

High-Temperature Superconductors: Their Physical Properties and Technological Applications

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Abstract:

Superconductivity is a unique physical phenomenon discovered over a century ago. Generally, it can be characterized by three essential properties, which are zero resistance, perfect diamagnetism, and microscopic quantum phenomenon (that known as the BCS theory). However, materials that have such as these significant properties when subjected to temperature below a critical temperature (T_c) become superconductor's materials. As a result, these advantages open up opportunities in front of researches and scientists to better understanding the mysteries that behind them. Furthermore, high-temperature super-conductors (abbreviated as HTS) play an important role in many applications and technologic fields. Therefore, it uses liquid nitrogen (LN) when cooling a sample, giving it a specified curial temperature compared to conventional superconductors that use liquid helium (LHe) in cooling. From this perceptive, began to use these materials in most disciples and modern development technologies. Indeed, the critical temperature of superconducting materials has been increasing progressively but still not approaching to the room temperature, which is still as a dream not achieving yet, because the high cost and needs refrigerators for their applications compared with traditional conductors. This paper is focusing on the history of high-temperature superconductors and also highlights the behavior of superconducting materials, their fundamental characteristics, and applications in nanotechnology.

Keywords: Superconductivity; High- T_c superconductors; Critical temperature, T_c ; Zero resistance; Perfect diamagnetism; Critical current, J_c ; The Meissner Effect.

الموصلات الفائقة ذات درجة الحرارة العالية: خصائصها الفيزيائية وتطبيقاتها التكنولوجية

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الملخص

الموصلية الفائقة هي ظاهرة فيزيائية فريدة تم اكتشافها قبل أكثر من قرن مضى. بشكل عام، يمكن تمييز الموصلية الفائقة بثلاثة خصائص أساسية وهي: المقاومة الصفريّة، والدايماغناطيسية المثالية، وظاهرة الكم المجهرية (والتي تعرف باسم نظرية BCS). ومع ذلك، فإن المواد التي تمتلك مثل هذه الخصائص الهامة عند تعرضها لدرجة حرارة أقل من درجة الحرارة الحرجة (T_c) تصبح مواد فائقة التوصيل. ونتيجة لذلك، فإن هذه المزايا تفتح العديد من الفرص أمام الباحثين والعلماء لفهم أفضل للأغز الكامنة وراءها. كما، تلعب الموصلات الفائقة عالية الحرارة (والمختصرة بـ HTS) دوراً مهماً في العديد من التطبيقات والمجالات التكنولوجية، وبالتالي فإنها تستخدم النيتروجين السائل (LN) عند تبريد العينة، مما يعطيها درجة حرارة حرجة مقارنة ب الموصلات الفائقة التقليدية، والتي تستخدم الهيليوم السائل (LHe) في عملية التبريد.

من وجهة النظر هذه، بدأ استخدام مثل هذه المواد في معظم التخصصات وتقنيات التطوير الحديثة. وفي الواقع، فإن درجة الحرارة الحرجة للمواد الفائقة التوصيل في ازدياد مستمر تدريجياً ولكنها لا تزال غير قريبة من درجة حرارة الغرفة، والتي لا تزال حلماً لم يتحقق بعد، بسبب التكلفة العالية والحاجة إلى ثلاجات لتطبيقاتها بالمقارنة مع الموصلات التقليدية. يركز هذا البحث على تاريخ الموصلات الفائقة ذات الحرارة العالية، كما يسلط الضوء على سلوك هذه المواد الفائقة التوصيل، ودراسة خصائصها الأساسية وتطبيقاتها في تقنية النانو.

الكلمات المفتاحية: الموصلية الفائقة- الموصلات الفائقة ذات درجات الحرارة العالية- درجة الحرارة الحرجة- المقاومة الصفيرية- المغناطيسية المثالية- التيار الحرج- تأثير ميسنر.

