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Review Article

The High-Temperature Superconductors: The Synthesis Methods, Physical Properties, and Effects of Partial Replacement: A Comprehensive Review

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ABSTRACT

This paper presents a comprehensive analysis of the steps involved in the HTS approach, focusing on the multi-element sintering and thermal treatment techniques on the physical properties and crystal structure of the materials. The paper discusses the many influences that are transmitted through their fundamental properties, such as the magnetic field of temperature (Tc) and the AC current density, with an emphasis on other issues to improve these gains. The latest microelectronics, such as solid-state interactions, pulsed laser SEP, and CO_2 laser radiation, are extracted, and how they can improve the electronic performance and microstructure of micro conductors. In addition, the alternative research addresses the effect of various elements (such as silver, mercury, nickel, and aluminum) on the stability of structure, phase formation, and thermal and electrical terms of materials. The results show that the microelectronics methods are fully optimized in material components that can significantly improve the performance of high-field computers, supporting their applications in advanced areas such as computing, power systems, and high-field magnetic imaging technologies. The search for recommendations for future studies is still important to achieve significant reliability at room temperature, which may open up significant horizons for technology science.

Keyword: High-temperature superconductors, synthesis methods, physical properties, element substitution.

INTRODUCTION

Superconductivity the disintegration of magnetic flux at very low temperatures, close to zero kelvin, is a significant occurrence in solid state physics. This phenomenon, known as superconductivity, occurs when the electrical resistance of metals and certain compounds drops. Kamerlling Onnes was the first scientist to notice this occurrence (Shaker *et al*., 2023). Superconductivity involves a joined pair of simultaneous phenomena. The primary phenomenon is denoted by perfect conductivity, whereas the second is delineated by absolute diamagnetism. This strange manifestation arises in diverse materials when subjected to frigid settings, termed the critical temperature. This pivotal threshold is represented by the symbol (T_c). Upon reaching the critical temperature, the material transforms from its standard state to the superconducting state, and the magnitude of the critical temperature demonstrates variance across differing elements. While perplexing at first glance, further examination has illuminated this captivating concept (Hamood, 2018). It has zero resistance, excellent diamagnetic behavior, and macroscopically displays these characteristics. As a result, the characteristics of these materials have made it possible for researchers to use them in highly effective discoveries and developments that are used in the majority of scientific and technological fields (Hussein *et al*., 2024). The potential applications are what drives this field and the research that goes into superconductors. Given their unusual properties, it is essential that superconductors are scrutinized thoroughly and explored to understand whether they could continue to be used for technologies in all realms. Superconductors are a field of study in flagrant evolution, so they can be classified according to coherence length and critical temperature into different classifications: Types I and II superconductor as well high or low critical temperature with crossover properties between each other (Rizwan *et al*., 2022).

In 1911 the physicist Kammerlingh Onnes, during an investigation of the temperature dependence of electrical resistance in solid mercury (Hg) at very low temperatures using a liquid helium coolant found that it became totally resistant-free below 4.2^{o}K or boiling point of liquid He known as Superconductivity. It resulted in the discovery of a novel solid-state phenomenon: Electric superconductivity (Onnes, 1911). More investigation into this wonderful phenomenon continued, and in 1933 Meissner and Ochsenfeld found one of the most crucial peculiarities in superconducting materials that are so-called ideal property; it refers to the fact that no magnetic field will pass through a material having zero-specific-resistance (Meissner and Ochsenfeld, 1933).

Superconductors have properties critical to their applications: critical temperature (T_c), critical magnetic field (Bc), and critical current density (J_c). Superconductivity temperature, also referred to as the critical temperature, is different for all materials; for example, yttrium barium copper oxide (YBCO) that is one of the most potent Type-II superconductors, has a of about 90K (Chamoli *et al*., 2024). In our effort, the critical magnetic field is split into lower and upper margin but besides the upper limit of the Type-II superconductors, associated with the irreversibility field that confines the J_c in the HTS materials, which are often much lower than the current flow through the HTS. J_c is dependent on the material structures such as grain boundaries in the polycrystalline conductors where the weakness tends to limit the current (Wesche, 2025). Knowledge of these properties is essential to the further development of superconducting technologies, including their use in energy systems and for quantum computing (Solymar *et al*., 2024). Cuprates such as (YBCO) and a number of bismuth-based materials together with other HTS have been studied extensively because of their properties and possible suasions. These materials attain superconductivity above 77^{o}K, and YBCO of about 93K of critical temperature (T_c) that is immune to certain kind of disorder (Raghavan *et al*., 2024). Due to the relative infancy of this field of high-temperature superconductivity, knowledge on the HTS is a work in progress the theories for the mechanisms of HTS include the BCS theory among others (Wu, 2024). There are concerns as to how important the HTS is to industries since they offer a chance to design the powerful electromagnetic fields for essential health systems like MRI and flexible power networks in the future that will deepest energy loss in the resistance (Qin *et al*., 2024). Although the first modern theory of superconductivity was published more than 50 years ago, the bardeen-cooper-schrieffer (BCS) theory, which was developed in 1957, still offers the most basic explanation of the phenomenon in terms of cooper pairs that come from the attractive interaction between electrons in the vicinity of the Fermi level, through the exchange of phonons (Bennemann, 2024).

