Superconducting Materials and Technologies: From Magnets to Quantum Computers

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Introduction

Since mankind first discovered electricity, we have sought to harness it to power machines and makes our lives easier. As technology has improved, our devices and machines have become more powerful and efficient, but still one thing thwarts us – electrical resistance. This property of a material means that a some of the electrical energy we generate is lost as heat, purely through transmission of electrical current from one place to another. In an ideal world we would have cables with zero losses, greatly improving the efficiency of our grid networks and helping to reduce the energy needs of the globe.

In the early 20th century, materials that lost their electrical resistance at low temperatures were observed for the first time, and while these initial materials were not particularly useful, lots of progress has been made in creating and improving new materials whose properties are able to meet those needed for engineering and scientific applications. Termed "superconductors", these materials are not only infinitely conductive, but also exhibit some unusual behaviour when interacting with magnetic fields. Nowadays, superconductors are used for a large number of applications, from the medical industry to fundamental science research and also quantum computing. Here we will cover a brief history of superconductivity, the unique properties of superconductors and their current and future applications

Discovery of Superconductivity

Thermal energy of atoms is the cause of resistivity in metals as the atomic lattice vibrations impede the flow of electrons through the material. It may therefore seem obvious that the best way to reduce this resistivity of a metal is to reduce the temperature. Up until the beginning of the 20th century, the electrical behaviour of metals at low temperatures was unknown, and therefore different hypotheses existed to predict what would be seen. These included the resistance dropping linearly to zero at 0 K or a plateau to a constant value as absolute zero is approached (figure 1).

It was this gap in our knowledge that spurred Kammerlingh Onnes, a Dutch physicist, to study this area. In 1908 he successfully liquified helium for the first time, which later won him the Nobel prize and would allow to him to study the behaviour of metals at temperatures approaching absolute zero. Later, in April 1911, while studying the resistance of mercury he noted that "Kwik nagenoeg nul"[1], or "Mercury almost zero", which contrasts with the behaviour seen with other metals. He later published his work, which demonstrated the first observation of superconductivity [2].

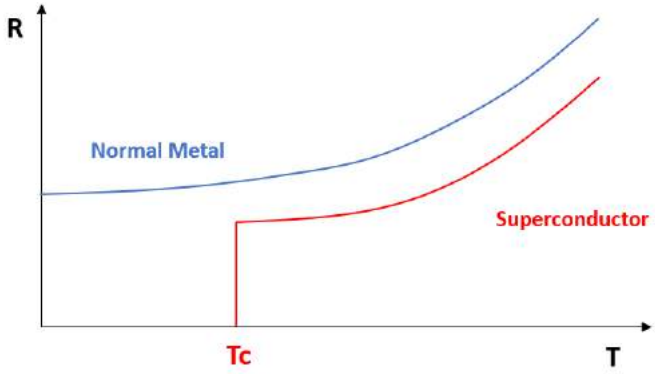

Figure 1: Schematic demonstration of the temperature dependence of resistance in a superconductor and normal metal.

Properties of Superconducting Materials

T_c, J_c & H_c

As Onnes noted, superconducting materials are only superconducting below a certain *critical temperature*, known as T_c. There are two other parameters that were found to determine whether the material is superconducting – *critical current density* (current per unit area), J_c, and the *critical magnetic field*, H_c. This means that even if the temperature is less than T_c, if the current being carried or the magnetic field is too high, then the material will 'quench' out of the superconducting state and become resistive like an ordinary material. These parameters define a 3D critical surface (figure 2) that illustrate when a material will be in the superconducting state. We will see later that this picture is not entirely true for all superconducting materials.

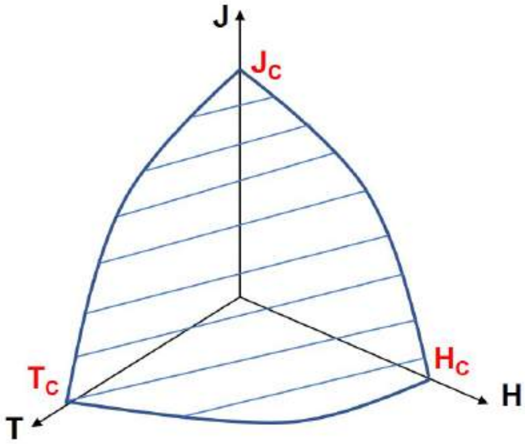

Figure 2: 3D surface defining the conditions for superconductivity in a superconducting material.

