Type 1 and type 2 superconductor

Superconductivity is a phenomenon which occurs in certain materials and is characterized by the absence of electrical resistivity. Until recently, this phenomenon had been restricted to metals and alloys with transition temperatures of less than 23K. In 1986, superconductivity was discovered in a ceramic material. This precipitated an onrush of ceramic based superconductors with transition temperatures as high as 120K. The ceramic-based materials are commonly known as high temperature (HTc) superconductors while the metallic and alloy materials are called low temperature (LTc) superconductors. Currently, only low temperature superconductors are of interest to the magnet designer and manufacturer. Superconductors are divided into two types depending on their characteristic behavior in the presence of a magnetic field. Type I superconductors are comprised of pure metals, whereas Type II superconductors are comprised primarily of alloys or intermetallic compounds. Both, however, have one common feature: below a critical temperature, Tc, their resistance vanishes. The critical temperature at which the resistance vanishes in a superconductor is reduced when a magnetic field is applied. The maximum field that can be applied to a superconductor at a particular temperature and still maintain superconductivity is call the critical field, or Hc. This field varies enormously between Type I and Type II superconductors. The maximum critical field (Hc) in any Type I superconductor is about 2000 Gauss (0.2 Tesla), but in Type II materials superconductivity can persist to several hundred thousand Gauss (Hc2). At fields greater than Hc in a Type I superconductor and greater than Hc2 in a Type II superconductor, the conductor reverts to the normal state and regains its normal state resistance. A Type I superconductor excludes the applied magnetic field from the center of the sample by establishing circulating currents on its surface that counteract the applied field. Type II superconductors, however, permit the field to penetrate through the sample in quantized amounts of flux. These quanta are comprised of circulating vortices of current and the flux contained in the vortices. The total flux in a vortex is 2 x 10-7 Gauss-cm2. Great numbers of these vortices, or fluxoids as they are frequently called, can exist in a superconductor. For example, at a field intensity of 80 kilogauss (8 Tesla) there are 4 x 1011 fluxoids/cm2. These fluxoids and their interactions with defects in the superconductor give rise to the high current carrying capabilities of superconducting magnets. Flux Pinning and Flux Flow Properties of superconducting materials are altered locally by the presence of defects in the materials. A fluxoid encompassing or adjacent to such a defect in the material has its energy altered and its free motion through the superconductor is inhibited. This phenomenon, known as flux pinning, causes a field gradient in the superconductor and gives rise to a net current in the material. In the absence of defects in a Type II superconductor, no bulk current can be conducted without a transition into the normally conducting resistive state. Since the pinning force is small, fluxoids can be broken loose from their pinning centers, resulting in a net creep of the flux through a conductor as a function of time. This results in an effective voltage in a Type II superconductor. If the current density is low and the magnetic field is not intense, flux creep is insignificant and the induced voltage and effective resistance of the conductor will be essentially zero. At very high fields and high current densities, fluxoids will migrate rapidly, giving rise to a phenomenon called flux flow. A Type 2 Layered Cuprate Type 2 Superconductors Except for the elements vanadium, technetium and niobium, the Type 2 category of superconductors is comprised of metallic compounds and alloys. The recently-discovered superconducting "perovskites" (metal-oxide ceramics that normally have a ratio of 2 metal atoms to every 3 oxygen atoms) belong to this Type 2 group. They achieve higher Tc's than Type 1 superconductors by a mechanism that is still not completely understood. Conventional wisdom holds that it relates to the planar layering within the crystalline structure (see above graphic). Although, other recent research suggests the holes of hypocharged oxygen in the charge reservoirs are responsible. (Holes are positively-charged vacancies within the lattice.) The superconducting cuprates (copper-oxides) have achieved astonishingly high Tc's when you consider that by 1985 known Tc's had only reached 23 Kelvin. To date, the highest Tc attained at ambient pressure for a material that will form stoichiometrically (by direct mixing) has been 147 Kelvin. And the highest Tc overall is 216 Celsius for a material which does not form stoichiometrically (see below list). It is almost certain that