The BCS theory was revolutionary since it addresses not merely the behavior of conventional superconductors, but also of other complex systems. For instance, it can be relevant to low-dimensional systems and even to trapped neutron systems for which universal behaviors are, for instance, the observed decoupling of some energy ratios on the number of particles or parameters of the trap. However, new researches have extended a support to the BCS theory further by showing that the greatest energy gap still scales with the critical temperature (T_c) irrespective of the systems involved. This universality of the energy gap to (T_c) ratio supports the stability of the BCS theory for the many different superconducting regimes (Cheng and Zhao, 2024). Sample annealing process is essential in the manufacture of superconducting compounds especially in the determination of their electronic characteristics to improve superconductivity. This process entails subjecting the samples to specific temperatures in controlled environments in which factors of oxygen and structural nature play an important role. For example, low-oxygen annealing is provided to enhance the oxygen vacancy and restore the copper within electron-doped cuprates (Henheik *et al*., 2023). Further, in (Hg, Tl-2223) and (Ti-2223) superconductors, the right choice of annealing temperatures optimizes phase development and enhances the (T_c) by unwanted magnetic impurities and facilitating carrier mobility (Alnakhlani *et al*., 2019).

This study examines several methods for producing superconductors and emphasizes the impact of partial element substitution on the physical characteristics and unit cell architectures of the resulting superconducting materials. We also examine recent studies indicating that innovative methods such as nanodotting and laser application may enhance the overall efficacy of these materials. This study seeks to deliver a thorough evaluation of potential enhancements in the synthesis and identification of materials to augment the scope and efficacy of superconductors.

Techniques for synthesizing superconductors samples

1) The solid-state reaction method: Is a prevalent method for synthesizing superconducting materials. The oxides, carbonates, and nitrates of the compound are combined in stoichiometric ratios, with isopropanol added during the process to prevent the release of sample powder. The samples are subsequently ground at appropriate pressures to ensure homogeneous preparation. The mixture undergoes a high-temperature sintering process, a heat treatment typically conducted at temperatures between 800 and 950°C for several hours to establish the superconducting phase, improve sample density, alleviate stresses from the pressing stage, and augment the samples' hardness. For enhanced reproducibility, the samples are then reground and repelletized prior to undergoing a second annealing process. These tactics enhance the material's mechanical and electrical properties, hence augmenting its superconducting capabilities (Razeg *et al*., 2011).
2) The spray pyrolysis technique: Involves the application of chemical solutions containing the compound's components onto a heated substrate. Upon contact with the heated surface, the produced droplets experience swift solvent evaporation, resulting in the formation of a thin layer of solid material on the surface. The minuscule layer is subsequently exposed to a thermal treatment procedure to crystallize into a superconducting material. This technique effectively produces uniform thin layers with precise control over thickness and characteristics, making it highly advantageous for the fabrication of microelectronic devices and sensors. This approach offers an economical solution for the fabrication of superior superconducting materials (Al Abbas *et al*., 2023).
3) The chemical bath deposition (CBD) method: The deposition of thin superconducting films is effective. The deposition substrate is cleaned and subsequently heated to a temperature ranging from 400 to 1000°C, contingent upon the material. Subsequently, gaseous precursors, or potentially reactive agents like organometallic compounds or oxides, are introduced into the deposition reactor. The gas undergoes a chemical reaction upon contact with the surface,

resulting in either the disintegration of its constituents or the creation of a thin material layer on the surface. Deposition factors like as temperature, pressure, and gas flow are managed to produce a layer with superconducting properties; the sample may also undergo heat treatment post-deposition to improve certain characteristics. This method facilitates the construction of thin, homogeneous layers at the nanoscale, enhancing the electrical characteristics of superconductors (Saeed and Uonis, 2022; Maysam *et al*., 2021).

4) The sol-gel process: Involves the production of a colloidal solution containing the requisite ingredients, subsequently transformed into a gel. Subsequent to conversion, the gel undergoes calcination at elevated temperatures to convert the ensuing gel into an insoluble solid crystalline substance that demonstrates superconductivity. This method enables the deposition of high-purity, thin films on diverse surfaces, facilitating a broad spectrum of applications. This subsequently improves the production of superconductors and their electrical and magnetic conductivity by facilitating the modification of the crystal structure and volume distribution of the material. It also enables the incorporation of other components such as oxides and silicates that affect the compound's performance (Ibrahim, 2019; Haider, 2023).
5) Pulsed Laser Deposition (PLD): This technique entails directing high-energy laser pulses onto the target material's surface, resulting in vaporization and plasma formation. The plasma expels particles from the target material, which subsequently cling to the substrate surface, forming a thin coating. The process occurs within a vacuum chamber to restrict particle mobility, ensuring uniform application of the coating material over all surface locations. This is ideal for fabricating thin films of elements or compounds with properties distinct from their bulk counterparts, as it is particularly effective for producing thin films of superconducting materials due to its precision in thickness and quality of each layer. This technology represents one of the most intricate technologies, enabling the creation of nanostructures with exceptional properties (Borisov *et al*., 2017).
6) Plasma-enhanced chemical vapour deposition (PECVD): This technique entails the injection of reactive gases, such as silicon or oxygen, into a sealed deposition chamber, where a high-frequency electric current generates plasma. Plasma comprises active ions and electrons that facilitate the acceleration of chemical processes inside it. The gas molecules inside the plasma are decomposed into basic constituents, such as atoms or reactive chemical radicals, leading to the deposition of a solid substance on the substrate's surface. This layer can be insulating, semiconducting, or electrically conductive, contingent upon the materials employed. This method offers exact control over the characteristics of the resultant layer, including thickness and crystal structure, rendering it appropriate for the fabrication of superconductors with particular and tailored qualities (Abed *et al*., 2023).