1. Introduction:

The mix of science, engineering, and technology that leads to the Nano scale, which is usually ranging from (1-100nm) is known as Nanotechnology. Thus, it can be defined as "the fabrication of materials and design, devices and systems with control at nanometer dimensions". Lately, it has become an integral part of many fields of life, such as: electronics, energy, environmental protection, solar cells, medicine, agriculture, and food industry. Nanotechnology has generated from the Greek prefix "Nannos", which means very small. Nano is "a unit of length in the metric system ($1 \text{ nm} = 10^{-9} \text{ m}$)". Figure 1 shows different materials with a small size at the nanometer scale [3]. Indeed, the classical sciences of biology, engineering, physics, and chemistry have all contributed to produce a modern area of nanotechnology. Nanoparticles synthesis and processing, self-assembly and replication techniques, fabrication of functional nanostructures with engineered properties, sintering of nanostructured metallic alloys, chemical, and biological templates, use quantum effects, supra-molecular chemistry, surface modification, films, and sensors are all examples of nanotechnology. In this paper, superconductivity phenomenon will define and demonstrates its most distinguished properties and focuses on the mechanism of conduction (electron-phonon interaction) according to the BCS theory [1] [2] [3] [4] [5]. In 1911, Dutch physicist Heike Kamerlingh Onnes discovered the mysterious phenomenon of superconductivity after the liquefaction of helium. Mercury (Hg) element is the first superconducting material was discovered, which showed a spectacular drop in electrical resistivity from 0.03Ω to $3 \times 10^{-6}\Omega$ within a temperature range of 0.01K, this property is known as zero dc resistivity [6] [7]. Figure 2 shows a historical plot of resistance (R) versus temperature (T_c) in mercury element (Hg) [8].

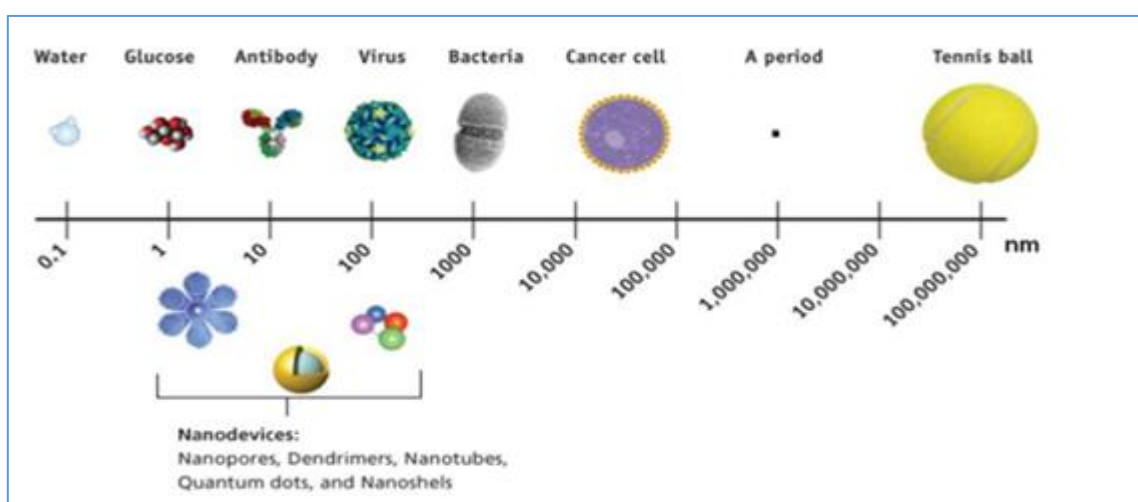


Figure 1: illustrates the different materials with a small size at the nanometer scale [3].

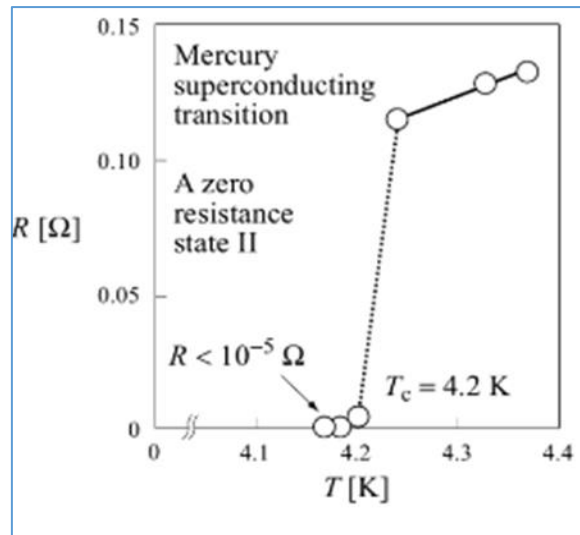


Figure 2: shows a historical plot of resistance (R) versus temperature (T_c) in mercury element (Hg) [8].

