time now. Owing to their large persistent current, ever since their discovery, SC coils have always been envisioned to be used for sturdy magnetic field production. However, a major challenge faced by Type-I (first generation) HTSs was the suppression of superconductivity by magnetic fields induced within the materials by injected current. This ceased Type-I SC's application in fields involving high current and high fields. To overcome this problem, a new class of SC materials naming Type-II (second generation) HTSs having longer magnetic penetration as compared to coherence length were fabricated. Longer penetration depths favor the presence of superconductivity even in magnetic fields presence up to a critical value (Hc_2) of induced field. Another modification in HTSs was the control of power dissipation caused by Lorentz force, by properly engineered "pinning centers" that modulate the magnetic flux generated in the system [71].

6.1 Transmission of commercial power

Extremely low resistance values make HTSs an ideal candidate for transmitting commercial power to the cities. However, high cost and practically impossible implication of cryogenic temperatures to such lengthy cables limit their

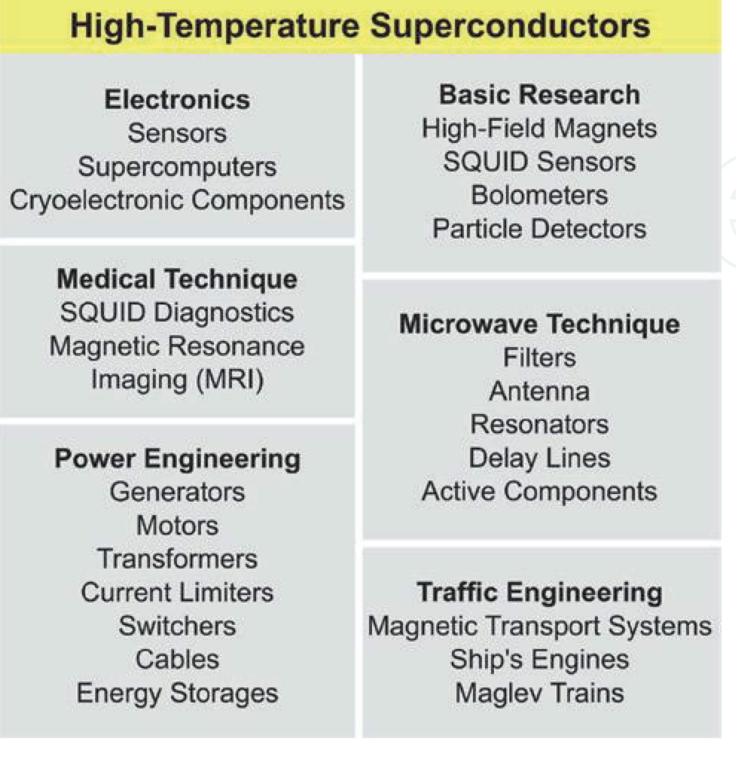

Figure 8.
Schematic overview of possible applications of HTSs. Reproduced from Ref. [59].

application for very short distances. One example of above-mentioned application was the transmission of electricity using HTSs to 150,000 citizens of Copenhagen, Denmark back in May 2001. The transmission cable was only 30 m in length which proved to be sufficient for testing. This was the first-ever commercial power transmission using superconducting cables in history. Later, USA and Japan successfully fabricated superconducting transformers using HTSC windings. Fault currents produced can be limited by Super-Foam which is produced from $YBa_2Cu_3O_z$ [13, 98].

6.2 Bio-magnetism

Another important application of HTSs is in the medical field for diagnostic purposes. Non-penetrating procedures are required in the field of bio-medicine to retrieve internal information of living body. Magnetic Resonance Imaging (MRI) has been frequently used for this purpose where a strong magnetic field has impinged into the body which imposes precessional motion of H_2 atoms present in the body. After removal of an external magnetic field, exciting H_2 atoms release energy which is detected and graphically presented by computer. Use of SC's can enhance MRI performance owing to high magnetic field induced in them due to large current flow. Before superconductor technology, it almost took 5 hours to produce single-image initially when MRI was discovered (July 3, 1977) [71].

