Materials Research Foundations 132 (2022) 1- 16 https://doi.org/10.21741/9781644902110-1

Chapter 1

Basic Concepts and Properties of Superconductors

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Abstract

The phenomenon of super conductance is quite fascinating due to enormous applications and hence intense research in this area attracted engineers, scientists and businessmen. In this Chapter, we will briefly elaborate the conversion of a normal conductor to a superconductor which is a fascinating material since its discovery as well as the role of critical temperature and critical magnetic field for the super phenomenon of superconductivity. A short historical journey of superconductors from 1911 to date is also the part of this chapter that started with the work of Onnes on extreme low temperatures in cryogenic laboratories. The difference between perfect conductor and superconductor, classification of superconductors and finally the fundamental properties of superconductors have been discussed precisely.

Keywords

Superconductors, Critical Temperature, Critical Magnetic Effect, Meissner Effect

Contents

Materials Research Foundations 132 (2022) 1- 16 https://doi.org/10.21741/9781644902110-1

1. Introduction and background

Conductors are the materials that let the electricity as well as the heat to pass through them for example metals, alloys, earth, animals and human body etc. But conductance of a material has a direct connection with the resistance of that material as resistance is one of the basic properties of the conductors. The resistance gives us qualitative as well as quantitative information about the flow of the electric current. Actually, electrical resistivity is the inverse of electrical conductivity. The conductors experience resistivity in the smooth flow of current at temperatures above the absolute zero [1].

This resistivity is because of the displacement of atoms from their equilibrium positions as a result of vibration motion of atoms at elevated temperatures. The freely moving conduction electrons carry the current through the conducting material and feel no resistivity in a crystalline structure with the atoms lying on a regular repetitive crystal lattice because electrons have a wave-like nature and it can pass through a perfectly periodic structure without being scattered in different directions. But the thermal vibrations of atoms at high temperature disrupt the regular symmetry of atoms causing a resistivity in the smooth flow of conduction electrons. However, on cooling the materials, resistivity decreases too. For pure metals, resistivity is almost zero at low temperatures but normally no material is perfectly pure [2]. The impurities in the materials cause resistivity even at low temperatures. Though, an unusual behaviour has been observed in certain metals on approaching the temperature a few degrees above the absolute zero. At this point the electrical resistance becomes almost zero and this is called the superconducting state of the materials [3].

So, the materials which have zero resistivity when they are subjected to a certain characteristic temperature are known as superconductors. The maximum temperature that is the characteristic of each material at which that material acts as a superconductor, is

Materials Research Foundations 132 (2022) 1- 16 https://doi.org/10.21741/9781644902110-1

known as the **"critical temperature"** and denoted by **Tc**. And the maximum magnetic field at which a material behaves as superconductors, is called the **"critical field"** denoted as $\mathbf{B_C}$. The magnitude of external magnetic fields larger than a critical value, terminate superconductivity. In fact, superconducting material cannot support a magnetic field inside it [4].

Theoretically, there are certain materials which exhibit this unusual behaviour of superconductivity. In point of fact, the superconductors are the normal conductors above the critical temperature [5]. The main difference between a superconductor and a normal conductor is that the normal conductor has finite resistance, on contrary to the superconductor which has zero electrical resistance. However, it is quite difficult to reach this superconducting state of the material which exists below the critical temperature. But once this state has been achieved by the material, the resistivity of the material falls to zero [6]. Recently, super conductors with high critical temperatures (130k) have been discovered.

Cuprate superconductors are considered as the main class whereas iron-based compounds as the second major class of high temperature superconductors [7]. To date, no material is known that can behave as a superconductor at ordinary conditions of temperature and pressure [8,9].

A cooling system is must for all high-temperature superconductors like liquid helium type problematic coolants (for metallic high temperature superconductors), liquid nitrogen type relatively friendly coolant (that can be used for the cooling of high temperature ceramic superconductors) but dry ice cannot work as coolant for superconductors [10].