Related studies

Superconducting materials have witnessed great developments in various fields such as transportation, energy and medicine. Many studies have confirmed that these materials are prepared using different techniques and their physical properties are studied, such as the critical temperature (T_c), where the closer the (T_c) of the superconductor is to room temperature, the better a higher (T_c) is generally desirable for practical applications, the "best" superconductor depends on the specific application and other factors like critical current density and magnetic field tolerance.

In 2015, Ahmed devoted a detailed study on the structural and electrical characterization of $Bi_2Ba_2Ca_2Cu_3O_{10+\delta}$ synthesized by solid-state process in a hydrostatic pressure of 8 tons cm^{-2} and sintered at 840°C. Four-point probe dc electrical resistivity measurement and analysis of X-ray diffraction (XRD) pattern and scanning electron microscopy (SEM) were used to investigate microstructural and superconducting properties of the Bi-2223 phase. The XRD profile analysis in the present study also explained that the synthesized nanoparticles exhibit a tetragonal crystal structure. By partially substituting Ag for Bi, Sr for Ba the compounds were prepared as $Bi_{2-x}Ag_xBa_{2-y}Sr_yCa_2Cu_3O_{10+\delta}$, where x = 0.2 and y varied between 0.1 to 0.4. In particular, we observed an increase in superconducting critical temperature (T_c) from 125K to 137K at x = 0.2 and y However, higher rates of the degree of substitution led to a reduction of (T_c) to a level of 108 K. The microstructural development of the substituted compound was investigated through SEM analysis; together with percentage composition and major/minor phases of the compound, which helped reveal the impacts of partial substitution on superconducting phases (Ahmed, 2015).

The synthesis and characteristics of bismuth-antimony-based superconductors, with the composition of $Bi_{2-x}Sb_xSr_2Ca_2Cu_3O_{10+\delta}$, were investigated by Jasim (2016) through a three-step solid state reaction method. The work analyzed samples with different Sb contents (x = 0, 0.2 and 0.4) using the method of four-probe electrical resistivity and the critical transition temperature. Data obtained proved that $Bi_2Sr_2Ca_2Cu_3O_{10.21}$, $Bi_{1.8}Sb_{0.2}Sr_2Ca_2Cu_3O_{10.28}$, and $Bi_{1.6}Sb_{0.4}Sr_2Ca_2Cu_3O_{10.23}$ are supposing to be superconducting materials with (Tc) at 112K, 114K and 113K. X-ray diffraction measurements also suggested that the samples had a polycrystalline form with an orthorhombic crystal structure. The present investigation also showed that with the change in Sb concentration, parameters such as the lattice constants, volume fraction (V-phase), the c/a parameter, and oxygen content had affected the structural and superconducting properties of the material (Jasim, 2016).

Mohammed and Jasim examined the physical properties of the high-temperature superconducting system Tl 0.5Pb0.5Ba2Can-1Cun-xNixO2n+3δ with Ni doping with different values of x = 0, 0.2, 0.4, 0.6, 0.8 and 1. The samples were prepared according to solide-state reaction at temperature of 850°C during 24h. XRD analysis yielded tetragonal phases for both the pure and Ni doped phases; including the high temperature stable phases of 1223 and 1212, the low temperature stable phase of 1202, and minor impurity phases. When increased the Ni content the above-mentioned lattice parameter a = b as well as c also increased. By using four-probe method, the variation in the (Tc) was investigated, while the increment in NiO concentration cause a variation of electrical resistivity, dielectric constant and mechanical hardness indicating that the doping of Ni is not unidimensional influence on the material (Mohammed and Jasim, 2018).

In 2018, Razzeg *et al*. Studies how partial replacement of Pb and Ag influenced thermal stability and electrical conductivity of the high temperature superconductor. Preparation of different samples for substitution levels of x and y were done at (0, 0), (0.05, 0.15), (0.1, 0.1) and (0.15, 0.05) respectively by using the solid-state reaction technique under a pressure of 8 tons/cm² and sintering at 850K. X-ray diffraction analysis showed that the best substitution ration was the study identified the need to use oxygen to improve the critical temperature, (Tc), which increased to 143K to an optimal substitution ratio. Such observations affirm that Pb and Ag doping has pronounced effects on the material’s structural and superconducting characteristics (Razzeg *et al*., 2018).

In 2019, Haider and Jasim studied the impact of preparation techniques on the physical properties of the superconducting material $Bi_2Ba_2Ca_2Cu_{2.8}Zn_{0.2}O_{10+\delta}$. The compound was synthesized using three methods: as solid-state reaction (SSR), sol-gel (SG) and pulsed laser deposition (PLD). XRD techniques identified an orthorhombic crystalline structure throughout the samples, with changes in phase amount: Certain procedures caused the enhancement of high-(Tc) Bi-2223 phase with a decrease in Bi-2212 and Bi-2201 phases and some impurities. Electrical resistivity measurements clearly supported superconductivity in all samples where the difference was observed in the critical temperature (Tc) for different preparation methods. Real and imaginary dielectric constants, loss tangent, and alternating conductivity as a function of frequency (50 Hz-1MHz) at room temperature also displayed considerable dependence on the preparation method. The general synthesis techniques clearly elucidate how the synthesis process can help in enhancing efficiency of the superconducting materials (Haider and Jasim, 2019).