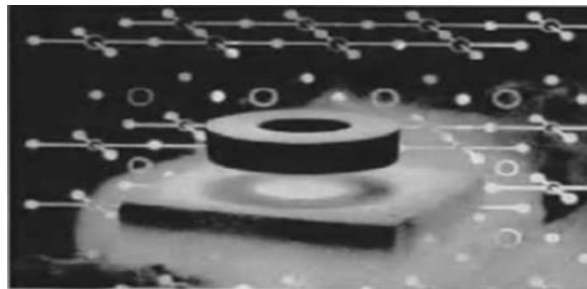


Figure 3: shows the Meissner effect [9].

The next important characteristic to understand superconductivity was occurred in 1933 by Meissner and Oshsefeld, which means, it expels the applied magnetic field from its interior. This is known as a perfect diamagnetism. They found that, when a sample cooled below to its transition temperature in a magnetic field cause expelling the magnetic flux externally. Therefore, such as this expulsion is known as the "Meissner Effect" [9] [10] [11] and Figure (3) is shown in photo [9].

2. The BCS Theory:

The microscopic BCS theory explains the superconducting mechanism in most alloys and metals. The physics scientists Bardeen, Cooper, and Schrieffer deployed this theory of superconductivity in 1957, which is commonly named the BCS theory [12]. The essential principle of the microscopic theory depends on electrons, which are known as Cooper pairs. According to this so-called BCS- theory, electrons in a superconductor could form into pairs due to phonons (i.e., lattice vibrations), which occur abruptly in the crystal lattice. Despite electrons are ferromagnetic, when they paired, they become bosons, which are not subjected to the Pauli Exclusion Principle and can condense into the same energy state (i.e., a single quantum state), giving the Bose- Einstein Condensation. The distance between the two electrons is called the coherence length, which is a material-dependent fundamental of superconductors. Depending on the BCS theory of pairing, one of the electrons with negative charged attracts by positive charged ions in the crystal lattice, hence providing an area of net positive charge which attracts the other electron (see figure 4). Finally, these electrons (cooper pairs) can travel freely into the crystal without any processes that give high rise to electrical resistivity, resulting in superconductivity [4] [7].

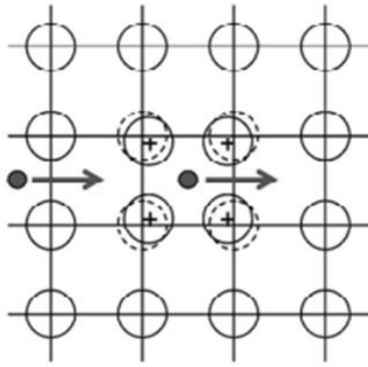


Figure 4: shows schematic diagram of the passage of the two electrons through the crystal lattice [6].

3. High-Temperature (T_c) Ceramic Superconductors:

In 1986, Alex müller and Georg Bednorz discovered the phenomenon of superconductivity in the copper oxide based materials of lanthanum (La) and Barium (Ba) at the critical temperature, $T_c = 35\text{K}$. Subsequently, they were awarded the Physical Noble Prize in 1987 for their efforts [13]. Soon the transition temperature, well over liquid nitrogen (77 K) was achieved. Because liquid nitrogen has many features such as cheap and plenty as a coolant which opened up the wide scale search of particular applications of superconductors. Nowadays, superconductors are used in a variety of medical diagnostics, construction of superconducting magnets, and electronic applications etc. [14]. After then, there was a remarkable jump for superconductivity, which was observed at a transition temperature approximately over 90K, which was achieving by Y replacement with most of the rare-earth elements resulting in the Y-Ba-Cu-O system. The superconducting material is so-called as "yttrium barium copper oxide superconductor", that is abbreviated as YBCO, and it's a chemical compound with a formula $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ with a transition temperature $T_c = 92\text{K}$. The YBCO has several phases such as (Y-123), (Y-124), and (Y-247) which indicate high temperature superconductivity. Besides, these materials have complicated perovskite-like crystal structure, where oxygen defect play a significant role in their superconducting properties [15] [16] [17]. Figure 5 depicts the structure of orthorhombic YBCO superconductor's and the Y is surrounded by the two CuO_2 planes, while the two BaO layers are separated by CuO chains [18].