2. History of superconductors

- A hundred years ago Heike Kamerlingh Onnes was the very first scientist whose work gave a new perspective to the researchers which became the basic cause of the marvellous phenomenon of super-conductance. He was working on the properties of materials at low temperatures in his cryogenic laboratory as shown in fig. 1. On his big achievement of liquefaction of helium, he was awarded the Nobel Prize in 1913 but during his work, he observed the sudden disappearance of resistivity mercury at the temperature of 4.2K as shown in fig. 2. This zero resistivity at low temperatures led to the great discovery of superconducting materials that was a breakthrough in the field of conductance at that time [11].
- Then his student Gilles Holst with the collaboration of Onnes measured the resistivity of mercury at low temperature. His work is shown in fig.2 [12].
- In 1933, W. Meissner and R. Ochsenfeld explained the exclusion of magnetic fields from inside the superconductors (now known as the Meissner effect) but this disappearance occurred under a definite critical field strength which depends on the critical temperature and the material of superconductors under study. Moreover,

Materials Research Foundations 132 (2022) 1- 16 https://doi.org/10.21741/9781644902110-1

they revealed that superconductors are superior to perfect conductors in the field of electronics [13].

Fig.1: Kamerling Onnes at work in his laboratory

- In 1972, John Bardeen, Leon Neil Cooper and John Robert Schrieffer mutually evolved a theory of superconductivity i.e., known as the *BCS-theory* and for this collectively developed BCS theory, all the three US physicists were awarded the Nobel Prize in Physics. The three scientists have also put forward the quantum theory for superconductors in 1957 [14].

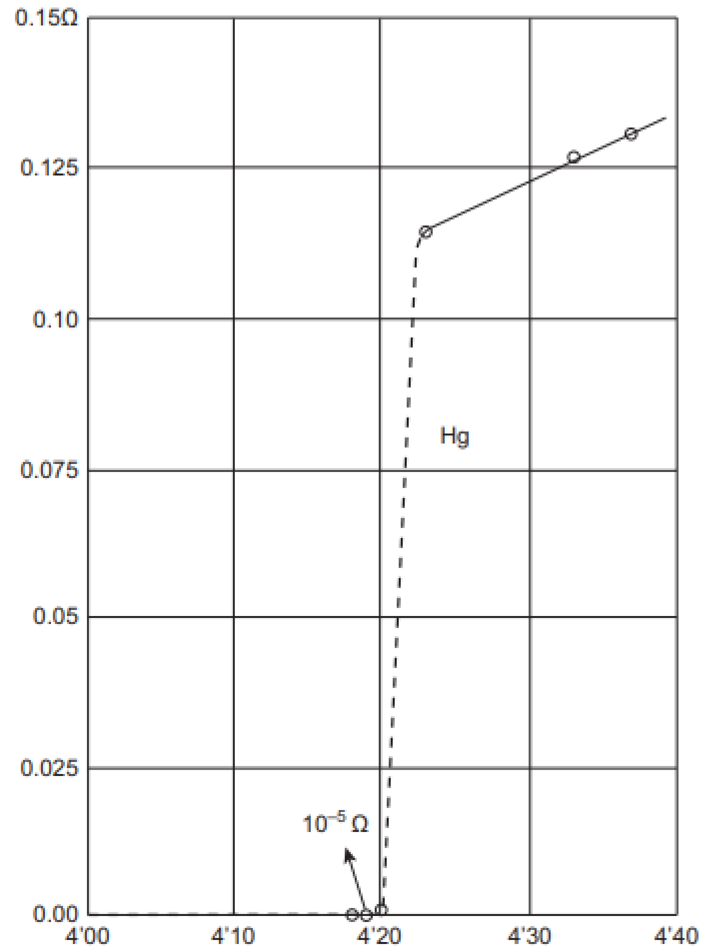

Fig.2: Resistivity of mercury at low temperature by Kamerlingh Onnes (1911)

- Another Noble prize was received by Brian Josephson in 1973 for a new improvement in the field of superconductors. Brian Josephson theoretically studied the properties of supercurrent through a tunnel barrier and made a hypothetical prediction for superconductors that is commonly called Josephson effect (see details in the last portion of this chapter).
- Later on, in 1986, IBM researchers G. Bednorz and K. A. Muller succeeded to create a superconductor ceramic compound with an amazing critical temperature of 30K although ceramics are isolators as compared to other ceramic materials which was an interesting area for researchers at that time. Both the aforementioned researchers got the Nobel Prize in 1987 for their discovery of the first cuprate superconductor with a critical temperature of 35K. This discovery opened new horizons of research at high temperature leading to enormous number of publications during 1986 to 2001 [15].