Meissner Effect

When you expose a normal metal to an external magnetic field the magnetic flux penetrates straight through the metal. In 1933, Meissner and Ochsenfeld discovered that the behaviour of a superconductor was much different [3]. They found that when you apply a magnetic field to a superconducting material below T_c, the magnetic field is mostly expelled from the material as shown below (figure 3).

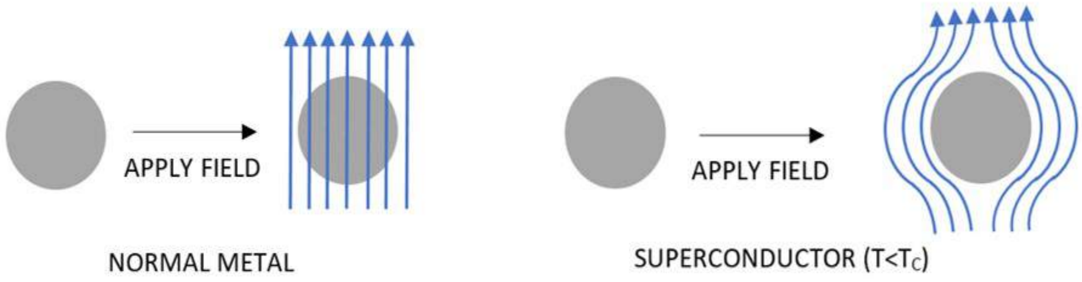

Figure 3: Effect on magnetic field lines when applying a field to a normal metal and a superconductor.

Due to electromagnetic induction, surface currents that screen the inside from the magnetic field would be expected for any perfectly conducting (zero resistance) material, resulting in similar behaviour to that seen from the superconductor above. What separates superconductors from perfectly conducting materials in this regard is the behaviour seen when cooling in an applied field. In such a field-cooling scenario, the superconductor once again expels all field as soon as $T<T_c$ whereas the field continues to penetrate the perfect conductor. This phenomenon is known as the Meissner effect, and is a demonstration of perfect diamagnetism in superconductors (figure 4).

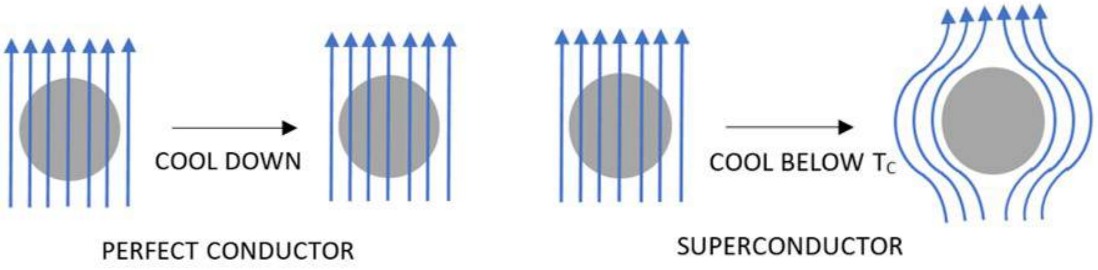

Figure 4: Effect on magnetic field lines when field-cooling a perfect conductor and a superconductor.

Type I and Type II

In reality, not all superconductors behave exactly as described above, and their behaviour falls into one of two categories, Type I or Type II. Ideal Type I materials behave as described above, and expel all magnetic field when in the superconducting state, undergoing a sharp first order superconducting transition when increasing the field. As such, there is a single defined value of H_c. In Type II materials, flux is able to penetrate the sample at a generally lower field strength known as H_{c1}. As the field is increased, the amount of magnetic flux that penetrates increases until a second critical field, H_{c2}. At this point the material loses its superconductivity, like how a Type I material would at its H_c. Why this distinction occurs will be explained shortly, but it is primarily explained by the surface energy between superconducting and normally-behaving areas of the material.

