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High-Temperature Superconductors: Materials And Applications.

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ABSTRACT

High temperature Superconductor is now centre of attraction because of its high-power density and high work efficiency. H. Kammerlingh Onnes in 1911 made a breakthrough in science by inventing superconductor. The origin of high temperature superconductor is unknown or not clear to the scientist. They are thinking that instead of conventional electron-phonon attraction mechanism, the more exotic pairing symmetries are involved in the superconductivity. There are huge applications of high temperature superconductor in electric devices and medical instrument like MRI machine.

Keywords: High Temperature Superconductor, Coolant, Ceramics, MRI, Meissner Effect.

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INTRODUCTION

High temperature semiconductor itself is a up gradation of superconductivity because of its high critical temperature (Tc), high power density and high efficiency [1]. Todays time is more exciting about finding more superconductor which shows potential in NMR and MRI imaging techniques and also keep its footprint in power transmission, levitating trains, energy storage, silicon crystal growers for computer parts and proton beam therapy for cancer treatment. The discovery of superconductor by H. Kammerlingh Onnes in 1911 is a breakthrough in science but it faces difficulties in commercialization in all purpose because of the requirement of very low temperature like 30K [2]. The discovery of George Bednorzand and K. Alex Muller in 1986 at IBM found that in a class of new ceramics particularly in copper oxide, whose resistance goes to zero at 35.1 K (above 77 K, above the boiling point of liquid nitrogen). They called it high temperature superconductor. This discovery removes the obstacles like requirement of expensive, hard to handle coolant and paved its way for commercial applications. Zero resistance comes with zero power loss i,e 100% current carrying capacity which was utmost interest of scientist but most of the high temperature superconductor are ceramics those are brittle in nature. Due to the brittleness of ceramic, it is quite problematic in fabrication of wire. The trails have been going on to manufacture high temperature superconductor at room temperature and it has been found that the only possibility to achieve this by applying high pressure which is not yet applicable in practical purpose. However, research is ongoing to surpass the limitations of superconductive substances manufacturing. There are mainly two types of high temperature superconductor, the first one is Rare-earth barium copper oxide (Ex: Yttrium barium copper oxide) and the other is iron based compound [3, 4].

Very recently, in 2021 a new type of high temperature superconductor had been reported and the compound was based on Cuprate of mercury, barium and calcium. The processing was at 133K and at ambient pressure [5].

The origin of high temperature superconductor is unknown or not clear to the scientist. They are thinking that instead of conventional electron-phonon attraction mechanism, the more exotic pairing symmetries are involved in the superconductivity and K. Alex Müller in 1986 at IBM which can go as high as 250K [6] paved its way for commercial applications he discovery of High Temperature superconductors by Georg Bednorz and K. Alex Müller in 1986 at IBM which can go as high as 250K [6] paved its way for commercial application

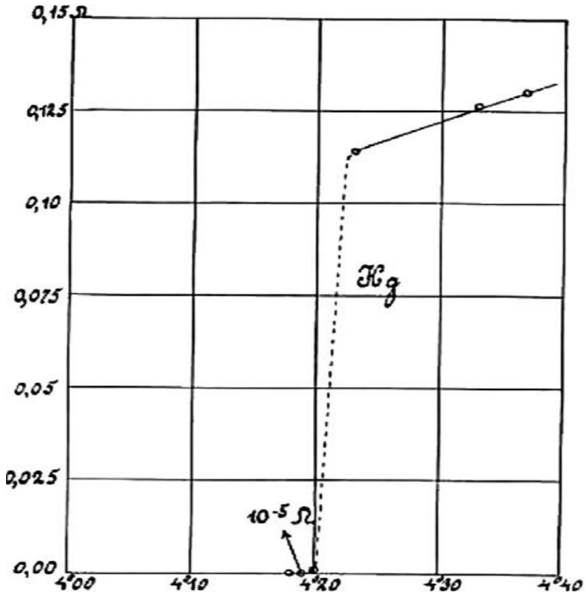

Figure 1: R.T. plot mercury, October, 1911, figure courtesy of Dirk van Delft, Museum Boerhaave, Leiden University the Netherlands.