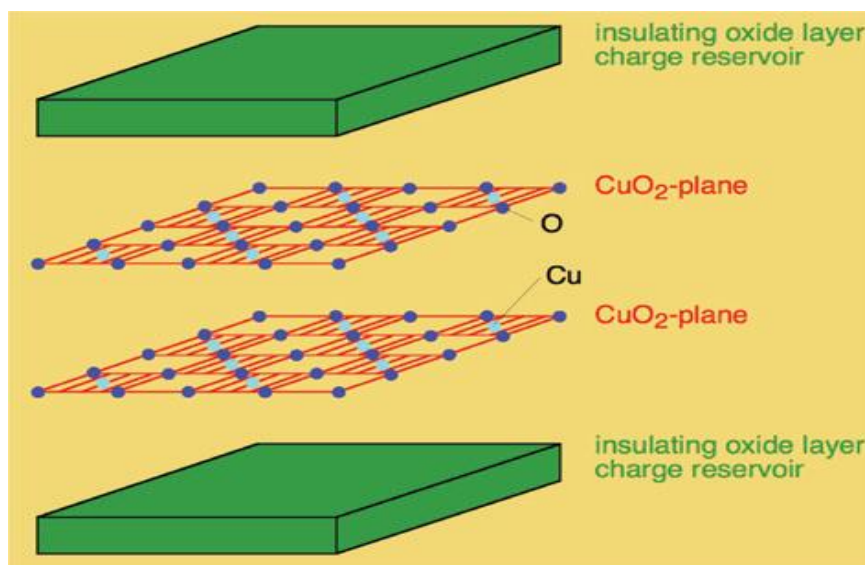


Figure5: Schematic structure of a copper-oxide based high- T_c superconductor's [18].

4. Critical Temperature, T_c :

A superconductor's material has a zero electrical resistance at a specific low temperature, typically known as the transition temperature, T_c . In general, the electrical resistivity of metallic conductors is related to their temperature. Hence, as the temperature of specific metallic conductors reduces, their electrical resistivity reduces progressively and suddenly decreases to zero resistance at a certain critical (transition) temperature. On the other hand, the stage transition from the normal state to the superconducting state is called a second-order transition, which happens at a temperature known as the critical temperature, T_c [19]. **Table (1.1)** shows an incomplete list of different types of superconductors and their superconducting transition temperature, T_c [18] and **Table (1.2)** shows classes of superconducting materials and their critical temperatures, T_c [6] [7].

Table (1.1): shows an incomplete list of different types of superconductors with their critical temperature T_c [18].

Type of SC	Substance	T_c (K)
Simple metal SC	Al	1.17
	In	3.41
	Hg	4.20
	Sn	3.72
	Pb	7.20
	Nb	9.25
Al5 SC	Nb ₃ Sn	18.0
	Nb ₃ Ge	23.2
Fullerene SC	C ₆₀ Rb ₃	31
Cuprate SC	La _{2-x} Sr _x CuO ₄	38
	YBa ₂ Cu ₃ O ₇	93
	Bi ₂ Sr ₂ Ca ₂ Cu ₃ O ₁₀	107
	Tl ₂ Ba ₂ Ca ₂ Cu ₃ O ₁₀	125
	HgBa ₂ Ca ₂ Cu ₃ O ₈	135
Magnesium diboride SC	MgB ₂	39
Iron-based SC	FeSe	8
	LaO _{0.89} F _{0.11} FeAs	26
	Sr _{0.5} Sm _{0.5} FeAsF	56

Table (1.2): shows classes of superconducting materials and their critical temperatures [6-7].