Type I

Relatively few of the known superconducting materials are actually Type I, and of those the majority are pure metals such as aluminium and the first ever discovered superconducting material, mercury. In such a material, the response to a magnetic field is heavily dependent on the sample geometry due to the demagnetizing effect [4]. Put simply, this effect describes how some areas of a sample surface may have a higher local magnetic field than others and, as a result, some parts of a superconducting sample can be above H_c, while others are not. Some parts of the sample will therefore be superconducting while other parts act normally, with the material considered to be in the *intermediate state* [5]. As described by the Ginzburg-Landau theory [6], in a Type I material, the aforementioned surface energy is positive, meaning that a high surface area between the superconducting and normal areas is energetically unfavourable. The balance between demagnetization energy, which favours many divided superconducting areas, and the surface energy means that the normal areas are usually in the form of tubes or lamellae of normally-behaving material that allow flux to penetrate the sample [7]. This can be demonstrated by coating the surface with magnetic particles, as demonstrated in figure 5.

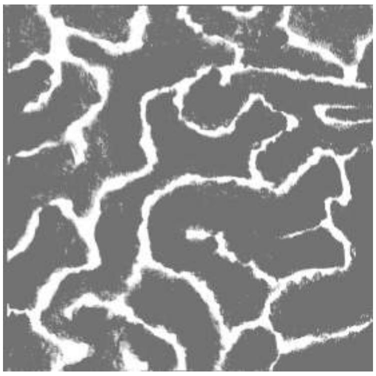

Figure5: Sketch showing how the intermediate state in aluminium is seen when decorating the surface with magnetic particles. The superconducting areas are dark.

Type II

Most superconductors are of the Type II variety. For these materials, the surface energy is negative, and so it is energetically favourable for high surface areas between the superconducting and normal regions. To minimise the energy the flux is therefore separated into many small regions of normal material within the superconductor, and this is referred to as the mixed state. The lowest energy configuration of flux lines was predicted to be a periodic lattice by Abrikosov [8]. Despite incorrectly predicting a square lattice, Abrikosov shared the Nobel prize with Ginzburg and Leggett in 2003. In reality, the lattice is triangular in a pure material, and can be nicely demonstrated using a scanning-tunnelling microscope (figure 6).

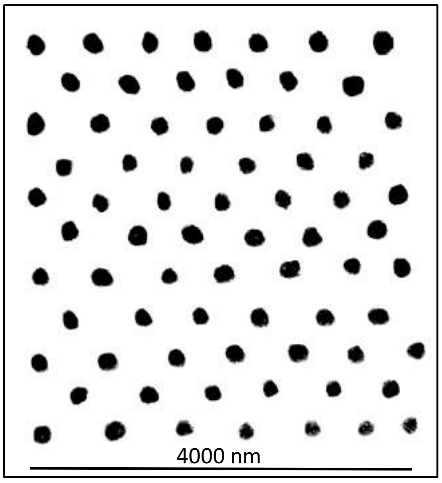

Figure 6: Sketch of how the triangular flux lattice expected in $NbSe_2$ would be seen in a scanning-tunnelling microscope.

When a current flows it generates its own magnetic field. The interaction between the magnetic field and a flux line via the Lorentz force ($\underline{\mathbf{F}} = \underline{\mathbf{J}} \times \underline{\mathbf{B}}$, where $\underline{\mathbf{F}}$ is the force per unit volume, $\underline{\mathbf{J}}$ is the critical current density and $\underline{\mathbf{B}}$ is the magnetic flux density vector [4]) would mean that in the presence of any current, the flux lattice would move and the critical current would be zero.

It is therefore necessary to include flux pinning centres in a material to have a non-zero J_c. Flux pinning can be due to defects, or features, in a material or artificial additions.

Alternating Current Operation

Most electrical current transportation is done using an alternating current (AC) as opposed to direct current (DC). In AC, as the current direction reverses the magnetic field direction also reverses causing the flux lines in a Type II material to move. This generates a voltage and results in the loss of energy, but the effect can be minimised in a few ways. Generally in superconducting wires, superconducting filaments are imbedded in a conductive matrix (e.g. copper or silver) to aid with stability [9] (see figure 7). One way to reduce the losses would be to decrease the size of the filaments. Coupling losses, due to the filaments touching each other at the ends of the wires can also be reduced by either twisting the wire or by increasing the resistivity of the conductive matrix, although this latter method reduces the stability.