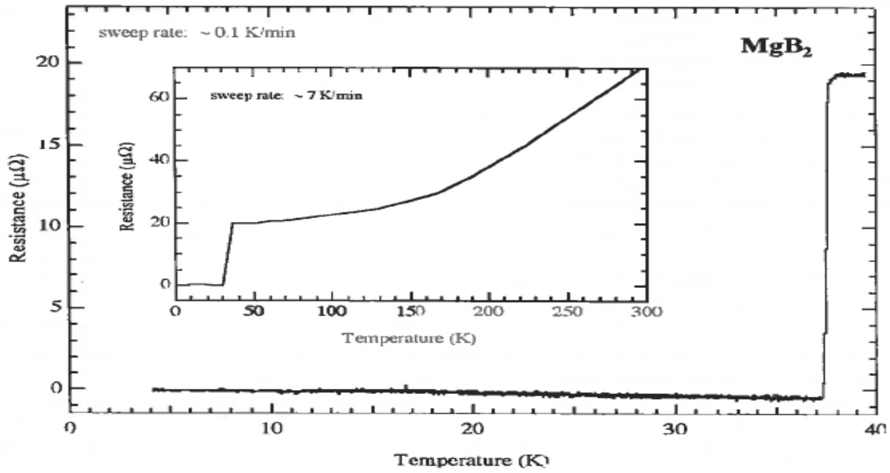

Figure 2: A drop to zero resistance at the critical temperature is seen in all superconductors, with the newly discovered superconductor MgB$_2$. Figure courtesy of R.A. Lewis and A.D. Martin, ISEM.

The Meissner Effect

The two essential properties of all superconductors are (i) zero resistance and (ii) expulsion of magnetic field. These two phenomenon can be explained by Meissner effect [6, 7]. Two German physicist W. Meissner and R. Ochsenfeld discovered this property of superconductor in 1933. When a conductor material keep in a applied magnetic field and cooled down to its critical temperature or below the critical temperature then electric resistance become zero and the the materials start to expel the magnetic field from the interior of the material [8-10]. This whole phenomenon is know as meissner effect. In a word, the transition from normal conductor to supercondor is known as meissner effect. During this process current loops would be generated to exactly cancel the imposed field. There is two types superconductor: (i) type-1 and (ii) type-II. In case of type-1 superconductor, with the increase of applied magnetic field strength there is a gradual decrease in superconductivity and when the field strength reaches above the critical value (Hc), the superconductor behaves like normal conductor. Always there is a chance of obtaining an intermediate state and that's completely depends on the geometry of the sample.

For type-II, with increase of applied magnetic field beyond the critical value, the number of magnetic flux penetrate into the superconductor materials increases, keeping the value of resistance at zero. If the supply of electric current increases too large amount, the resistance of the materials no longer remain zero. On the other hand, if the increment of the applied magnetic field touches the second critical field strength, immediately the superconductor looses its superconductivity. Generally, pure elemental compounds are belong to type-I and impure compounds belong to type-II superconductor.

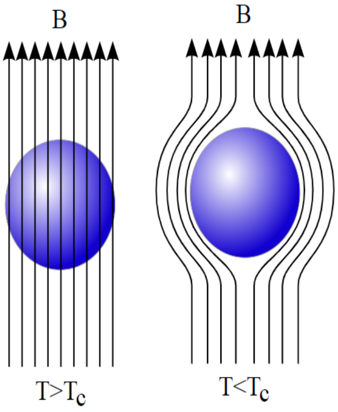

Figure 3: Diagram of The Meissner Effect, magnetic field lines, represented as arrows, which omitted from a superconductor when it is bellow its critical temperature

The Josephson Effect

When two superconductors are sandwich with a very thin insulator (~ 1 nm), then without generating any voltage suppercurrent flows across the device. This phenomenon is known as Josephson effect and the junction of two superconductors is known as Josephson junction.