other, more-synergistic compounds still await discovery among the high-temperature superconductors. The first superconducting Type 2 compound, an alloy of lead and bismuth, was fabricated in 1930 by W. de Haas and J. Voogd. But, was not recognized as such until later, after the Meissner effect had been discovered. This new category of superconductors was identified by L.V. Shubnikov at the Kharkov Institute of Science and Technology in the Ukraine in 1936(1) when he found two distinct critical magnetic fields (known as Hc1 and Hc2) in PbTl2. The first of the oxide superconductors was created in 1973 by DuPont researcher Art Sleight when Ba(Pb,Bi)O3 was found to have a Tc of 13K. The superconducting oxocuprates followed in 1986. Type 2 superconductors - also known as the "hard" superconductors - differ from Type 1 in that their transition from a normal to a superconducting state is gradual across a region of "mixed state" behavior. Since a Type 2 will allow some penetration by an external magnetic field into its surface, this creates some rather novel mesoscopic phenomena like superconducting "stripes" and "flux-lattice vortices". While there are far too many to list in totality, some of the more interesting Type 2 superconductors are listed below by similarity and with descending Tc's. Where available, the lattice structure of the system is also noted. (Hg0.8Tl0.2)Ba2Ca2Cu3O8.33* HgBa2Ca2Cu3O8 HgBa2Ca3Cu4O10+ HgBa2(Ca1-xSrx)Cu2O6+ HgBa2CuO4+ 138 K 133-135 K 125-126 K 123-125 K 94-98 K Lattice: TET * Note: As a result of a topological "defect", Hg will also go into the Cu atomic sites. Thus, the volume fraction of the intended structure type is typically just 15 - 30% of the bulk. Tl2Ba2TeCu3O8 Tl2Ba2YCu2O6 Tl2Ba2Ca2Cu3O10 (Tl1.6Hg0.4)Ba2Ca2Cu3O10+ TlBa2Ca2Cu3O9+ (TlSn)Ba4TmCaCu4O14+ (Tl0.5Pb0.5)Sr2Ca2Cu3O9 Tl2Ba2CaCu2O6 TlBa2Ca3Cu4O11 (Tl0.5Pb0.5Sn)Ba4Tm3Cu5O16+ TlBa2CaCu2O7+ Tl2Ba2CuO6 TlSnBa4Y2Cu4Ox 147 K (Superconductors.ORG - 2016) 139 K (Superconductors.ORG - 2016) 127-128 K 126 K 123 K 121 K (Superconductors.ORG - 2005) 118-120 K 118 K 112 K 105 K (Superconductors.ORG - 2011) 103 K 95 K 86 K (Superconductors.ORG - 2007) Lattice: TET Lattice: ORTH *** Though not always listed as a component, a small amount of Lead (x=.2-.26) is often used with Bismuth compounds to help facilitate a higher-Tc crystalline phase. *** The above compounds are all "infinite layer". Lattice: ORTH Comment: All of the above compounds have the copper-chain structure. GaSr2(Ca0.5Tm0.5)Cu2O7 Ga2Sr4Y2CaCu5Ox Ga2Sr4Tm2CaCu5Ox La2Ba2CaCu5O9+ (Sr,Ca)5Cu4O10 GaSr2(Ca, Y)Cu2O7 (In0.3Pb0.7)Sr2(Ca0.8Y0.2)Cu2Ox (La,Sr,Ca)3Cu2O6 La2CaCu2O6+ (Eu,Ce)2(Ba,Eu)2Cu3O10+ (La1.85Sr0.15)CuO4 SrNdCuO**** (La,Ba)2CuO4 (Nd,Sr,Ce)2CuO4 Pb2(Sr,La)2Cu2O6 (La1.85Ba.15)CuO4 99 K (Superconductors.ORG - 2006) 85 K (Superconductors.ORG - 2006) 81 K (Superconductors.ORG - 2006) 79 K (Saurashtra Univ., Rajkot, India - 2002) 70 K 70 K 60 K 58 K 45 K 43 K 40 K 40 K 35-38 K 35 K 32 K 30 K (First HTS ceramic SC discovered - 1986) **** First ceramic superconductor discovered without a non-superconducting oxide layer. Comment: All of the above are copper perovskites, even though their metal-to-oxygen ratios are not exactly 2-to-3. FeSe (monolayer) GdFeAsO1-x (Ca,Sr,Ba)Fe2As2 LiFeAs 65 K 53.5 K 38 K 18 K Comment: The above are members of the newly-discovered iron pnictide family. Nb3Ge Nb3Si Nb3Sn Nb3Al V3Si Ta3Pb V3Ga Nb3Ga V3In 23.2 K 19 K 18.1 K 18 K 17.1 K 17 K 16.8 K 14.5 K 13.9 K Lattice: A15 Comment: Among the binary alloys, these are some of the best performers; combining Group 5B metals in a ratio of 3-to-1 with 4A or 3A elements. PuCoGa5 18.5 K (First SC transuranic compound) Comment: After NbTi (below) NbN is the most widely used low-temperature superconductor. C Nb Tc V 15 K (as highly-aligned, single-walled nanotubes) 9.25 K 7.80 K 5.40 K Lattice: C=Fullerene, Nb=BCC, Tc=HEX, V=BCC Comment: These four are the only elemental Type 2 superconductors. Comment: The above 7 compounds are all rare ferromagnetic superconductors. Lattice: TET Comment: This is the first oxide insulator found to be superconductive. (1.) "History of Physics Research in Ukraine", by Oleksandr Bakai and Yurij Raniuk, Kharkov Institute of Science and Technology, 1993. Author's Comment: The Tc's noted on this page were obtained from a variety of sources including, but not limited to, the CRC Handbook of Chemistry and Physics, the N.I.S.T. database, Physica C, industry news sources, and various private researchers. In cases where there was a discrepancy between sources, the higher Tc or a range of Tc's has been listed. [Last page rev: June 2021] Type I superconductors have only one critical magnetic field. When that value is reached, the superconductive characteristics of a material gone. Type II superconductors, on the other hand, have two critical magnetic fields. Below the first value, the material will be a diamagnetic superconductor. Above the upper critical