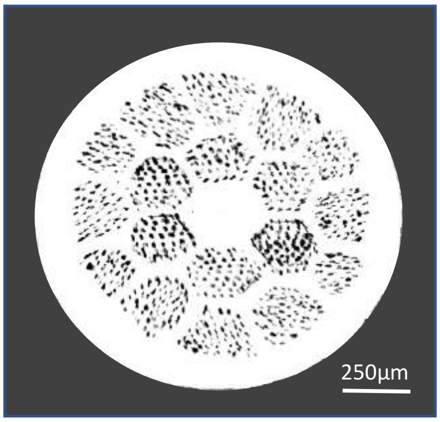

Figure7: A sketch of a cross-section of a BSCCO-2212 wire, showing the silver matrix (light) and the BSCCO-2212 filaments (dark spots).

A Brief Quantum Description

As we have seen, the properties of superconductors are quite weird, but we have not touched upon why exactly these properties are exhibited by these materials. The reason is quantum mechanical in nature and so will not be described in detail here, but the overall effect is that we see coupling of electrons into *Cooper pairs* at the superconducting transition. Cooper pairs do not act as fermions, like electrons, but as bosons, with the two electrons separated by a distance known as the *coherence length*. These bosons do not obey the Pauli exclusion principle and so can call occupy the same energy level. BCS (Bardeen, Cooper & Schrieffer) theory describes how this process occurs, and predicts all the phenomenon described above [10], [11]. It was such an important theory that the three were awarded the Nobel Prize for Physics as a consequence.

Which Materials are Superconducting?

A wide range of materials have been shown to superconduct since the discovery of this in mercury. A good demonstration of the improvements in superconducting properties over the years is shown in figure 8. Particularly exciting developments occurred during the late 1980s when Yttrium Barium Copper Oxide, or YBCO for short, was first produced. A ceramic superconductor, it was the first found to have a T_c above the temperature of liquid nitrogen [12]. The operating costs associated with a high T_c material could be potentially much lower than if liquid helium was used. While there are many interesting materials that we could explore, we will only cover a few of the most important ones here.