This phenomenon was first observed and discovered by British physicist Brayan David Josephson in 1962 and he received the noble prize in 1973 for this amazing discovery [10-14].

The expression of the flow of a lossless super current is-

$$I_S = I_C \sin\Phi,$$

Where, Φ = phase difference in wave function across the junction, I_C is the maximum, or critical supercurrent. The critical current reflects the strength of the electrode coupling.

The original Josephson devices are tunnel junctions, the general concept of overlapping wave functions leads equally well to other weakly coupled superconducting structures [15]. The major applications of Josephson Effect are superconducting quantum interference devices (SQUIDs) [16] and single flux quantum logic [17] requires a single-valued (non-hysteretic) current–voltage (I–V) characteristic.

There are many theoretical models which can explain the superconductivity. The London theory (1935) and the subsequent Ginzburg-Landau (GL) theory along with quantum effects were phenomenological. But these theories fails to explain superconductivity on a microscopic level, but achieved good success in describing super current behaviour [1].

The BCS theory (1957):

A microscopic theory was made by Bardeen, Cooper and Schrieffer in 1957 which is popularly known as BCS Theory for the explanation of the behaviour of superconductors that were known at the time. Such an explanation requires the particles composing of bosons which have integral spin. Bosons obey Bose-Einstein statistics. The bosons in a superconductor can be assembled in the lowest possible energy state to form the condensate bellow the critical temperature and the greater the number that have assembled, the harder it is for one of them to leave. BCS theory explained how the interaction between the electrons and the photons or lattice vibrations in the metal causes an electron-electron attraction. It is evident from this theory that superconductivity is only possible at very low temperatures [1].

The success of this theory are as follows [18]

- The theory delivered a gap at T = 0 K of 3.5 kT_C, in good agreement with the experimental values of 3 to 4 kT_C.
- The gap width approaches to zero when T approaches to T_C.
- The temperature dependence of the electronic specific heat agrees very well with the experiments.
- The magnitude and temperature dependence of the penetration depth are in superior according to experimental data [19]

The first practical superconductors

The "Type II" period was unveiled by Kunzler *et al* in 1961 by drawing a Nb tube filled with Nb_3Sn powder into a wire with a current density J_c of ~10^5 A/cm^2. Up to fields of 8.8 Tesla the wire stayed superconductor. After a while type II alloys such as Nb-Ti and Nb-Zr which are able to carry high transport currents at high magnetic fields were discovered. In a type II superconductor there are two critical temperatures (or magnetic fields at a given temperature).

The low temperature superconductor:

The low critical temperature superconductors are of the mixed state as magnetic flux lines penetrate the material, with each associated by a vortex of supercurrent surrounding a normal state core.

By using low critical temperature (LTS) superconductors, extra high field magnets, transmission cables, generators electric resonators have been manufactured and are found in big particle accelerators such as CERN and Fermilab. The present commercial LTS superconductors for large-scale applications are typically NbTi or Nb_3Sn superconducting strands embedded in a copper matrix. [1]

The high temperature superconductors

Bednorz and Muller first found the cuprate superconductor in 1986 and they won the noble prize in 1987 for their discovery. Cuprate superconductors are layered structure and the layers made of copper oxide (CuO2), separated by alternative spacer layers of lanthanum or barium or a strontium. These spacer layers are actually act as a charge reservoir of dropped electrons or holes. These layered structures are very much closely related to perovskit stucture. The copper oxide planes are chechboard lattice, where O^{2-} occupy the corners and Cu^{2+} ion remains in centre of the each square.