6.3 High magnetic field in Tokamaks

Developments in fusion energy department have been made after the introduction of high-temperature superconductor (HTS) based technologies that imply high magnetic field induction (>18 T) for compact experiments in fusion power plants. Operation in high magnetic fields, large current densities, higher value of cryogenic temperature, and ability to withhold extreme tensile stress make HTS a suitable candidate as compared to LTS (Low-Temperature Superconductors). A large operating magnetic field range opens new opportunities to fabricate novel magnetic designs and improved magnetic confinement can be achieved for higher magnetic fields (> 16 T) with the help of HTS [99]. A maximum achievable induced field that depends upon current density present in HTSs has been a primary factor in fabrication of magnetic devices for fusion reactors as explained in basic tokamak design, in-depth studies, system codes, and tokamak magnet designs [100]. HTS offers a significant increase (~7.5 to 10–12 T) in on-axis BT in tokamak reactor which allows a significant increase in an applicable field in coil from 16 T to >20 T) as compared to LTS. Other advantages of HTS technology in fusion energy department include:

1. Small Burning Plasma: In mid-1980s, U.S. planted burning plasma-based fusion reactor based on the implication of SC's ability to induce large magnetic fields at a small size. The phenomenon has been successfully explained with the help of Alcator devices [99].

2. A lot of research work proposed that such small sized high field devices for burning plasma can be fabricated using copper-based magnets. Even smaller sizes can be achieved for such high field copper-based devices with the help of HTS reducing their heating and structural issues as well [101].

3. Performance: High power density and energy gain can be attained in small-sized devices based on B^3-B^4 dependence for commercial realization of such fusion reactors. However, heat exhaust and diverter limit reduction in size and high power density.

4. Operational Robustness: Compact high-field devices suffer no typical intrinsic limits (density, pressure) as they operate in normalized plasma domains. Currently, operative devices demonstrate such operating domains including safety factor (q), normalized beta (βN), and confinement enhancement factor (H).

5. Steady-State Physics: A blend of high-field, compact size, improved current profile, and high value of safety factor will generate a device having steady-state operation and high gain with good control over external current [101, 102].

6.4 Future tool kit for advanced application

As previously mentioned, HTS technology is enriched with many novel applications with medical diagnostics and energy transport/harvesting being top of the list (**Figure 8**). A major challenge faced by HTS technology is the need for extremely low temperature which is generally achieved with the help of liquid nitrogen or helium which is much costly. On the other hand, the use of H_2S for cooling purposes requires high values of pressure. Fabrication of superconductors having critical temperature (Tc) values in room temperature (RT) range with easily employable materials is a challenging task. The unavailability of any predictive route and no unique agreement on pairing mechanism of HTS technology limit the scope of this search. Apart from this drawback, low manufacturing cost is another challenge that can be overcome with use of materials existing abundantly on this planet. Stability, easy fabrication procedures, and flexibility are also required. Novel and advanced approaches need to be developed to meet all these challenges for a sustainable future [103, 104].

Although seems difficult, current scientific knowledge proposes a high probability of realizing fabrication of RT superconductors in near future. Successful manufacturing of such devices will open a vast field of applications especially in the field of energy production and transport at low cost (at ambient pressure). The development of novel technologies and advanced devices could be realized and different Gedanken experiments would be applicable with the help of RT superconductors. Imagine a conducting cable having almost zero energy losses where electrical current can flow forever with no power loss. Advanced high power generating grids could be installed using RT superconductivity technology to fabricate improved transformers, fault current limiters, and novel synchronous condensers. Moreover, a wire with never depleting current could also be used as an RT SMES (superconducting magnetic energy storage) device. RT SMES device, as opposed to other typical storage devices, would offer everlasting storage of energy with negligible losses [105].

Another similar application of RT superconductors is the development of advanced bearings to be used in flywheel energy storage. Other applications include production of high-field superconducting magnets for scientific and technical use while cost-effective and improved MRI scanners would be available for medical applications. Compact and simplified fabrication (no cooling required) of rotating motors, generators, and other electromechanical devices would also be possible with RTS technology. This would open new opportunities for the production of electric motor cars and electric storage devices in the future. In transport department, a significant enhancement in levitating trains technology is also expected where superconducting magnetic levitation phenomenon could be employed. Improvement in low-power technologies like SQUIDS, detectors, filters, and sensors is also expected with the use of RT superconductors which would bring revolutionary changes in medical and information technology. Lastly, realization of compact and efficient quantum and Josephson computers will also become possible with this novel technology [59, 60, 106, 107].