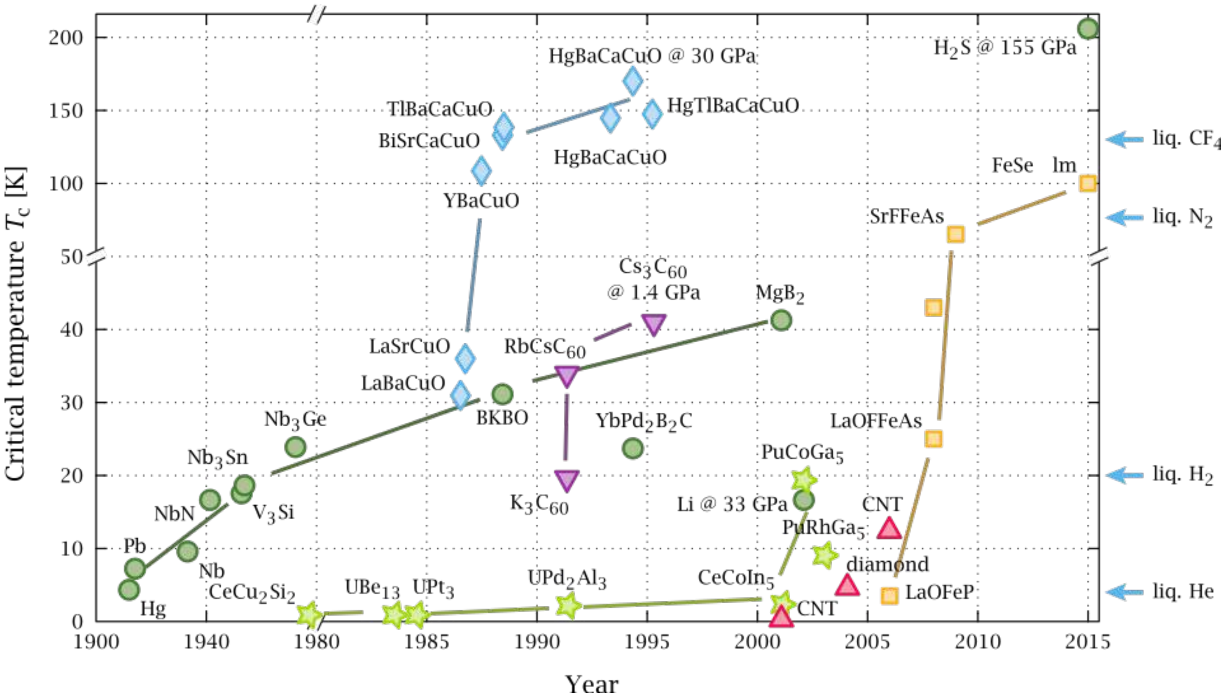

Figure 8: Timeline showing the progression in T_C in superconductors. Image by PJRay licensed under CC BY-SA 4.0 [29]

NbTi

Perhaps the most important superconductor in use at the moment is NbTi. With an optimised composition of Nb – 47wt% Ti, NbTi is the workhorse material for most superconducting applications. It has a T_c of only 9.8K, but its good ductility makes it an excellent candidate for wires, and the manufacturing process of NbTi has led to a microstructure that is excellent for flux pinning. Filaments are usually made of NbTi alloy ingots sheathed in Nb (to prevent diffusion between Ti and Cu) which are placed in Cu tubing. These are then stacked within a larger Cu tube before a complex series of heat treatments and drawing stages are used to form the wire. The final microstructure contains ribbons of α-Ti precipitates [13] which are spaced at approximately the distance equal to that expected for the flux lattice, resulting in very effective flux pinning and therefore high critical currents.

Nb$_3$Sn

Nb$_3$Sn is another commonly used alloy based on Nb. It has a higher T_c than NbTi at 18.3 K and can be produced by several manufacturing methods. The first method is called the *bronze process* [14] and involves placing Nb filaments in a bronze matrix before various drawing and annealing stages and the final reaction heat treatment. A second common method is known as the *internal tin process* [15] in which a tin rod is used as the source of tin to react with Nb filaments in a Cu matrix. Finally, the *powder-in-tube process* (PIT), uses Nb-Sn intermetallics as the source of Sn. Here the Nb-Sn powder is packed in small Nb tubes, spaced by a Cu lining, and are then further stacked in a copper tube before the heat treatments and drawing stages.

Unfortunately, the material is much less ductile than NbTi, complicating the manufacturing processes, but the material is more suitable to generate the highest magnetic fields that are used in some applications. Internal tin wires are commonly used for high current applications whereas the bronze process is cheaper and is used when persistent currents are necessary. PIT wires are less common due to their higher production costs.

High-Temperature Cuprates

The class of high-temperature superconductors became realised with the discovery of the cuprates [16]. With complicated crystal structures (e.g. in figure 9), these materials are very oxygen sensitive, adding complications with processing, and their superconducting properties are often anisotropic, meaning that the properties can be poor when current travels in one direction but excellent in a perpendicular direction. One example of this is the Bi-Sr-Ca-Cu-O system [17]. There are multiple forms of BSCCO including BSCCO-2223 (meaning $Bi_2Sr_2Ca_2Cu_3O_{10+x}$). This material has a remarkable T_c of 110K [18], making it suitable for operation at liquid nitrogen temperatures. While this material can be produced in tapes, another material known as BSCCO-2212 can be produced in wire form using a powder-in-tube method. Its T_c is lower at 95 K, making it a bit less suitable for liquid nitrogen operation (T_c is usually desired to be much higher than the operating temperature for a material to be useful).