field, superconductivity and diamagnetism are destroyed. However, in between the two critical magnetic fields, the superconductor exists in a mixed state where it exhibits zero electric resistance, but is no longer a perfect diamagnet.Figure 6: Type II superconductors have 2 critical magnetic fieldsImage courtesy of: does this happen? Type II superconductors usually exist in a vortex state which means there are small (usually around 300nm) normal state cores surrounded by superconducting areas. This means that magnetic fields can penetrate the material while still maintaining superconductivity, as shown by the partial penetration of the material in Figure 7. As the temperature rises, the cores move closer together and eventually superconductivity is destroyed. Since the material is still superconductive during the mixed state, type II superconductors typically have much higher critical temperatures.Figure 7:Magnetic fields can penetrate normal vortex cores in Type II superconductorsImage courtesy of:: For decades it was assumed that all superconductors, elements and alloys, behaved in similar ways, and that any differences could be attributed to impurities or defects in the materials. However, in 1957, Abrikosov predicted the existence of a different sort of superconductor, and Figure 23 shows direct evidence for the existence of what are now known as type-II superconductors. A comparison of Figures 23 and 22 indicates that the effect of an applied field on a type-II superconductor is rather different from that for type-I superconductors. Figure 23 Surface of a superconducting alloy that had a magnetic field applied perpendicular to the surface. The dark regions were normal and the light regions superconducting. In this case, small ferromagnetic particles were applied to the surface, and collected where the field strength was largest. The particles remained in position when the specimen warmed up to room temperature, and the surface was then imaged with an electron microscope.For simplicity, we shall consider first a long cylindrical specimen of type-II material, and apply a field parallel to its axis. Below a certain critical field strength, known as the lower critical field strength and denoted by the symbol Bc1, the applied magnetic field is excluded from the bulk of the material, penetrating into only a thin layer at the surface, just as for type-I materials. But above Bc1, the material does not make a sudden transition to the normal state. Instead, very thin cylindrical regions of normal material appear, passing through the specimen parallel to its axis. We shall refer to such a normal region as a normal core. The normal cores are arranged on a triangular lattice, as shown in Figure 23, and as the applied field is increased, more normal cores appear and they become more and more closely packed together. Eventually, a second critical field strength, the upper critical field strength Bc2, is reached, above which the material reverts to the normal state. The state that exists between the lower and upper critical field strengths, in which a type-II superconductor is threaded by normal cores, is known as the mixed state. As Figure 24 shows, both the upper and lower critical field strengths depend on temperature in a similar way to the critical field strength for a type-I material (Figure 11). Figure 24 Temperature dependence of the lower critical field strength (Bc1) and upper critical field strength (Bc2) for a type-II superconductor.The normal cores that exist in type-II superconductors in the mixed state are not sharply delineated. Figure 25 shows how the number density of superelectrons and the magnetic field strength vary along a line passing through the axes of three neighbouring cores. The value of ns is zero at the centres of the cores and rises over a characteristic distance ξ, the coherence length. The magnetic field associated with each normal core is spread over a region with a diameter of 2λ, and each normal core is surrounded by a vortex of circulating current. Figure 25 Number density of superelectrons ns and magnetic field strength B around normal cores in a type-II superconductor.You can see from Figure 25 that the coherence length ξ, the characteristic distance for changes in ns, is shorter than the penetration depth λ, the characteristic distance for changes in the magnetic field in a superconductor. This is generally true for type-II superconductors, whereas for type-I superconductors, ξ > λ (Figure 20). For a pure type-I superconductor, typical values of the characteristic lengths are ξ ~ 1 μm and λ = 50 nm. Contrast this with the values for a widely-used type-II alloy of niobium and tin, Nb3Sn, for which ξ ~ 3.5 nm and λ = 80 nm.The reason that the relative magnitude of the coherence length and the penetration depth is so important is that when ξ > λ, the surface energy associated with the boundary between superconducting and normal regions is positive, whereas when ξ