The first discovered a cuprate high temperature superconductor (HTS) ($(La,Ba)_2CuO_4$) showed critical temperature of 35 K. After that many HTS oxides were quickly discovered. The highest record HTS critical temperature is now ~133.5 K (160 K at high pressure) for $HgBa_2Ca_2Cu_3O_{8+x}$. Most of the present experiments of cuprate superconductors are focussed on two types of materials: (i) YBCO [$YBa_2Cu_3O_{7-x}$, T_c~92K] and BSCCO [$BiSr_2Ca_1Cu_2O_{8+x}$] , (ii) (Bi2212), T_c ~ 85 K, and $BiSr_2Ca_2Cu_3O_{10+x}$ (Bi-2223), T_c ~ 110 K]. These superconductors are the example of type II superconductor. The moving electrons within the layer of Cu2O is responsible for superconductivity of cuprates. Exact mechanism of superconductivity in cuprates still a matter of debate and scientist suggest that electron-electron interaction in dx^2-y^2 orbital of Cu rather than electron-phonon interaction could be a prime reason behind the superconductivity.

It should be remembered that still there is no accepted microscopic theory for high temperature superconductivity. A team led by Jun Akimitsu at Aoyama-Gakuin University, Tokyo discovered a new superconductor MgB_2 which is not a copper oxide and whose critical temperature is 39 K. There is a confusion whether it is simply an LTS type II superconductor with an unusually high critical temperature or represents a whole new superconductor family [1].

Methods to prepare high temperature superconductors

There are so many ways to synthesize products as a pure HTS with optimal morphology and physical properties. The 'ceramic' technique [20], which is the usual method to prepare superconductors involves mixing, grinding and heating of powders of metal oxides and carbonates. Many chemical preparation techniques [21] for precursors have been developed (coprecipitation– filtration [22, 23], sol–gel [24], spray–drying [25, 26] in which the reagents are mixed at a molecular level in solution which lead to more homogeneous final products which can be prepared at lower temperatures and/or in shorter times.

The separation of a precipitate containing various ionic species which are chemically bounded to one another from a solution involves the co precipitation method . The control of the stoichiometry in the precipitate is too much difficult and therefore a repetitive procedure [27, 28] is used to adjust the concentration of metal ions in the start solutions in order to obtain the desired cationic or stoichiometric ratio in the precipitate. By the mixing of precipitating agent solution with the solution of the metal ions by two motor-driven burettes (Schott Gerate T100) at the same speed and under continuous stirring in a thermostatted case (25.0 ± 0.2 °C), the precipitates are prepared. Then the precipitates are subsequently filtered off, washed and dried.

A precursor for $YBa_2Cu_3O_{7-\delta}$ (Y-123) is prepared [29] by co-precipitation of hydroxides. The precursor is calcined at 940 °C for 10 h, pelletized, sintered at 940 °C for 24 h and finally annealed for 10 h at 400 °C. The entire heat treatment is performed in flowing oxygen. An oxalate precursor for $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) is prepared by precipitation of a 0.59 M nitric acid solution containing 0.02 M $Bi(NO_3)_3$, 0.07485 M $Sr(NO_3)_2$, 0.01880 M $Ca(NO_3)_2$ and 0.0264 M $Cu(NO_3)_2$ with an aqueous solution of 0.3 M $(NH_4)_2C_2O_4$. The obtained oxalate powder is calcined for 16 h in flowing oxygen, reground in an agate mortar, pre-fired at 850 ˚C for 16 h in flowing oxygen, reground, pelletized and finally sintered at 860 ˚C for 50 h in air.[30] An acetate–tartrate sol–gel method is used to prepare precursor gel of $YBa_2Cu_4O_8$ (Y-124) [31]; the gel is dried and calcined for 10 h at 800 ˚ C in flowing oxygen, reground in an agate mortar, pelletized and again heated for 80 h at 800 ˚C or 40 h at 820 ˚C in oxygen. By using usual ceramic route, starting as products Y_2O_3, $BaCO_3$ and CuO for $YBa2Cu_3O_{7-\delta}$ and $YBa_2Cu_4O_8$, and Bi_2O_3, $SrCO_3$,$CaCO_3$ and CuO for $Bi_2Sr_2CaCu_2O_{8+\delta}$ the samples are also synthesised..[30]