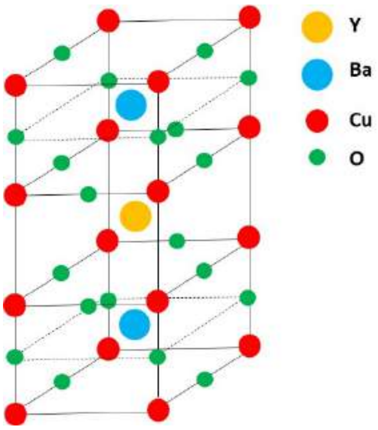

Figure 9: The crystal structure of YBCO

YBCO ($YBa_2Cu_3O_{7-x}$), mentioned previously, requires a particular crystal orientation in order to get good superconducting properties, resulting in the coating conductor method as the preferred manufacturing process. Here, YBCO is grown on a substrate that influences the growth of the YBCO. The YBCO itself can be grown by pulsed laser deposition in a research scenario, but for a higher production rate metalorganic chemical vapour deposition (MOCVD) can be used. YBCO is not used in many applications due to poor properties in polycrystalline samples and issues associated with processing the material.

Common Applications

MRI and NMR (Nuclear Magnetic Resonance)

The vast majority of superconducting wires that are currently produced are used in Magnetic Resonance Imaging (MRI) scanners. These machines require very high magnetic fields of several Tesla (for comparison, the magnetic field generated by a typical fridge magnet is 0.01 T[19]), as well as high stability and a uniform field to give high resolution data. Good stability is achieved using wires with a high percentage of copper conductor, and the magnets are operated in persistent current mode whereby the circuit is detached from the power supply and the current is left flowing around the superconducting loop – MRI scanners are therefore nearly always left on. Nuclear Magnetic Resonance (NMR) spectroscopy is another application with very similar superconductor requirements, however the relative amount of superconductor is generally higher as generally lower stability is required. It is also possible to achieve very high fields of ~9 T using Nb_3Sn [20] rather than NbTi.

High Energy Physics

High energy physics is also a large consumer of superconducting wires, although the demand for them is less regular. The Large Hadron Collider (LHC) is one such example, which uses mostly NbTi-based magnets to control the high energy particle beam path [21]. These parts are crucial to some of the most exciting physics experiments being performed today, including the discovery of the Higgs boson in 2012. Experimental fusion reactors also employ superconductor-based magnets to control the plasma during the reaction [22]. Here the required fields are higher than can be achieved by NbTi so Nb_3Sn is often used instead.

Josephson Junctions

In a much different application, superconductors can be used to produce Josephson junctions. These devices are made up of two superconductors separated by a non-superconducting material. Cooper pairs can flow (or tunnel) from one superconductor to the other by the Josephson effect [23], [24], an effect which has application in SQUIDs (superconducting quantum interference devices) [25] for precise magnetic field measurements among other things, including the potential for use in quantum computers.

Looking to the Future

Room Temperature Superconductivity

One of the main goals of research into superconducting materials is developing a material that is able to superconduct at room temperature. While the high-temperature cuprates are a promising set of materials, T_c is still 100 K away from room temperature. In 2015, Drozdov *et al* [26] demonstrated the highest ever recorded T_c of 203 K in H_2S. While this a further amazing step towards room temperature superconductivity, this was also achieved at a pressure of 155 GPa (atmospheric pressure is ~101 kPa) and so is still far from superconductivity at ambient conditions. Another promising set of candidate materials is the iron pnictides. Discovered in 2008 [27], these materials are similar in their layered structure to the cuprates. However, the anisotropy in properties is less pronounced, resulting in the potential for easier processing methods.

Quantum Computing

In current computing technologies, progression is becoming limited by the reduced size of our current transistor technologies. Eventually we will hit a point where it is no longer possible to improve processing power this way and we might want to look at a different form of computer altogether. Quantum computers are a popular option, using quantum phenomena such as superposition to perform their calculations. In theory, these types of computers would be much faster than classical computers at solving particular tasks. While the technology is still in its infancy, superconducting materials have the potential for use as superconducting qubits (quantum bits) using Josephson junctions [28].

Conclusion

Over the course of this article we have covered the basics of superconductivity, from its discovery all the way to current day uses. The basic properties of a superconductor have been discussed, with a brief description of the differences between Type I and II, and examples of important technological superconducting materials and their applications. Aside from electrical current transport and magnetic field generation, there are many other interesting applications for superconductors including quantum computing and many more that have not been discussed here. Superconducting materials will become increasingly important as we try to meet the world's energy and technological demands and so the motivation for finding better materials is stronger than ever. So, while we are still far from usable room temperature superconductors, hopefully it is not too long before we see a paper announcing the discovery of superconductivity at 298 K.

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