- In 2003, Abrikosov was awarded the Nobel Prize for his revolutionary work on the theory of superconductors and super fluids. Several works have been reported on superconductors which are difficult to be summarised here [16,17].
- After a concise super past of Superconductors, it is necessary to address some relevant terms regarding superconductors in order to understand the nature of the super phenomenon of superconductivity.

3. Superconductors vs perfect conductors

In electronics, superconductors and perfect conductors are the two commonly used but quite confusing terms that is why they are usually misunderstood. In a real sense, the two terms are quite dissimilar [18].

- Superconductors exist in reality, or superconductors are approachable materials in reality while a perfect conductor is just a conceptual approach.
- Super conductor is an actual indication of zero resistivity as compared to perfect conductor that is an assumption and sometimes it is used to simplify the calculations and designs where the resistivity is quite insignificant.
- In order to be a superconductor, subcritical temperature is quite an important factor whereas a perfect conductor can have zero or low resistivity at any temperature.
- A lot of external factors like critical temperature, critical magnetic field etc. are necessary to achieve the super conductance but a perfect conductor does not need any external factor to achieve the perfect conductance or this is not the case for perfect conductor [19].

4. Phenomenon of superconductivity

If we talk about superconductivity, it is an extensively studied quantum mechanical phenomenon in solid state physics that is an outstanding combination of magnetic and electric properties below the critical temperatures. A superconductor experiences the Meissner Effect when kept in a magnetic field. This effect is related to removal of magnetic fields when a superconductor is cooled down to the point of its critical temperature. This is perhaps the most essential property of superconductors and pointed towards the zero resistivity [20].

In 1933, this Meissner effect was discovered by the physicists named W. Meissner and R. Ochsenfeld while working on lead as well as tin materials. So according to the Meissner effect, superconductors show zero (or close to zero) resistivity to electrical currents; moreover, they are perfect diamagnet [21]. Amazingly, some superconducting samples may attract magnetic fields in quite a few recent experiments that is the so-called paramagnetic Meissner effect [22].

Materials Research Foundations 132 (2022) 1- 16 https://doi.org/10.21741/9781644902110-1

In order to understand the above-mentioned phenomenon of superconductivity, it is important to address the following terms:

- Zero resistance
- Super-electron
- Critical temperature

4.1 Zero resistance

Zero resistance is the commonly used term for superconductors. Only those materials come under the heading of superconductors which fulfil this condition of zero resistance. Experiments have been done for the confirmation whether resistance is indeed zero or if there is any small residue of resistance. Gallop was the first scientist who finally justified the zero resistance of superconductors otherwise it is not possible to measure the current circulating in a superconducting loop by implanting an ammeter into the loop because current would definitely decay due to the resistance of the ammeter [23].

Moreover, the current in the loop and magnetic field are directly linked with each other so magnetic field quantification is possible without consuming energy from the circuit. This type of repetition of experiments over periods of years, confirmed the constant value of superconducting current and this persistent *current* is the main characteristic of superconductors which proves the zero resistance of superconductors.

For superconductors, it is quite preferable to define them in terms of R*esistivity* rather than conductivity since Resistivity is the reciprocal of conductivity (σ)

$$\rho = \sigma^{-1}.$$

So, mostly the superconductors are described by $\rho = 0$ rather than by $\sigma = \infty$.

As discussed under previous heading that it has been deducted from the lack of any decay of the current that the resistivity ρ of a superconductor metal is less than 10^{-26} Ω m whereas the resistivity of copper is 10^{-8} Ω m at room temperature. It is clear that the resistivity of superconductor metal is 18 times less than the resistivity of copper that is a normal conductor at room temperature [24]. Hence, it seems that we are justified in treating the resistivity of a superconducting metal as zero.

4.2 Super-electron

The electrons that cause the phenomenon of superconductivity are called super-electrons. It is assumed that their resistivity is nearly zero regarding that they are succeeding one another without any type of collision. They act in a vacuum. For resistance to less electrons, it is necessary that the current must be the same towards the path of electrons. The product of electron density and electron velocity may maintain the constant current. But in superconductors ions of metals are fixed, therefore, the electron density cannot be varied. In this way the current is the same and electrons don’t have an electric field and cannot be accelerated [25].