Classes of materials	T_c (K)	Examples
Conventional superconductors	≤ 39	Pb, Hg, Al, MgB ₂ , Nb ₃ Sn
Iron-arsenide	≤ 50	RFeAsOF
Organic superconductors	< 42	K ₃ C ₆₀ , [BEDT-TTF] ₂ X
Heavy fermion	< 1	CeCu ₂ Si ₂
Copper-oxide superconductors	≤ 164	YBCO- HBCCO- BSCCO
Non-copper oxide superconductors	< 30	SrTiO _{3-δ} , Ba _{0.63} K _{0.37} BiO ₃
Boronitride & borocarbide	< 23	La ₃ Ni ₂ B ₂ N ₃

5. Types of Superconductors:

Superconductors can be divided into two special categories depending upon their behavior in an external magnetic field, which are namely as:

- Type- I superconductors
- Type- II superconductors

5.1 Type- I superconductors:

Type- I superconductors are commonly called soft superconductors because low decline intensity magnetic field, which can lose their superconductivity readily. Also, the conductivity

is generally demonstrated by the BCS. Many pure elements are considered to be type- I superconductors such as: Mercury (Hg), Zinc (Zn), Stannum (Sn), Lead (Pb), and Tantalum (Ta) etc except vanadium (V), technetium (Tc), niobium (Nb), and carbon nanotubes (CNTc). Below the critical temperature (T_c) these materials completely expel magnetic flux in the superconducting state when the critical magnetic field (H_c) is higher than magnetic field ($H < H_c$), so these materials are strongly obeying the Meissner effect [20] [21] [22]. These superconductors exhibit the magnetization of the form as given in figure 6 [23].

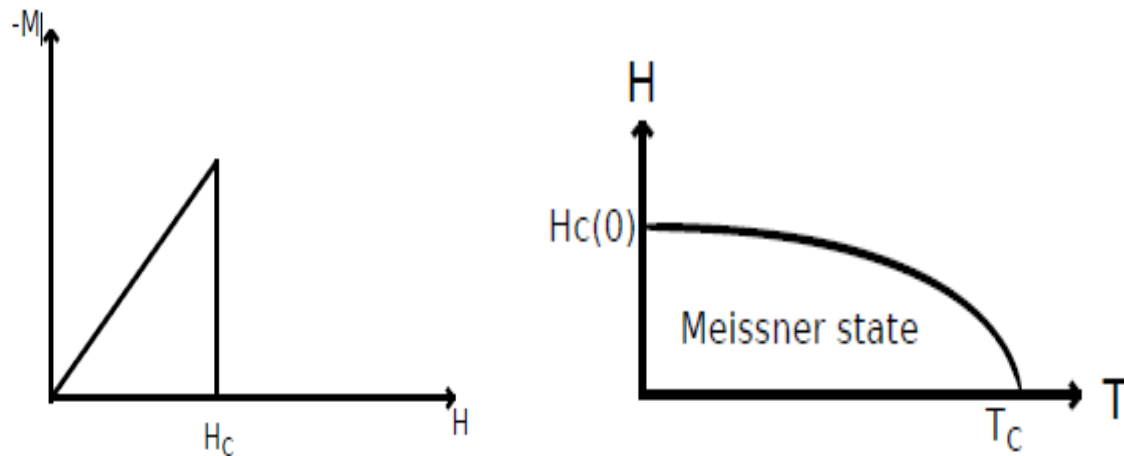


Figure 6: (left) shows intensity of magnetization versus a magnetic field for a type- I superconductor, and (right) show the phase diagram for type- I superconductors [23].

5.2 Type- II superconductors:

Type- II superconductors are entirely contrary with type- I superconductors, they are typically called hard superconductors because the external magnetic field cannot simply to destroy their superconductivity and the conductivity cannot be demonstrate by the BCS theory [20]. Also, such as these materials do not obey the Meissner effect. In this type- II of superconductors, when a magnetic field is applied, they are progressively lose their superconductivity starting from lower critical field (H_{c1}) and totally lose their superconductivity at upper critical magnetic field (H_{c2}) [24]. Besides, there is a partial penetration when the applied field is in the area (state) between minor significant magnetic field and upper critical magnetic field, which is known as intermediate state or the vortex state [20] [22]. Below the critical magnetic field (H_{c1}) the superconducting material acts as a type- I superconductors and above (H_{c2}) the entire material becomes in the normal state [25]. High $-T_c$ ceramics and alloys are examples of type- II superconductors for instant: Nb-Ti, Nb₃Sn, and Nb₃Al etc. H_{c1} and H_{c2} as a function of temperature have a parabolic shape shown in figure7 [23].