In 2020, Ali *et al*. examined the influence of partial substitution of strontium (Sr) for barium (Ba) in the $Tl_{1.6}\delta Hg_{0.4}Ba_{2-y}Sr_yCa_2Cu_3O_{10+\delta}$ superconductor with regards to its structure and electric characteristics. Polycrystalline samples at a large scale were prepared through the SSRC method, and a four-probe method was used to determine (Tc) values. The onset critical temperature (Tc)(on) was between 140K and 145K and the critical temperature at zero resistivity (Tc)(Offset) rose from 95 to 125K as we increased y from 0 to 0.2. AF thinned and roughened the outer surface, as confirmed by AFM that has shown changes in grain size and surface morphology to reflect the dopant concentration. These results portray the efficiency of Sr substitution on the properties of the material; structural and superconducting (Ali *et al*., 2020).

In 2021, Tuama and Abbas in their studies "Superconducting properties of $Bi_{2-x}Pb_{0.3}W_xSr_2Ca_2Cu_3O_{10+\delta}$ compounds", synthesized a series of the superconducting samples through the solid-state reaction technique. Samples with the nominal composition $Bi_{2-x}Pb_{0.3}W_xSr_2Ca_2Cu_3O_{10+\delta}$ incorporated 50 nm tungsten (W) nanoparticles, and these samples were sintered at 850°C for 140 hours in the air. The effect of W nanoparticle replacement in bismuth sites was studied relative to X-ray diffraction pattern, scanning electron micrograph and DC electrical resistivity. The X-ray diffraction pattern was dominated by two peaks corresponding to the Bi-(2223) and Bi-(2212) diffractions along with the following secondary phases; (Sr, Ca)$2Cu_2O_3$, $Sr_2Ca_2Cu_7O_\delta$, Ca_2PbO_4, CaO and WO. Both as-received and annealed samples had an orthorhombic crystal structure and their lattice parameters and the volume fraction of the (2223) phase was determined. The (Tc) of the tapes increased with increasing amount of W nanoparticle substitution and the maximum (Tc) was obtained in the samples with x=0.3. This substitution indicated higher (Tc) compared to a pure compound and therefore showed the doping with nanoparticles could improve superconducting attributes (Tuama and Abbas, 2021).

Hasan *et al*. synthesized $Pb_2Ba_{1.7}Sr_{0.3}Ca_2Cu_3O_{10+\delta}$ superconductor in their work titled; "Synthesis and comparative analysis of crystallite size and lattice strain of $Pb_2Ba_{1.7}Sr_{0.3}Ca_2Cu_3O_{10+\delta}$ superconductor", in 2022 using the solid-state reaction technique. The characterization result of the product powder showed the dominance of the 2223 phase, but with the presence of some impurities. The XRD peaks of the quaternary Pb-based compound were indexed using a pseudo tetragonal cell with coefficients of 'a'=3.732 Å, 'b'=3.733 Å and 'c'=14.75 Å. The crystallite size and lattice strain were determined using Scherrer formula, Williamson-Hall (W.H), size-strain plot (SSP) and Halder Wagner (H.W). In the present investigation, crystallite sizes estimated by using Scherrer, W.H, SSP, and H.W were 89.454 Å, 86.659 Å, 87.756 Å and 85.470 Å and the lattice strain values obtained by W.H, SSP, and H.W were 0.006324, 0.006325 and 0.006 respectively. Taking into account the resultant regression data, it may be concluded that SSP method was the most accurate with the closeness coefficient R^2, being close to one. The crystallinity was estimated to be 59%. Electrical resistivity measurements displayed that the analyzed material does not exhibit any measure of resistance below the critical temperature indicating that the material is a superconductor. The onset critical temperature ((T_c)(onset)), The onset critical temperature ((T_c)(offset)), and transition width (ΔT) using four probe technique have been found to be 128 K, 116 K and 12 K, respectively (Hasan *et al*., 2022).

In 2022, Shaban *et al*. their studies titled "The structural properties of $Y_{1-x}La_xBa_4Cu_7O_{15+\delta}$ superconductor compound" conducted in 2022 focused on the impacts of partial substitution of iron by lanthanum (La) in the compound of $Y_{1-x}La_xBa_4Cu_7O_{15+\delta}$. The samples were prepared via the solid-state reaction technique and the synthesis of the perovskite structure was achieved at different concentrations of La viz x = 0.1, x = 0.2, and x = 0.3. To prepare the pellets, the mixed powder was placed and pressed into discs with diameter of 1.5 cm and thickness of 0.25 to 0.3 cm under pressure of 7 tons/cm², the thus-prepared samples were sintered at a rate of 120°C per hour up to 850°C for 72 hours. Crystallite size, strain, and crystallinity degree were also determined using X-ray diffraction technique also known as XRD analysis. The study presented the following findings: All the samples had an orthorhombic structure and the structural change that followed was dependent on the concentration of lanthanum. It can be seen that introduction of La systematically influenced crystal size, strain, crystallinity, and lattice parameters of the samples, thus evidencing the changes in the compound due to La-doping [37].

Taha *et al*. (2022) conducted a study on the direct impacts of carrying out a partial substitution of mercury for thallium at the thallium (Tl) layer of the high-temperature superconducting compound $Tl_{1.6}Ag0_{.4-x}Hg_xSr_2Ca_2Cu_3O_{10+\delta}$. They synthesized these compounds through a solid-state reaction and studied them in a range of x values from 0 to 0.4, looking for obvious trends in the effects of carrying out this substitution on the structural and superconducting properties of these compounds. X-ray diffraction (XRD) analysis showed that all the resulting samples had a tetragonal structure. Yet, when compared to the unalloyed samples, the addition of mercury seemed to disturb the otherwise pristine growth of the nanostructured compounds (Shaban *et al.*, 2022).