7. Outlook and future prospects

Around the world, a neglected hope exists to reduce energy costs using superconductivity in power transmissions. In the nearby future of transportation, Mag-1 eV trains use superconductivity for eliminating friction to poise train cars above the rail. Who knows? Maybe one-day smartphones with long-lasting battery timing up to months or more would be manufactured based on superconductivity electronics. High-Tc era exposed remarkable production with a new superconductor family (Tc ≥ 23 K) discovered every few years in its first 25 years. Prediction of future discoveries is difficult as each class is chemically distinct from the others but some indicators are quite obvious. Future HTSCs are incredible having considerable (≥50%) nonmetal content based on known materials with high-T_c. 'Metal-nonmetal' group associates very high Tc's having nonmetal contents of 40–60% with simple ionic bond considerations. Since 2008, none of any element in previous high-Tc families had featured except Fe. Spin–Spin fluctuations are necessary for the superconducting mechanism of cuprates and iron arsenide materials with highest-Tc, where transition metals are required in heavy-fermion (intermetallic) superconductor PuCoGa (Tc = 18 K) with f-block magnetism [29, 108]. In near future, such materials doped with nonmetals would lead towards tremendous discoveries. Other electronic instabilities may arise on basis of non-magnetic mechanisms, as suppression of charge disproportionation for the bismuthate superconductors. In metal-nonmetal families, chemical doping is prescribed to put an end to spin/charge-ordered ground state inducing superconductivity. This may happen due to incidental band overlap (as in $YBa_2Cu_3O_7$) but sometimes by non-aliovalent substitutions of non-stoichiometry. However, disorders in metal-non-metal's networks lead to subduing superconductivity. To obtain high-Tc's, chemical tuning of additional parts of the network (charge reservoir) manifested via difference between maximum Tc for $BaBi_{1-x}Pb_xO_3$ (13 K, essential Bi sites doping) and for $Ba_{1-x}K_xBiO_3$ (30 K, secondary Ba sites doping). Another high-Tc materials class is portrayed by bonding among metals and nonmetals which is attributed to high content values of nonmetals (100% in case of pure organic SCs). Elements forming strong covalent bonds and networks, B and C are restricted to this group but similar nonmetals (O, N, S, P, Si) can act as dopants as well. Highest obtained Tc (41 K) so far, owing to predictions from optimal BCS (weak-coupling) and superconductivity acts like BCS in this group. For A_3C_{60} and MgB_2 (and also YPd_2B_2C) with proper stoichiometry, the optimal electronic structure for superconductivity is attained while Tc isn't affected by chemical doping.

Conflict of interest

Authors have declared no 'conflict of interest'.

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References

[1] S. J. Blundell, *Superconductivity: a very short introduction*. OUP Oxford, 2009.

[2] H. Rogalla and P. H. Kes, *100 years of superconductivity*. Taylor & Francis, 2011.

[3] R. B. Laughlin, *A different universe: Reinventing physics from the bottom down*. Basic Books (AZ), 2005.

[4] R. Radebaugh and Y. Bar-Cohen, "Low Temperature Materials and Mechanisms: Applications and Challenges," in *Low Temperature Materials and Mechanisms*: CRC Press, 2016, pp. 455-494.

[5] S. Prestemon, "High Temperature Superconductor Cable Test Facility Specifications," 2020.

[6] J. Huang and H. Wang, "Effective magnetic pinning schemes for enhanced superconducting property in high temperature superconductor YBa2Cu3O7−x: a review," *Superconductor Science and Technology,* vol. 30, no. 11, p. 114004, 2017/10/27 2017.

[7] T. Liu, J. J. He, and F. Nori, "Majorana corner states in a two-dimensional magnetic topological insulator on a high-temperature superconductor," *Physical Review B,* vol. 98, no. 24, p. 245413, 12/13/2018.

[8] D. Uglietti, "A review of commercial high temperature superconducting materials for large magnets: from wires and tapes to cables and conductors," *Superconductor Science and Technology,* vol. 32, no. 5, p. 053001, 2019/04/09 2019.

[9] T. T. Saraiva *et al.*, "Multiband Material with a Quasi-1D Band as a Robust High-Temperature Superconductor," *Physical Review Letters,* vol. 125, no. 21, p. 217003, 11/18/2020.

[10] V. S. Vulusala G and S. Madichetty, "Application of superconducting magnetic energy storage in electrical power and energy systems: a review," vol. 42, no. 2, pp. 358-368, 2018.

[11] P. Mukherjee and V. V. Rao, "Design and development of high temperature superconducting magnetic energy storage for power applications - A review," *Physica C: Superconductivity and its Applications,* vol. 563, pp. 67-73, 2019/08/15/2019.

[12] U. Pinsook, "In search for near-room-temperature superconducting critical temperature of metal superhydrides under high pressure: A review," *Journal of Metals, Materials and Minerals,* vol. 30, no. 2, 06/30 2020.