Applications of High Temperature Superconductors

Electronics

Microwave

The high temperature superconducting materials are hugely used in microwave. The first requisite to apply HTS in the microwave range is that, the temperatures should be significantly well below T_c. Therefore, the higher the T_c of HTS, the higher the possible operating temperature or the lower the expected losses at a given T (e.g. 77K). The second important requirement of HTS consists with high phase purity and crystalline quality to avoid parasitic microwave losses. A widely used HTS material which is $YBa_2Cu_3O_{7-\delta}$ (YBCO) [32], provide a lower loss than copper or gold at 77 K up to some 100 GHz. Other examples of HTS are Bi-Sr-Ca-Cu-O (BSCCO) and the Tl-Ba-Ca-Cu-O (TBCCO) compounds with the 2223 metal stoichiometry. BSCCO shows extremely high surface resistance values due to phase impurities (concluded from single crystal measurements) [33] and because of high vapour pressure of TI-oxides TBCCO is very difficult to handle and it also suffer from granularity at high field level [34]. Strontium aluminate ($LaSrAlO_4$) [35] is another potentially efficient name to form good HTS films.

$LaSrAl0_4$ has the structure of K_2NiF_4 and is isostructural with $La_{2-x}Ba_xCu0_4$ which is the first discovered high T_c compound. The structure of $LaSrAI0_4$ is related to the perovskite structure with compositions such as $LaAlO_3$ or $SrTiO_3$.

The thermal expansion of single-crystal $LaSrAl0_4$ is lower than that of other perovskite-type materials which are of 10-11 ppm/°C and polycrystalline bulk $YBa_2Cu_30_y$, 11-12 ppm/°C. The expansion coefficient of $LaSrAl0_4$ is 7.38 ppm/°C measured from room temperature to 462°C and 7.45 ppm/°C measured from 300 to 830°C. Due to large mismatch between substrate and film might causes film stress leading to reduced performance and possibly film failure. Nevertheless, the substrate has a smaller lattice constant than the YBCO material. There is no evidence about crystallographic transformation obtained by Debye-Sherrer powder diffraction method. The temperature effect on the lattice dimensions of $LaSrAl0_4$ is compared to other substrate materials and to YBCO in Figure 6.

Measuring the optical properties of $LaSrAI0_4$, we can see that there is no significant fluorescence under ultraviolet exposure in the 0.02-0.3μ*m* range, suggesting a low level of defect states. From figure 7, which compares three perovskite-type substrates and sapphire, we see the $LaSrAl0_4$ is more transparent in the infrared than either perovskite. There are also no impurities, determined by Rutherford backscattering spectroscopy at 2.0 MeV.

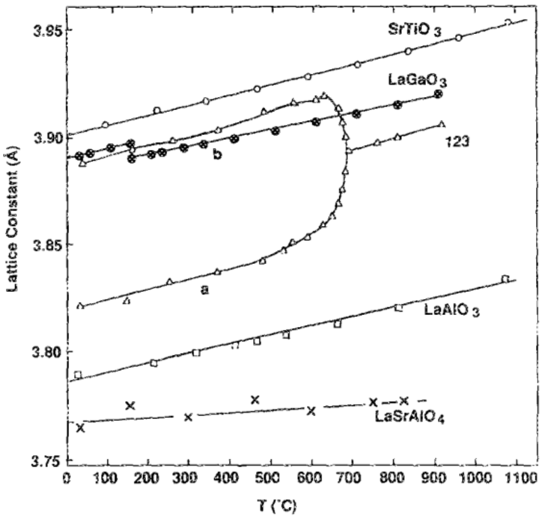

Figure 4: Temperature dependence of lattice constant of perovskite substrate and YBCO superconductor. Figure courtesy of R. Brown, V. Pendrick, D. Kalokitis and B. H. T. Chai.