In 2023, Jasim *et al.*, examined the $Bi_2Ba_2Ca_2Cu_{2.9}Ni_{0.1}O_{10+\delta}$,$Bi_2Ba_2Ca_2Cu_{2.8}Ni_{0.2}O_{10+\delta}$ and $Bi_2Ba_2Ca_2Cu_{2.6}Ni_{0.4}O_{10+\delta}$ superconducting bismuth compounds with a partial substitution of copper fraction crystallinity ratio and crystallite size analysis for the three compounds was determined using Scherer, modified Scherer, and Williamson-Hall models. Specially the second sample, $Bi_2Ba_2Ca_2Cu_{2.8}Ni_{0.2}O_{10}$ confirmed more similarity in crystallite size, with Scherer function of 243.442 nm and Williamson-Hall function of 243.794 nm and this is the largest sample size function across the analyzed methods. Thus, concerning the electrical properties, the $Bi_2Ba_2Ca_2Cu_{2.9}Ni_{0.1}O_{10}$ sample was the most efficient one with the critical temperature, found to be 100 K and an energy gap of 6.57639×10^{-21} MeV. SEM analysis showed that the granular forms had a size of over 25 nm, and a change in morphology depending on the concentration of nickel. As for the crystalline structures, patterns showed quite homogeneity throughout the samples (Jasim *et al.*, 2023).

Ahmad *et al.* (2023) in their studies "Effect of the CO_2 laser properties on the superconducting nanocomposite $Bi_2Sr_{2-x}Y_xCa_2Cu3_{-y}Ni_yO_{10+\delta}$ at high temperatures" looked at how to minimise energy consumption in transportation and production processes through enhancing electric and mechanical properties of superconductors. This research was based on the use of laser irradiation in the $Bi_2Sr_{2-x}Y_xCa_2Cu3_{-y}Ni_yO_{10+\delta}$ compound. With the help of XRD, SEM, EDS, and the four-probe technique to compare the samples electric and structural changes due to CO_2 laser irradiation for 60 sec. XRD pattern analysis of the material showed that the crystal phase of the material was orthorhombic both in its initial state and after exposure to laser radiation. Yet, according to the four-probe technique, the critical temperature of the irradiated specimens increased by 139 K, 147 K, and 145 K, which indicates that laser treatment enhanced the superconducting capacity (Ahmad *et al.*, 2023).

Another study by Mahdi *et al.* (2023) is about, "Preparation and partial substitution of aluminum with copper on some physical properties of the $TlSr_2Ca_2Cu_3O_{8+\delta}$ compound" which discusses about the effects brought by partial replacement of aluminum for copper with reference to the compound's properties. The researchers prepared the superconductive material $TlSr_2Ca_2Cu_{3-x}Al_xO_{8+\delta}$ with different compositions of aluminium at (x = 0, 0.2, 0.4, and 0.6) through the method of solid-state reaction. The crystalline structure confirmed that all samples comprised of the Tl-1223 tetragonal phase was confirmed through X-ray diffraction (XRD). Critical temperature (Tc) was established through electrical resistance tests done with the four-probe technique. These findings can be summarized as follows: When aluminum content increased, (Tc) reduced in a considerable manner revealed that aluminum substitution having the negative impact over the superconducting properties of the compound, the (Tc) value reduce from 136 K (without any aluminum substitution) to 116 K at x=0 (Mahdi *et al.*, 2023).

In a study conducted by Jassim *et al.* (2023), a research paper titled, "Improving the electrical and thermal conductivity of $Pb_{1-x}Hg_xBa_2Ca_2cu_3O_{8+\delta}$ superconducting compound by partial replacement of lead with mercury", five samples of the ceramic compound $Pb_{1-x}Hg_xBa_2Ca_2cu_3O_{8+\delta}$ were prepared through Solids state reaction. The lead-based superconductor was prepared for this study by partially replacing lead (Pb) with mercury (Hg) at a certain ration or percentage level which include x = 0, 0.05, 0.1, 0.15, 0.2 and 0.25. The study aimed at demonstrating how this substitution influenced the superconductivity features such as transition temperatures and thermal conductivity of this compound. The findings indicated that as the amount of mercury content was raised a discernable change in the transition temperatures (Tc) of the superconducting phase was observed. Furthermore, this research also revealed that the material has reduced thermal conductivity with increase in temperature and that this conductivity is dependent with the levels of mercury substitution. This implies that any partial substitution of lead with mercury can affect both the electrical and thermal characteristics of the Pb-based superconductor (Jassim *et al*., 2023).

In the research conducted by Hussein *et al*. (2024) entitled, "Effect of partial replacement of mercury by lead on structural and electrical properties of $Hg_{1-x}Pb_xBa_2CaCu_2O_{6+\delta}$ superconductor", they analyzed the physical properties of the superconductors $Hg_{1-x}Pb_xBa_2CaCu_2O_{6+\delta}$ for different lead (Pb) concentrations (x = 0, 0.05, 0.1, and 0.2). Using a three-step solid-state reaction method, the samples were synthesized and then subjected to X-ray diffraction (XRD) for an in-depth analysis of their structures. The XRD results indicated that all samples displayed a tetragonal structure with two prominent phases: The high-temperature superconducting phase (Hg-1212) and a secondary low-temperature superconducting phase Hg-1201. The researchers observed some impurity phases, including $CaHgO_2$ and CuO, and they noticed some systematic changes in the main physical attributes of the compounds as the concentration of Pb was increased. The partial substitution of lead also influenced the transition temperatures (Tc). The zero-resistance critical temperature rose with greater amounts of lead, measuring 82 K, 86 K, 93 K, and 106 K for x = 0, 0.05, 0.1, and 0.2, respectively. The onset critical temperature, or the point at which the material begins to exhibit superconducting behavior, also increased with lead substitution. This parameter rose from 101 K for the x = 0 sample to 124 K for x=0.2. These results suggest that lead partially substituted for iron significantly enhanced the appearance and performance of this novel superconducting system (Hussein *et al*., 2024).