[13] D. I. Doukas, "Superconducting Transmission Systems: Review, Classification, and Technology Readiness Assessment," IEEE Transactions on Applied Superconductivity, vol. 29, no. 5, pp. 1-5, 2019.

[14] M. N. Gastiasoro, J. Ruhman, and R. M. Fernandes, "Superconductivity in dilute SrTiO3: A review," *Annals of Physics,* vol. 417, p. 168107, 2020/06/01/2020.

[15] S. Hüfner, M. A. Hossain, A. Damascelli, and G. A. Sawatzky, "Two gaps make a high-temperature superconductor?," *Reports on Progress in Physics,* vol. 71, no. 6, p. 062501, 2008/05/02 2008.

[16] M. Noe and M. Steurer, "High-temperature superconductor fault current limiters: concepts, applications, and development status," *Superconductor Science and*

Technology, vol. 20, no. 3, pp. R15-R29, 2007/01/15 2007.

[17] B. Lake *et al.*, "Antiferromagnetic order induced by an applied magnetic field in a high-temperature superconductor," *Nature,* vol. 415, no. 6869, pp. 299-302, 2002/01/01 2002.

[18] A. P. Malozemoff *et al.*, "Progress in high temperature superconductor coated conductors and their applications," *Superconductor Science and Technology,* vol. 21, no. 3, p. 034005, 2008/02/20 2008.

[19] M. Kumar, "High-Temperature Superconductivity : Milestone in the Field of Electronics," 2017.

[20] J. Lloberas, A. Sumper, M. Sanmarti, and X. Granados, "A review of high temperature superconductors for offshore wind power synchronous generators," *Renewable and Sustainable Energy Reviews,* vol. 38, pp. 404-414, 2014/10/01/2014.

[21] A. Mourachkine, *Room-temperature superconductivity*. Cambridge Int Science Publishing, 2004.

[22] S. K. Verma, A. Kumari, A. Gupta, and B. D. Indu, "The high-temperature superconductor gap equation," *Physica Scripta,* vol. 94, no. 3, p. 035701, 2019/01/24 2019.

[23] S. J. J. i. Tanaka, "High-temperature superconductivity: History and outlook," vol. 4, no. 4, pp. 17-22, 2001.

[24] J. Zhang *et al.*, "High-temperature superconductivity in the Ti-H system at high pressures," *Physical Review B,* vol. 101, no. 13, p. 134108, 04/17/2020.

[25] R. Wesche, "High-Temperature Superconductors," in *Springer Handbook of Electronic and Photonic Materials*, S. Kasap and P. Capper, Eds. Cham: Springer International Publishing, 2017, pp. 1-1.

[26] E. Snider *et al.*, "Room-temperature superconductivity in a carbonaceous sulfur hydride," *Nature,* vol. 586, no. 7829, pp. 373-377, 2020/10/01 2020.

[27] A. P. Drozdov *et al.*, "Superconductivity at 250 K in lanthanum hydride under high pressures," *Nature,* vol. 569, no. 7757, pp. 528-531, 2019/05/01 2019.

[28] A. P. Drozdov, M. I. Eremets, I. A. Troyan, V. Ksenofontov, and S. I. Shylin, "Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system," *Nature,* vol. 525, no. 7567, pp. 73-76, 2015/09/01 2015.

[29] J. P. Attfield, "Chemistry and high temperature superconductivity," *Journal of Materials Chemistry,* 10.1039/C0JM03274C vol. 21, no. 13, pp. 4756-4764, 2011.

[30] J. R. Hull and M. Murakami, "Applications of bulk high-temperature Superconductors," Proceedings of the IEEE, vol. 92, no. 10, pp. 1705-1718, 2004.

[31] R. J. Cava, "Oxide Superconductors," vol. 83, no. 1, pp. 5-28, 2000.

[32] T. Y. Chen, Z. Tesanovic, R. H. Liu, X. H. Chen, and C. L. Chien, "A BCS-like gap in the superconductor SmFeAsO0.85F0.15," (in eng), *Nature,* vol. 453, no. 7199, pp. 1224-7, Jun 26 2008.

[33] J. Prakash, S. J. Singh, S. Patnaik, and A. K. Ganguli, "Superconductivity at 11.3 K induced by cobalt doping in CeFeAsO," *Solid State Communications,* vol. 149, no. 5, pp. 181-183, 2009/02/01/2009.

[34] K. Vinod, R. G. A. Kumar, and U. Syamaprasad, "Prospects for MgB2superconductors for magnet application," *Superconductor Science and Technology,* vol. 20, no. 1, pp. R1-R13, 2006/12/04 2006.