Materials Research Foundations 132 (2022) 1- 16 https://doi.org/10.21741/9781644902110-1

4.3 Critical temperature for superconductors

The temperature at which the resistivity of superconductors vanishes is called critical or transition temperature of the superconductors [26]. Its value is not specific, i.e., varies from metal to metal and depends on the material's purity. Some metals are so sensitive that if little amount of impurity is present then they will not exhibit the phenomenon of superconductivity like iridium and molybdenum [27]. But this imagination is not for all metals like Cu and Na. This concept reveals the new type of superconductors. There are many metallic elements and alloys showing the property of superconductors. Some two metallic elements are not superconductors itself but their combination in the form of alloy exhibit the superconductivity phenomenon [28].

5. Classification of superconductors

Those materials which exhibit superconductivity when sufficiently cooled are called superconductors. It has been considered for many years that the basic behavioural pattern of all superconductors is almost similar but in 1957 theoretical investigations of Abrosov led to the classification of superconductors that is based on the fact that superconductivity can vanish through two distinct situations. In other words, the actual basis of division of superconductors are the differences in their magnetic behaviour [29]. So, their classification as follows:

- Type-I superconductors,
- Type-II superconductors

Although the two classes have many similar properties even then the differences are enough for the bifurcation of superconductors into two distinct classes [30].
A brief tabulated difference of the aforementioned classes is as follows (Table 1):

Table 1. Difference between Type 1 and Type-II superconductors

Type-l superconductors	**Type-ll superconductor**
These are called soft superconductors because low intensity magnetic fields can destroy their superconductivity.	These are called hard superconductors because it's not easy to destroy their superconductivity by an external magnetic field.
They are usually pure elemental superconductors like pure metals (except niobium, vanadium, technetium and carbon nanotubes). Some examples are Zn, Hg, Pb, Sn, Ta etc.	They are usually almost impure and compound superconductors like alloys and high critical temperature ceramics e.g., Nb_3Sn, Bi-Pd, Nb-Ti etc.

Materials Research Foundations 132 (2022) 1- 16 https://doi.org/10.21741/9781644902110-1

The conductivity of type-I superconductors is normally explained by BCS theory.	The conductivity of these type-II superconductors cannot be explained by BCS theory.
These are strongly diamagnetic in nature.	These are partially diamagnetic.
These are low temperature superconductors. (0-10K)	These are high temperature superconductors. (Above 10K)
These are used to prepare electromagnets. [31]	These cannot be used to prepare electromagnets.
This type of superconductors strongly follows the Meissner effect	These do not perfectly obey the Meissner effect but somewhat follow this effect.
They have low value of critical temperature and critical magnetic field (up to 1T)	They have a high value of critical temperature and magnetic field (greater than 1T).

6. Properties of superconductor

The fundamental properties of superconductors are as follows….

- Evanesce of the electrical resistance
- Diamagnetism as well as Flux lines
- Quantization of flux in superconductors
- Quantum interference
- Josephson currents

6.1 Evanesce of electrical resistance

The resistivity of a superconductor e.g., mercury suddenly decreases when it reaches a superconducting state. The basic method of resistance was used and voltage was measured when passing the electric current. Experimentally it is not possible to exactly prove the resistance value equal to zero, however, its upper range can be found.

For this purpose, highly sensitive methods were used to get the minimum possible residual resistance. In 1914 Kamerlingh-Onnes experimented with the decay of flow of electric current in a closed ring made of superconductor e.g., lead. The ring is kept in a normal state of temperature which is above the transition temperature and a magnetic rod adjusts in the ring-opening. Now down the temperature from the transition temperature T_c at which the ring becomes a superconductor by keeping magnetic field constant and sudden removal of magnetic rod induced electric current. Since the change in magnetic flux Φ caused, electric voltage then generates an electric current. Assumed that ring diameter is 5 cm with 1 mm of wire thickness, self-induction *L* coefficient is 1.3×10^{-7}H and the current decreasing by 1% in an hour then applying exponential decay law resulting there would be a change in magnitude of superconducting state more than eight orders [32].