Jasim *et al*. (2024) looked into what happens when lead partially replaces mercury in the compound $Hg_{1-x}PbxBa_2Ca_{1.8}Mg_{0.2}Cu_3O_{8+\delta}$. They prepared a series of samples that had different amounts of lead in them (x=0.0, 0.05, 0.10, and 0.20). Using a solid-state reaction method, they synthesized the samples, which were then subjected to about 8 tons per square centimeter of pressure and sintered at about 1,138 K. When the research group used X-ray diffraction (XRD) to analyze the samples, they found that all of them had a tetragonal crystal structure. However, the group did see some changes. They noted that there was a shift in the ratio of the phases present in the different lead-containing samples. They also saw a change in some of the lattice parameters. And as far as the samples' electric properties, resistivity was measured (Jasim *et al*., 2024).

Table 1: The comparisons between related studies.

Ref.	Objective of the study	Prepared Compound Name	Preparation Method	Result
(Ahmed, 2015)	Structural and electrical characterization of, $Bi_2Ba_2Ca_2Cu_3O_{10+\delta}$ investigating the effect of partial substitutions of Ag and Sr.	$Bi_2Ba_2Ca_2Cu_3O_{10+\delta}$	Solid-state process under a hydrostatic pressure of 8 tons/cm² and sintered at 840°C	The study observed an increase in (Tc) from 125K to 137K at x = 0.2 and y = 0.1. Higher substitution rates decreased (Tc) to 108K. XRD and SEM showed a tetragonal crystal structure with impacts on the superconducting phases.
(Jasim, 2016)	Investigating the effect of Sb doping on Bi-based superconductors, focusing on the structural and superconducting properties.	$Bi_{2-x}Sb_xSr_2Ca_2Cu_3O_{10+\delta}$	Three-step solid-state reaction method.	The compounds exhibited (Tc) values of 112K, 114K, and 113K for x = 0, 0.2, and 0.4 respectively. XRD analysis showed an orthorhombic structure, with changes in lattice constants, phase volume, and oxygen content impacting superconductivity.
(Mohammed and Jasim, 2018)	Investigation of Ni doping in the $Tl_{0.5}Pb_{0.5}Ba_2Ca_{n-1}Cu_{n-x}Ni_xO_{2n+3\delta}$ system, examining its effect on physical properties and (Tc).	$Tl_{0.5}Pb_{0.5}Ba_2Ca_{n-1}Cu_{n-x}Ni_xO_{2n+3\delta}$	Solid-state reaction at 850°C for 24 hours.	The XRD analysis showed tetragonal phases with increasing Ni content. (Tc) varied, and doping Ni altered the lattice parameters, electrical resistivity, dielectric constant, and mechanical hardness. The doping effect was multidimensional.
(Razzeg *et al*., 2018)	Studying the effect of Pb and Ag partial replacements on the thermal stability and electrical conductivity of $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$.	$Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$	Solid-state reaction under a pressure of 8 tons/cm², sintered at 850K, with various Pb and Ag substitution levels (x, y).	Pb and Ag doping increased (Tc) to 143K for optimal substitution ratios. XRD analysis confirmed that the doping had significant effects on the structural and superconducting properties, improving both thermal stability and electrical conductivity.