[35] B. A. Glowacki *et al.*, "MgB2 superconductors for applications," *Physica C: Superconductivity,* vol. 387, no. 1, pp. 153-161, 2003/05/01/2003.

[36] S. Katano, J. A. Fernandez-Baca, S. Funahashi, N. Môri, Y. Ueda, and K. Koga, "Crystal structure and superconductivity of La2−xBaxCuO4 (0.03≤x≤0.24)," *Physica C: Superconductivity,* vol. 214, no. 1, pp. 64-72, 1993/09/01/1993.

[37] Z. Guguchia, A. Maisuradze, G. Ghambashidze, R. Khasanov, A. Shengelaya, and H. Keller, "Tuning the static spin-stripe phase and superconductivity in La2−xBaxCuO4 (x = 1/8) by hydrostatic pressure," *New Journal of Physics,* vol. 15, no. 9, p. 093005, 2013/09/03 2013.

[38] X. Xu, "A review and prospects for Nb3Sn superconductor development," *Superconductor Science and Technology,* vol. 30, no. 9, p. 093001, 2017/08/02 2017.

[39] J.-F. Zhang, M. Gao, K. Liu, and Z.-Y. Lu, "First-principles study of the robust superconducting state of NbTi alloys under ultrahigh pressures," *Physical Review B,* vol. 102, no. 19, p. 195140, 11/23/2020.

[40] T. Davies, C. R. M. Grovenor, and S. C. Speller, "Atmospheric oxidation of NbTi superconductor," *Journal of Alloys and Compounds,* vol. 848, p. 156345, 2020/12/25/2020.

[41] C. Kittel, P. McEuen, and P. McEuen, *Introduction to solid state physics*. Wiley New York, 1996.

[42] K. O. Moura *et al.*, "Superconducting Properties in Arrays of Nanostructured β-Gallium," *Scientific Reports,* vol. 7, no. 1, p. 15306, 2017/11/10 2017.

[43] P. W. Anderson, "Comment on "Two-Dimensional Antiferromagnetic Quantum Spin-Fluid State in La_2CuO_4""," *Physical Review Letters,* vol. 59, no. 21, pp. 2497-2497, 11/23/1987.

[44] N. E. Bickers, D. J. Scalapino, and R. T. Scalettar, "CDW AND SDW MEDIATED PAIRING INTERACTIONS," vol. 01, no. 03n04, pp. 687-695, 1987.

[45] C. Lee, W. Yang, and R. G. Parr, "Development of the Colle-Salvetti correlation-energy formula into a functional of the electron density," *Physical Review B,* vol. 37, no. 2, pp. 785-789, 01/15/1988.

[46] C. Gros, D. Poilblanc, T. M. Rice, and F. C. Zhang, "Superconductivity in correlated wavefunctions," *Physica C: Superconductivity,* vol. 153-155, pp. 543-548, 1988/06/01/1988.

[47] T. Yanagisawa, "Mechanism of High-Temperature Superconductivity in Correlated-Electron Systems," *Condensed Matter,* vol. 4, no. 2, 2019.

[48] S. Putilin, E. Antipov, O. Chmaissen, and M. J. N. Marezio, "Nature 362 226 Schilling A, Cantoni M, Guo JD and Ott HR 1993," vol. 363, p. 56, 1993.

[49] M. Buzzi *et al.*, "Photomolecular High-Temperature Superconductivity," *Physical Review X,* vol. 10, no. 3, p. 031028, 08/06/2020.

[50] S. R. Xie, G. R. Stewart, J. J. Hamlin, P. J. Hirschfeld, and R. G. Hennig, "Functional form of the superconducting critical temperature from machine learning," *Physical Review B,* vol. 100, no. 17, p. 174513, 11/18/2019.

[51] B. Dalla Piazza *et al.*, "Fractional excitations in the square-lattice quantum antiferromagnet," *Nature Physics,* vol. 11, no. 1, pp. 62-68, 2015/01/01 2015.

[52] N. Hao and J. Hu, "Topological quantum states of matter in iron-based superconductors: from concept to material realization," National Science Review, vol. 6, no. 2, pp. 213-226, 2018.

[53] X. Lin, Z. Zhu, B. Fauqué, and K. Behnia, "Fermi Surface of the Most Dilute Superconductor," *Physical Review X,* vol. 3, no. 2, p. 021002, 04/15/2013.