Kamer-Lingh as well as Tuyn used another setup that contained 2 superconducting rings which produced a permanent flow of current. The ring present inside is held by a torsional strand and to some extent moved far-off its place, it seems that permanent current attracts thread to its side resulting in equilibrium in angular momentum of thread and permanent current. The equilibrium observed via light beam indicates no change in permanent current has been found [33].

To monitor the upper range of resistance in a superconducting state geometrically depends on self-induction coefficient *L* which value is required to be very small and time of observation. In the present time, it is known that the resistance jump during superconductor entry is at least 14 orders of magnitude. A superconductor can have a maximum of 17 orders of magnitudes of electrical-resistance that is lesser than the specific resistance of copper. From the above debate, finally it is inferred that electrical resistance vanishes in the superconducting state [34].

6.2 Flux lines and diamagnetism

In 1924 Kamerlingh-Onnes experimented with the magnetic behaviour of superconductors. He cooled down the lead-made hollow sphere to the transition temperature and applied the external magnetic field, then off the external magnetic field considering R equals zero. Keeping in view the history, applying the same conditions to the material which could be moved into the various states. It concludes that there would be exactly no single superconducting phase but different phases along arbitrary shielding currents [35]. In contrast to the ideal electrical conductors, the superconductor behaves differently [36].

Reassuming a sample cooled to the critical temperature and applied a very small magnetic field then the field escaped from the inner of sample excluding the outer coating of material resulting as an ideal diamagnetic state [37]. It was first discovered by Meissner and Ochsenfeld in 1933 and the phenomenon was observed on lead or Tin made rods. The experiment was done on a permanent magnet placed on a lead bowl having the magnetic field applied externally when $T>T_c$ and cool down to the critical temperature. On reaching the critical temperature $T<T_c$ then permanent magnet expelled by the magnetic field and raised from the lead bowl to the position gained after equilibrium. The image shown above is for reference. Because two types exist in superconductors, their behaviours relevant to the magnetic field are also different [38].

- Type I superconductors e.g., lead and mercury eject magnetic field to the critical field which converts superconductor to the normal conducting state when applied to the field of larger magnitude.
- Type II superconductors e.g., mostly alloys show ideal diamagnetism at lower critical magnetic field B_{c1} smaller than the usual magnetic field. To apply the upper critical magnetic field B_{c2} causing dissipation of superconducting property.

Materials Research Foundations 132 (2022) 1- 16 https://doi.org/10.21741/9781644902110-1

However critical fields in both type I and type II superconductors reach zero on reaching the critical temperature. Keeping in view the behaviour of superconductors of type-II at the lowest and the upper critical limits of magnetic-field subsequently also known as Shubnikov phase passes the shielding current and concentrates the magnetic field to generate a flux line system known as Abrikosov Vortices [39]. He got a Nobel prize in 2003 for studying this quantized phenomenon of flux-lines. Ideally, the flux line system is arranged in a superconductor in an equilateral triangular manner. The flux lines consisted of circulating current in combination with externally applied magnetic-field to form magnetic-flux resulting in a decrease in magnetic field between flux-lines. Conclude that increasing the external magnetic field in the superconductor causes the decrease in distance between flux lines [40].

6.3 Flux quantization in superconductors

A permanent current can be induced by the superconducting ring in the presence of the magnetic field. Magnetic current can be calculated via $\Phi=LI$. Concerning the macroscopic studies, the permanent current of any value can be induced with proper selection of magnetic field and any arbitrary value of magnetic flux from the ring can be taken. The magnetic-field of flux-lines carries flux quantum Φ_o. Here flux quantum is significant for a superconductor's performance. This idea was first taken by Fritz London in 1950 based on probability [41].

The experiment on the superconducting hollow cylinder was done to measure the magnetic flux quantization in 1961. It was worked and published by the two groups of physicists at Stanford; the first group including members was Munich, Deaver, and Fairbank and the second one's name was Doll and Nabauer, Experiment, the lead made a small hollow cylinder of 10μm evaporated to quartz rod was used and permanent current induced by cooling the small superconducting ring (known as freezing field B_f) by keeping it in parallel position to axis of cylinder. After reaching the critical temperature off the field resulting in a permanent magnet [42]. The calculation of flux in frozen may be calculated via torque applied on perpendicular position of field and cylinder axis which is why the sample is attached with the quartz rod. The light indicator and mirror were used for the deflection. The further self-resonance technique was used by the physicists because the torque value obtained in the case was too small. They excite the torsional oscillation of the system by using a photocell and a light beam so the field follows the resonance frequency which would reverse periodically at the frequency of oscillation resulting in the large amplitude of torque measured [43].