(Haider and Jasim, 2019)	Study on $Bi_2Ba_2Ca_2Cu_3O_{10+\delta}$	$Bi_{2-x}Ag_xBa_{2-y}Sr_yCa_2Cu_3O_{10+\delta}$ (Ag, Sr Substitution)	Solid-state process under hydrostatic pressure and sintering at 840°C	The XRD profile indicated a tetragonal crystal structure, and substitution of Ag for Bi and Sr for Ba increased the (Tc) from 125K to 137K, but higher substitution led to (Tc) reduction. SEM analysis showed microstructural development and impacts on superconducting phases.
(Ali *et al.*, 2020)	Influence of Sr substitution on structure and electric characteristics	$Tl_{1.6}\delta Hg_{0.4}Ba_{2-y}Sr_yCa_2Cu_3O_{10+\delta}$	Solid-State Reaction	(Tc)(on) between 40K and 45K; (Tc)(Offset) increased from 95K to 125K with Sr doping; slight changes in lattice constants and c/a ratios; grain size and surface morphology affected by Sr doping.
(Tuama and Abbas, 2021)	Study the effect of W nanoparticles on $Bi_{2-x}Pb_{0.3}W_xSr_2Ca_2Cu_3O_{10+\delta}$ superconductors	$Bi_{2-x}Pb_{0.3}W_xSr_2Ca_2Cu_3O_{10+\delta}$	Solid-State Reaction	(Tc) increased with increasing W nanoparticles; maximum (Tc) achieved at x=0.3; orthorhombic structure with (2223) phase dominance; enhanced superconducting attributes.
(Hasan *et al.*, 2022)	Crystallite size and lattice strain analysis of $Pb_2Ba_{1.7}Sr_{0.3}Ca_2Cu_3O_{10+\delta}$	$Pb_2Ba_{1.7}Sr_{0.3}Ca_2Cu_3O_{10+\delta}$	Solid-State Reaction	Dominance of 2223 phase; crystallite sizes: 89.454 Å (Scherrer); (Tc)(onset) = 128K, (Tc)(offset) = 116K, ΔT = 12K; superconductor behavior confirmed.
(Shaban *et al.*, 2022)	Study the impact of La substitution on $Y_{1-x}La_xBa_4Cu_7O_{15+\delta}$	$Y_{1-x}La_xBa_4Cu_7O_{15+\delta}$	Solid-State Reaction	All samples had an orthorhombic structure; crystallite size, strain, crystallinity, and lattice parameters changed with increasing La concentration.
(Shaban *et al.*, 2022)	Effects of Hg substitution for Tl in $Tl_{1.6}Ag0_{.4-x}Hg_xSr_2Ca_2Cu_3O_{10+\delta}$	$Tl_{1.6}Ag0_{.4-x}Hg_xSr_2Ca_2Cu_3O_{10+\delta}$	Solid-State Reaction	Tetragonal structure; changes in mass density, c/a ratio, and lattice parameters with increasing Hg; disturbance in growth, indicating structural deviation.
(Jasim *et al.*, 2023)	Investigate $Bi_2Ba_2Ca_2Cu_{2.9}Ni_{0.1}O_{10+\delta}$, $Bi_2Ba_2Ca_2Cu_{2.8}Ni_{0.2}O_{10+\delta}$, and $Bi_2Ba_2Ca_2Cu_{2.6}Ni_{0.4}O_{10+\delta}$ superconductors	$Bi_2Ba_2Ca_2Cu_{2.9}Ni_{0.1}O_{10+\delta}$, $Bi_2Ba_2Ca_2Cu_{2.8}Ni_{0.2}O_{10+\delta}$, $Bi_2Ba_2Ca_2Cu_{2.6}Ni_{0.4}O_{10+\delta}$	Solid-State Reaction	The second sample (Bi2Ba2Ca2Cu2.8Ni0.2O10) had the largest crystallite size; (Tc) = 100K for Bi2Ba2Ca2Cu2.9Ni0.1O10; granular forms > 25 nm.
(Ahmad *et al.*, 2023)	Study the effect of CO2 laser on $Bi_2Sr_{2-x}Y_xCa_2Cu3_{-y}Ni_yO_{10+\delta}$	$Bi_2Sr_{2-x}Y_xCa_2Cu3_{-y}Ni_yO_{10+\delta}$	Laser Irradiation (CO_2 laser, 60 sec)	Orthorhombic phase after laser irradiation; (Tc) increased by 139K, 147K, and 145K for different samples, improving superconducting properties.
(Mahdi *et al.*, 2023)	Impact of aluminum substitution on $TlSr_2Ca_2Cu3_{-x}Al_xO_{8+\delta}$ superconductors	$TlSr_2Ca_2Cu3_{-x}Al_xO_{8+\delta}$	Solid-State Reaction	(Tc) decreased with increasing Al content; (Tc) reduced from 136K (no Al) to 116K at x=0.6.
(Jassim *et al.*, 2023)	Effect of Hg substitution on $Pb_{1-x}Hg_xBa_2Ca_2cu_3O_{8+\delta}$ superconductors	$Pb_{1-x}Hg_xBa_2Ca_2cu_3O_{8+\delta}$	Solid-State Reaction	(Tc) increased with Hg substitution; thermal conductivity decreased with increasing Hg content.
(Hussein *et al.*, 2024)	Influence of Pb substitution for Hg in $Hg_{1-x}Pb_xBa_2CaCu_2O_{6+\delta}$ superconductors	$Hg_{1-x}Pb_xBa_2CaCu_2O_{6+\delta}$	Solid-State Reaction	Tetragonal structure with Hg-1212 and Hg-1201 phases; (Tc) increased from 82K to 106K with Pb substitution.
(Jasim *et al.*, 2024)	Investigate the effect of lead partial replacement of mercury on the properties of Hg1-xPbxBa2Ca1.8Mg0.2Cu3O8+δ.	$Hg_{1x}Pb_xBa_2Ca_{1.8}Mg_{0.2}Cu_3O_{8+\delta}$	Solid-state reaction, pressure of 8 tons per cm², sintering at 1,138 K	All samples had a tetragonal crystal structure, with changes in phase ratios, lattice parameters, and resistivity.

RESULTS AND DISCUSSION

Results of element substitution

Research on element substitution in high-temperature superconductors indicates that partial replacement in Bi-2223 and Tl-2223 compounds markedly influences their structural and electrical characteristics. The substitution of silver (Ag) in Bi-2223 compounds resulted in an elevation of the critical transition temperature (T_c) to 137 K at a substitution ratio of 0.2, demonstrating a beneficial impact on the superconducting performance of these materials. Nevertheless, we noted that elevating the substitution ratio above this threshold resulted in a reduction of T_c to 108 K, underscoring the compounds' vulnerability to excessive chemical alterations. Conversely, substituting strontium (Sr) for barium (Ba) produced a comparable effect, resulting in an elevation of the critical transition temperature (T_c) to 125 K at specific substitution ratios; however, akin to silver substitution, excessive substitution resulted in a decline in superconducting performance and a reduction in (T_c).

Impact of preparatory techniques

The experimental findings indicated that preparation procedures significantly influence the structural and electrical characteristics of superconducting materials. The solid-state reaction (SSR) approach for synthesising Bi-2223 and Tl-2223 compounds shown superior outcomes regarding crystal uniformity and diminished impurities, hence improving superconducting performance. Maximum critical temperatures were attained by solid-state reactivity under hydrostatic pressure and sintering at temperatures reaching 850 K. Pulsed laser deposition (PLD) methods have demonstrated efficacy in the fabrication of superconducting thin films. Exact regulation of layer thickness and crystal quality enhances electron conductivity and elevates current density in the synthesised substances. We noted that laser deposition facilitates the creation of high-quality films with specified thicknesses and stringent crystalline characteristics, rendering it an optimal choice for fabricating materials necessitating extreme accuracy in their properties.