[54] F. J. Kedves, S. Mészáros, K. Vad, G. Halász, B. Keszei, and L. Mihály, "Estimation of maximum electrical resistivity of high Tc superconducting ceramics by the meissner effect," *Solid State Communications,* vol. 63, no. 11, pp. 991-992, 1987/09/01/1987.

[55] I. Tamir *et al.*, "Sensitivity of the superconducting state in thin films," vol. 5, no. 3, p. eaau3826, 2019.

[56] A. F. Kemper, T. A. Maier, S. Graser, H. P. Cheng, P. J. Hirschfeld, and D. J. Scalapino, "Sensitivity of the superconducting state and magnetic susceptibility to key aspects of electronic structure in ferropnictides," *New Journal of Physics,* vol. 12, no. 7, p. 073030, 2010/07/23 2010.

[57] S. Maiti, M. M. Korshunov, T. A. Maier, P. J. Hirschfeld, and A. V. Chubukov, "Evolution of the Superconducting State of Fe-Based Compounds with Doping," *Physical Review Letters,* vol. 107, no. 14, p. 147002, 09/27/2011.

[58] L. Hao and T. K. Lee, "Surface spectral function in the superconducting state of a topological insulator," *Physical Review B,* vol. 83, no. 13, p. 134516, 04/18/2011.

[59] A. Bussmann-Holder and H. Keller, "High-temperature superconductors: underlying physics and applications," (in English), *Zeitschrift für Naturforschung B,* vol. 75, no. 1-2, pp. 3-14, 01 Feb. 2020 2020.

[60] N. Plakida, *High-Temperature Cuprate Superconductors: Experiment, Theory, and Applications*. Springer Science & Business Media, 2010.

[61] A. Rahman, Z. Rahaman, N. J. A. J. o. P. Samsuddoha, and Applications, "A review on cuprate based superconducting materials including characteristics and applications," vol. 3, no. 2, pp. 39-56, 2015.

[62] C. C. Tsuei and J. R. Kirtley, "Pairing symmetry in cuprate superconductors," *Reviews of Modern Physics,* vol. 72, no. 4, pp. 969-1016, 10/01/2000.

[63] J. L. Tallon, "Oxygen in High-Tc Cuprate Superconductors," in *Frontiers in Superconducting Materials*, A. V. Narlikar, Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2005, pp. 295-330.

[64] G. Deutscher, "Andreev--Saint-James reflections: A probe of cuprate superconductors," *Reviews of Modern Physics,* vol. 77, no. 1, pp. 109-135, 03/23/2005.

[65] L. Taillefer, "Scattering and Pairing in Cuprate Superconductors," vol. 1, no. 1, pp. 51-70, 2010.

[66] A. Damascelli, Z. Hussain, and Z.-X. Shen, "Angle-resolved photoemission studies of the cuprate superconductors," *Reviews of Modern Physics,* vol. 75, no. 2, pp. 473-541, 04/17/2003.

[67] U. Chatterjee *et al.*, "Electronic phase diagram of high-temperature copper oxide superconductors,"*Proceedings of the National Academy of Sciences*, vol. 108, no. 23, pp. 9346-9349, 2011

[68] C. Weber, K. Haule, and G. Kotliar, "Strength of correlations in electron- and hole-doped cuprates," *Nature Physics,* vol. 6, no. 8, pp. 574-578, 2010/08/01 2010.

[69] S. W. Jang, H. Sakakibara, H. Kino, T. Kotani, K. Kuroki, and M. J. Han, "Direct theoretical evidence for weaker correlations in electron-doped and Hg-based hole-doped cuprates," *Scientific Reports,* vol. 6, no. 1, p. 33397, 2016/09/16 2016.

[70] N. P. Armitage, P. Fournier, and R. L. Greene, "Progress and perspectives on electron-doped cuprates," *Reviews of Modern Physics,* vol. 82, no. 3, pp. 2421-2487, 09/10/2010.

[71] A. Saleem and S. T. Hussain, "Review the High Temperature Superconductor (HTSC) Cuprates-Properties and Applications," Journal of Surfaces and Interfaces of Materials, vol. 1, no. 2, pp. 97-119, 2013.

[72] N. Khare, *Handbook of High-Temperature Superconductor*. CRC Press, 2003.

[73] S. Yamanaka, E. Enishi, H. Fukuoka, and M. Yasukawa, "High-Pressure Synthesis of a New Silicon Clathrate Superconductor, Ba8Si46," *Inorganic Chemistry,* vol. 39, no. 1, pp. 56-58, 2000/01/01 2000.