Deaver and Fairybank used a superconducting hollow cylinder for the determination of elementary flux quantum Φ_o. They find the frozen-in-flux differently. They used a small detector coil and the oscillation end to end along the axis with a frequency at 100 Hz resulting in the generation of inductive voltage. The voltages were then further amplified to consider their value for measurement [44].

Materials Research Foundations 132 (2022) 1- 16 https://doi.org/10.21741/9781644902110-1

6.4 Quantum interference

The effect of coherent matter-wave in a superconductor is another aspect of study and demonstrated by diffraction and interference. Interference is the phenomenon in which light passes through a double slit and projects to the screen. Sagnac Interferometer, a laser beam from the source ejected, passed through the semi-transparent mirror and splits into two beams travelling in the spherical path by opposite direction, three furthermore mirrors adjusted circularly [45].

If both waves with the same phase reached the detector, then a large signal would be obtained due to constructive interference. If the setup moves in a clockwise direction, then the mirror rotates in the opposite direction of the beam. As a result, the ray has to cover more distance than before to reach the sensor compared to the ray that travels in a counter clockwise direction. Due to this behaviour, the phase difference aroused in the detector causes aggression in the rotational velocity of measurement setup which then affects the periodic signal gain between upper and lower value [46].

To overcome this issue, the Sagnac interferometer as a gyroscope can be used. The phenomenon can occur in superconductors using coherent matter waves which can be further elaborated via the Josephson effect.

6.5 Josephson current

Two superconductors are placed up and down in the form of a sandwich and there is minor space between them also called a non-superconductor insulator or barrier. When the insulator is too small, electrons from one superconductor can move to the other superconductor due to quantum mechanical tunnelling. Wavefunction works here briefing the reason for moving or leaking electrons from the metal area. when another metal is passed near the barrier, then the current can flow between the sandwich structure [47, 48]. Due to the flow of electrons between superconductors, a weak supercurrent passes through the barrier. This weak supercurrent is also known as *Josephson current* which was predicted by Brain D. Josephson in 1962 and got a Nobel prize in 1973 due to the discovery of amazing properties related to superconductors. Properties of the Josephson junction are very important for the elaboration of macroscopic-wave-function that is proportional to Josephson current [49]. As discussed above sandwich form of superconductors, consider the same scenario with leakage of coherent matter-wave from superconductors and for this purpose, the Josephson equation has been derived as follow:

$$\frac{\mathrm{d}}{\mathrm{d}t}(\varphi_2 - \varphi_1) = \frac{2eU}{\hbar} = \frac{2\pi}{\Phi_0} U$$

Most barriers and superconductors follow the Josephson equations and these equations are valid in most cases. The junctions, elaborate as SIS junction is superconductor-insulator-superconductor in which insulator should be 1-2nm thick SNS junction is superconductor-normal conductor-superconductor, it operates with high thickness of normal conductor due to cooper pair which have less penetration in oxide layer than normal conductors.

Moreover, resistance is the important factor between normal conductors and oxide junctions; normal conductors have less resistance (10^{-8} per square) than oxide junctions (10^{-4} – 10^{-3} per square) [50, 51].

Conclusion

Finally, it may conclude that superconductors are the materials which behave as normal conductors at standard values of room temperature and pressure. They show resistance in the flow of current but on cooling below their critical values of temperature (above the absolute zero) and magnetic field, they exhibit the rare phenomenon of super conductance i.e., zero resistivity. These specific values of critical temperature and critical magnetic field at which conductors become superconductors principally depend upon the nature of super conducting material. However, there is a difference between perfect conductor and super conductor where the former one is ideal and does not exist in real, but the later one is practically approachable. Since the discovery of superconductors by Onnes in 1911, a lot of developments have been done in this field to date and few scientists got noble prize for their extra ordinary work on superconductors. The main properties of superconductors are the disappearance of electrical resistance and perfect diamagnetism. Flux quantum as well as Josephson equations are also significant for superconductors.

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