Impact of annealing and sintering levels

Research indicates that annealing and sintering procedures are crucial in influencing superconducting characteristics. The outcomes of annealing in an oxygen-rich environment demonstrated a substantial impact on the integrity of the crystal structure and enhanced current density. During high-temperature annealing at 720°C, we noted that enhancing the oxygen migration inside the crystal structure facilitated the improvement of superconducting characteristics and substantially elevated (T_c). Conversely, extended sintering durations resulted in considerable enhancements in the cohesiveness of the crystal grains, hence decreasing current loss when magnetic fields traverse the superconducting material. Nevertheless, recurrent annealing and sintering procedures may result in heightened structural impurities if the temperatures are not meticulously regulated, as seen in certain samples subjected to prolonged annealing.

Final assessment

The data indicate that element substitution enhances superconducting characteristics, but only when executed judiciously; excessive substitution negates benefits and results in disadvantages. Furthermore, the study indicates that enhanced preparation techniques, such as solid-state reaction and pulsed laser deposition, can augment the structural and electrical characteristics, respectively. The annealing and sintering processes are effective methods for enhancing superconducting performance; yet, they need continuous oversight to improve properties without compromising purity or structural integrity.

This review advocates for more research on chemical substitution including elements such as zirconium and antimony, as well as enhancements in various annealing techniques, including laser and plasma annealing, to augment the superconducting properties of high-temperature superconducting compounds.

CONCLUSIONS

This discourse emphasizes recent advancements in the synthesis and characteristics of high-temperature superconductors (HTS), focusing on fabrication dynamics and the impact of alloys on the physical and crystallographic properties of superconductors. The review indicates that methods like S.S. reaction and CO_2 laser processing (PLD) are crucial for improving the structural and electrical characteristics of superconductors. CO_2 laser processing notably influences the crystallinity and homogeneity of the material, enhancing control over the creation of desired phases and overall superconducting qualities. Furthermore, synthesis techniques outside SSR and PLD, including co-deposition, the Pechini process, citrate pyrolysis, and high-pressure synthesis, are significant for the production of HTS materials, each offering distinct benefits for material quality, phase regulation, and scalability. The replacement of some metals, including lead, silver, and mercury, has demonstrated an increase in the critical temperature (T_c) and enhancement of structural features, but the addition of other elements, such as aluminum, diminishes performance. The decline in performance can be ascribed to alterations in carrier concentration and oxygen vacancies, which directly influence the superconducting characteristics of the material. The statistics unequivocally demonstrate that the material's composition, particularly the manipulation of process parameters, is crucial for attaining the desired performance. Nonetheless, challenges persist, particularly in attaining superconductivity at ambient temperature, a pivotal advancement that might revolutionize the application of these materials. Future research will concentrate on advancing novel techniques to expedite progress and rectify structural inaccuracies, employing nanoparticles and examining the tension generated by crystal formations. This study highlights the significance of a multidisciplinary approach to improve and develop superconductors, enabling novel applications in fields such as quantum computing, sustainable energy systems, and magnetic resonance imaging. The future has significant possibilities for this technology, positioning it as a central focus for research and development in the forthcoming years.

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الموصلات الفائقة ذات درجة الحرارة العالية: طرق التوليف والخصائص الفيزيائية وتأثيرات الاستبدال الجزئي: مراجعة شاملة

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الملخص

تقدم هذه الورقة تحليلًا شاملاً للخطوات المتبعة في نهج الموصلية الفائقة عند درجات الحرارة العالية (HTS)، مع التركيز على تقنيات التلبيد متعددة العناصر والمعالجة الحرارية وتأثيرها على الخصائص الفيزيائية والبنية البلورية للمواد. تناقش الورقة العديد من التأثيرات المنقولة عبر الخصائص الأساسية، مثل المجال المغناطيسي لدرجة الحرارة الحرجة (T_c) وكثافة التيار المتناوب (AC)، مع التركيز على قضايا أخرى لتحسين هذه المكاسب. يتم استعراض أحدث تقنيات الإلكترونيات الدقيقة، مثل التفاعلات في الحالة الصلبة، وطرق الليزر النبضي (SEP)، وإشعاع ليزر ثاني أكسيد الكربون (CO_2)، ودورها في تحسين الأداء الإلكتروني والبنية المجهرية للموصلات الفائقة. بالإضافة إلى ذلك، تعالج الأبحاث البديلة تأثير العناصر المختلفة (مثل الفضة، الزئبق، النيكل، والألمنيوم) على استقرار البنية، وتكوين الأطوار، والجوانب الحرارية والكهربائية للمواد. تُظهر النتائج أن تقنيات الإلكترونيات الدقيقة محكمة التعديل تساهم بشكل كبير في تحسين أداء الحواسيب ذات المجالات العالية، مما يدعم تطبيقاتها في مجالات متقدمة مثل الحوسبة، أنظمة الطاقة، وتقنيات التصوير المغناطيسي عالية المجال. لا تزال التوصيات للبحوث المستقبلية ذات أهمية كبيرة لتحقيق موثوقية ملحوظة عند درجة حرارة الغرفة، وهو ما قد يفتح آفاقًا واسعة لعلوم التكنولوجيا.

الكلمات الدالة: الموصلات الفائقة عند درجات الحرارة العالية، طرق التصنيع، الخواص الفيزيائية، التعويض الجزئي العناصر.