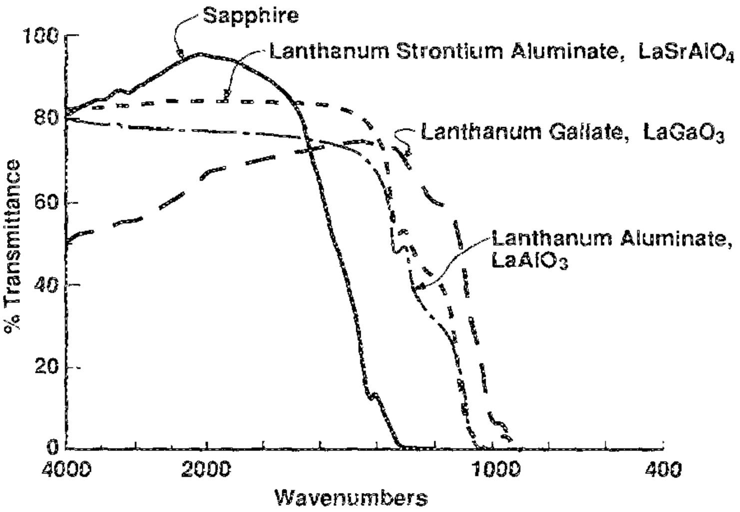

Figure 5: Infrared transmission of single-crystal perovskite substrate materials and sapphire. Figure courtesy of R. Brown, V. Pendrick,, D. Kalokitis and B. H. T. Chai .

The dielectric losses of $LaSrAl_4$ were calculated by comparing *Q* measurements at 5 K of niobium resonators to similar resonators fabricated on substrates of known dielectric loss, such as alumina [36]. Figure 8 shows the measured *Q* values of resonators fabricated on $LaSrAl0_4$, polycrystalline 99,95% $A1_20_3$, $LaAI0_3$, and $LaGa0_3$. From the figure 8 it is clear that the $LaSrAl_4$ has highest resonator *Q* value indicating the substrate has low dielectric loss and good surface properties, both necessary for microwave applications. The dielectric constant of $LaSrIO_4$ [37] is approximately 27 at 8 GHz and 5 K.

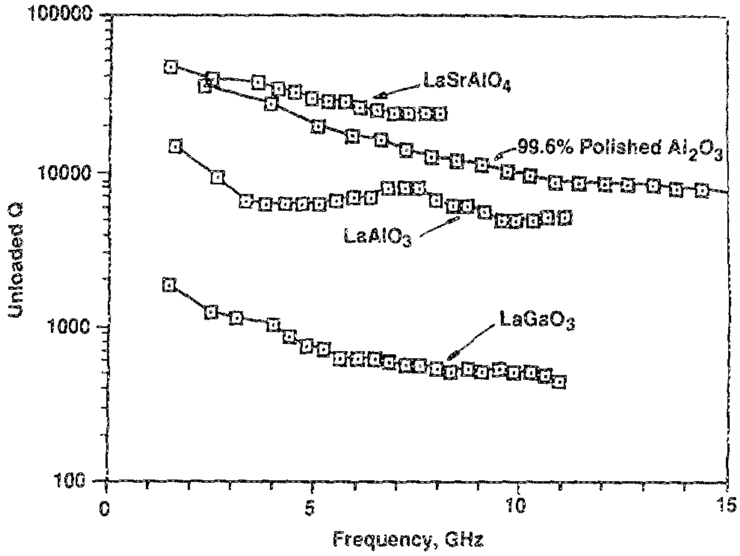

Figure 6. Unloaded Q of patterned niobium resonators at 5 K. Figure courtesy of R. Brown, V. Pendrick, D. Kalokitis and B. H. T. Chai.