[74] M. Rotta *et al.*, "One-pot-like facile synthesis of YBa2Cu3O7-δ superconducting ceramic: Using PVP to obtain a precursor solution in two steps," *Materials Chemistry and Physics,* vol. 243, p. 122607, 2020/03/01/2020.

[75] Y. Shi *et al.*, "Synthesis of YBa2Cu3O7−δ and Y2BaCuO5 Nanocrystalline Powders for YBCO Superconductors Using Carbon Nanotube Templates," *ACS Nano,* vol. 6, no. 6, pp. 5395-5403, 2012/06/26 2012.

[76] J. M. Tarascon *et al.*, "Preparation, structure, and properties of the superconducting compound series $Bi_2Sr_2Ca_{n-1}Cu_nO_y$ with n = 1, 2, and 3," *Physical Review B,* vol. 38, no. 13, pp. 8885-8892, 11/01/1988.

[77] D. Shi *et al.*, "Origin of enhanced growth of the 110 K superconducting phase by Pb doping in the Bi-Sr-Ca-Cu-O system," vol. 55, no. 7, pp. 699-701, 1989.

[78] E. Pomjakushina, K. Conder, V. Pomjakushin, M. Bendele, and R. Khasanov, "Synthesis, crystal structure, and chemical stability of the superconductor $FeSe_{1-x}$," *Physical Review B,* vol. 80, no. 2, p. 024517, 07/30/2009.

[79] W. Kautek, B. Roas, and L. Schultz, "Formation of Y Ba Cu oxide thin films by pulsed laser deposition: A comparative study in the UV, visible and IR range," *Thin Solid Films,* vol. 191, no. 2, pp. 317-334, 1990/10/15/1990.

[80] J. J. Olaya, L. Huerta, S. E. Rodil, and R. Escamilla, "Superconducting niobium nitride films deposited by unbalanced magnetron sputtering," *Thin Solid Films,* vol. 516, no. 23, pp. 8768-8773, 2008/10/01/2008.

[81] K. Salamon, O. Milat, N. Radić, P. Dubček, M. Jerčinović, and S. Bernstorff, "Structure and morphology of magnetron sputtered W films studied by x-ray methods," *Journal of Physics D: Applied Physics,* vol. 46, no. 9, p. 095304, 2013/02/05 2013.

[82] B. Jayaram, H. Chen, and J. Callaway, "Magnetism of Fe, Ni, and Zn in $Nd_{1.85}Ce_{0.15}CuO_4$: Comparison of experiment and theory," *Physical Review B,* vol. 52, no. 5, pp. 3742-3747, 08/01/1995.

[83] K. Iida *et al.*, "Epitaxial Growth of Superconducting Ba(Fe1-xCox)2As2Thin Films on Technical Ion Beam Assisted Deposition MgO Substrates," *Applied Physics Express,* vol. 4, no. 1, p. 013103, 2010/12/24 2010.

[84] J. B. Mooney *et al.*, "Electrophoretic Deposition of High-Temperature Superconductor Thick Films," *MRS*

Proceedings, vol. 169, p. 759, 1989, Art. no. 759.

[85] K. Endo, H. Yamasaki, S. Misawa, S. Yoshida, and K. J. N. Kajimura, "High-quality superconducting thin films of Bi2Sr2Ca2Cu3Ox grown in situ by metalorganic CVD," vol. 355, no. 6358, pp. 327-328, 1992.

[86] S. Ghalsasi, Y. X. Zhou, J. Chen, B. Lv, and K. Salama, "MOD multi-layer YBCO films on single-crystal substrate," *Superconductor Science and Technology,* vol. 21, no. 4, p. 045015, 2008/03/06 2008.

[87] K. Matsumoto, S. Kim, I. Hirabayashi, T. Watanabe, N. Uno, and M. Ikeda, "High critical current density YBa2Cu3O7−δ tapes prepared by the surface-oxidation epitaxy method," *Physica C: Superconductivity,* vol. 330, no. 3, pp. 150-154, 2000/03/15/2000.

[88] T. Watanabe, Y. Ohashi, T. Maeda, M. Mimura, and I. Hirabayashi, "Fabrication of Y-Ba-Cu-O films on surface-oxidation epitaxy (SOE) processed substrates," IEEE Transactions on Applied Superconductivity, vol. 13, no. 2, pp. 2484-2487, 2003.

[89] P. E. Dyer, A. Issa, and P. H. Key, "Dynamics of excimer laser ablation of superconductors in an oxygen environment," vol. 57, no. 2, pp. 186-188, 1990.