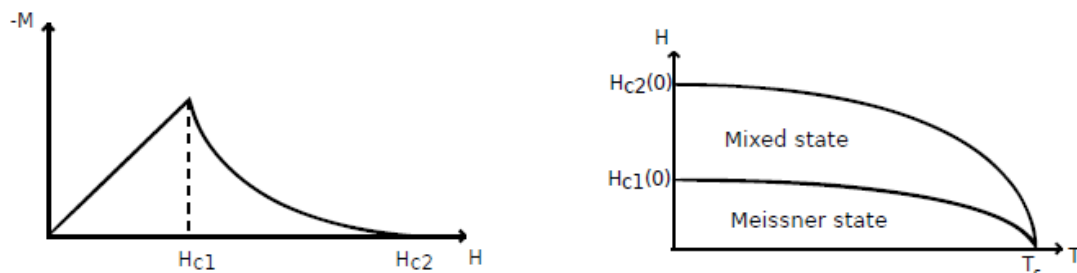


Figure 7: (left) shows intensity of magnetization versus a magnetic field for a type- II superconductor, and (right) show the phase diagram for type- II superconductors [23].

7. Critical Current density, J_c :

From the standpoint of particular applications, the most significant feature of any superconductor is its critical current density, which is the maximum electrical current that can pass through a unit area of material (particularly a superconducting material) before its transition to the normal state. So, when the electrical current flows through any wire, it generates a magnetic field with its highest value at the surface of the conductor. The self-generated field at the wire's surface must not go beyond the critical value of the magnetic field; otherwise, superconductivity is destroyed. As a result, the current must be limited to a small value to preserve the superconducting state [26] [27].

8. Technological Applications:

In general, the two important properties of superconductors, which are zero dc resistance and perfect diamagnetism, can be employed to enhance the performance for any devices. Therefore, the applications of superconductors can be divided into two categories, which are small scale and large scale. Small scale application includes superconducting Quantum Interference Devices (SQUIDs), Josephson devices, resonators, and microwave devices. A large scale application includes magnetic energy storage, magnetic levitation train (Maglev), magnetic resonance imaging (MRI) for medical applications, and high energy physics experiments. In this paper only superconductor for transportations is considered [7] [22]. The electric Levitation Technology is one of the most advanced and large scale complex applications of superconductivity in modern transportation and engineering technologies. It has been demonstrated in the United State, China, South Korea, and Japan [28]. This technology is named as the magnetic levitation train (abbreviated as Maglev), and it is a modern and fast train compared with the conventional train, which moves forward by the friction between wheels and rails. Meanwhile, Maglev utilizes electromagnets to float above the tracks and produce the levitate force electromechanically without any communication (see figure 8) [29].



Figure 8: Magnetic Levitation Trains (Maglev) [30].

9. Conclusion:

Ultimately, it may be concluded that high temperature superconductors (HTSC) represent a physical intriguing phenomenon with distinct properties in condensed matter physics and modern materials science. Their distinct properties exhibit zero electrical resistance and the expulsion of magnetic field from interior (the Meissner effect) at relatively high temperatures compared with conventional superconductors. These characterizations open the door to transformative future applications with tremendous promise across various technological fields in transportation, energy system, medical instrumentation, and quantum computing. Despite

superconductors still require cooling by liquid nitrogen to reach the superconducting state; HTS materials provide important advantages such as high current density and minimal energy loss. However, the challenges and barriers remain, which include theoretical complexity of the mechanism underling high-temperature superconductivity continues to be one of the most challenging and fascinating issues in condensed-matter physics, as well as the brittleness of ceramic superconductor's material, the difficulty of fabrication them into flexible wires. In addition, transition temperature has been increasing gradually but still not achieving a room temperature. This paper explained the fundamental properties of superconductor's material, the history of HTS, the physical principles underling the behavior and potential applications in nanotechnology.

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Compliance with ethical standards

Disclosure of conflict of interest

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