[90] D. B. Geohegan, "Physics and diagnostics of laser ablation plume propagation for high-Tc superconductor film growth," *Thin Solid Films,* vol. 220, no. 1, pp. 138-145, 1992/11/20/1992.

[91] T. J. Jackson and S. B. Palmer, "Oxide superconductor and magnetic metal thin film deposition by pulsed laser ablation: a review," *Journal of Physics D: Applied Physics,* vol. 27, no. 8, pp. 1581-1594, 1994/08/14 1994.

[92] L. Zhang, S. Tong, H. Liu, Y. Li, and Z. Wang, "Effects of sputtering and assisting ions on the orientation of titanium nitride films fabricated by ion beam assisted sputtering deposition from metal target," *Materials Letters,* vol. 171, pp. 304-307, 2016/05/15/2016.

[93] R. Córdoba, A. Ibarra, D. Mailly, and J. M. De Teresa, "Vertical Growth of Superconducting Crystalline Hollow Nanowires by He+ Focused Ion Beam Induced Deposition," *Nano Letters,* vol. 18, no. 2, pp. 1379-1386, 2018/02/14 2018.

[94] H.-U. Habermeier, G. Beddies, B. Leibold, G. Lu, and G. Wagner, "Y-Ba-Cu-O high temperature superconductor thin film preparation by pulsed laser deposition and RF sputtering: A comparative study," *Physica C: Superconductivity,* vol. 180, no. 1, pp. 17-25, 1991/09/01/1991.

[95] M. S. Raven, "Radio frequency sputtering and the deposition of high-temperature superconductors," *Journal of Materials Science: Materials in Electronics,* vol. 5, no. 3, pp. 129-146, 1994/06/01 1994.

[96] E. A. Duarte, P. A. Quintero, M. W. Meisel, and J. C. Nino, "Electrospinning synthesis of superconducting BSCCO nanowires," *Physica C: Superconductivity,* vol. 495, pp. 109-113, 2013/12/15/2013.

[97] H. Yang, X. Yu, Y. Ji, and Y. Qi, "Surface treatment of nickel substrate for the preparation of BSCCO film through sol–gel method," *Applied Surface Science,* vol. 258, no. 11, pp. 4852-4856, 2012/03/15/2012.

[98] R. Inoue, K. Igarashi, Y. Nagasaki, D. Miyagi, M. Tsuda, and H. Matsuki, "Electric Power Transmission Characteristics of a Wireless Power Transmission System Using High Temperature Superconducting Coils for Railway Vehicle," IEEE Transactions on

Applied Superconductivity, vol. 29, no. 5, pp. 1-5, 2019.

[99] P. Bruzzone *et al.*, "High temperature superconductors for fusion magnets," *Nuclear Fusion,* vol. 58, no. 10, p. 103001, 2018/08/22 2018.

[100] F. D. Marco, L. Pieroni, F. Santini, and S. E. Segre, "High magnetic field tokamaks," *Nuclear Fusion*, vol. 26, no. 9, pp. 1193-1241, 1986/09/01 1986.

[101] M. Lewandowska, A. Dembkowska, R. Heller, J. Świerblewski, and M. Wolf, "Hydraulic characterization of conductor prototypes for fusion magnets," *Cryogenics,* vol. 105, p. 103013, 2020/01/01/2020.

[102] J. Wesson and D. J. Campbell, *Tokamaks*. Oxford university press, 2011.

[103] S. Foner and B. B. Schwartz, *Superconductor materials science: metallurgy, fabrication, and applications*. Springer Science & Business Media, 2012.

[104] F. Grilli *et al.*, "Superconducting motors for aircraft propulsion: the Advanced Superconducting Motor Experimental Demonstrator project," *Journal of Physics: Conference Series,* vol. 1590, p. 012051, 2020/07 2020.

[105] S. S. Kalsi, *Applications of high temperature superconductors to electric power equipment*. John Wiley & Sons, 2011.

[106] R. L. Fagaly, "Superconducting quantum interference device instruments and applications," vol. 77, no. 10, p. 101101, 2006.

[107] I. Pallecchi, M. Eisterer, A. Malagoli, and M. Putti, "Application potential of Fe-based superconductors," *Superconductor Science and Technology,* vol. 28, no. 11, p. 114005, 2015/10/07 2015.

[108] J. L. Sarrao *et al.*, "Plutonium-based superconductivity with a transition temperature above 18 K," *Nature,* vol. 420, no. 6913, pp. 297-299, 2002/11/01 2002.