The high dielectric constant and low loss, high transmissivity in the infra-red makes $LaSrAl0_4$ a very good superconductor material as compared to other perovskite for microwave applications.

In the US, the military uses HTS filters in aircraft electronics, e.g. for better rejection of interference noise in aircraft radar systems, is still strong. By the use of HTS, there is improvement if noise data compared to conventional solutions which result in a lower percentage of dropped calls. The use of HTS filters can allow to reduce the rf?? power of the handsets in urban areas. Rf coverage can be achieved by a smaller number of base stations in rural areas.[38]

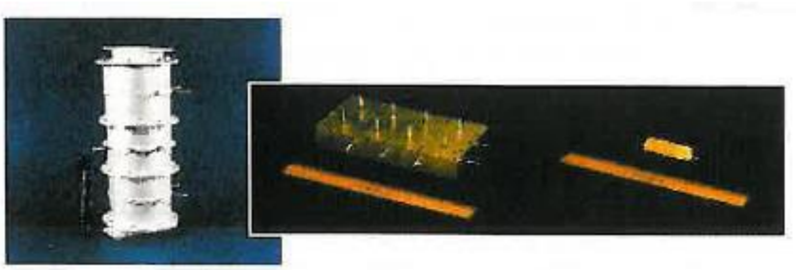

Figure 7: Commercial HTS microwave filters. The filter on the left is of a cavity type, while the others are microstrip filters. Figure courtesy of T.M. Silver, S.X. Dou and J.X. fin, Institute for Superconducting and Electronic Materials, University of Wollongong, Wollongong, NSW2522, Australia.

Sensors

SQUID

We can detect magnetic field by the help of superconducting quantum interference devices (SQUIDs). The high-temperature superconductors (HTS) materials can be used in SQUIDs which have great applications in geophysical prospect. One of the noticeable applications of HTS SQUIDs is the availability of liquid nitrogen cryogen which has 60 times greater latent heat of liquid nitrogen compared to liquid helium. The applications of SQUIDs for geophysics is contributed by the research group from IPHT Jena, and Research Centre Juelich (both German), JOGMEC (Japan), and CSIRO (Australia). The HTS SQUID which is used in TEM sensor has been used in discoveries of nickel-sulphide whose market values are billions of dollars [39]. The observations of magnetic signals in the presence of disturbing background fields without the load of magnetic shielding [40-44] can be done by HTS SQUID. In the field of biomedical [41-44], non-destructive evaluation [45,46] and geophysical applications [47] mobile non-shielded HTS SQUID can be used.

Figure 8: A HTS SQUID device from Tristan Technologies which contains a chip with a superconducting ring. The ring has one or more Josephson junctions. When a current, larger than the critical current of Josephson Junctions is introduced into the SQUID a voltage appears that is proportional to the magnetic flux through the SQUID ring. It can measure magnetic fields dowm to 10^{-14}[48].Figure courtesy of T.M. Silver, S.X. Dou and J.X. fin, Institute for Superconducting and Electronic Materials, University of Wollongong, Wollongong, NSW2522, Australia .

Bolometers

The high temperature superconductor (HTS) can be used to produce bolometers operating in the transition temperature. Thin films of $YBa_2Cu_3O_7$ (YBCO) have been used for the production of bolometer [49]. As LN_2 cooling is common practice for semiconductor IR radiation sensors, HTS bolometers could easily be inserted in such detector systems. A Gd-123 based bolometer can be used for a sensor for IR observation of OH molecules in the atmosphere in a satellite project [50]. Hot-electron bolometers with small thermal relaxation time are used for high-frequency signals in the range of several 100 GHz [51].

Magnets

The high temperature superconductors are currently used for the generation of magnetic fields in particle accelerators, magnetic resonance imaging (MRI), electric motors and generators, superconducting magnetic energy storage (SMES) devices, power transformers transmission cables and fusion devices (for example, the International Thermonuclear Experimental Reactor, ITER) as well as for other scientific and industrial uses . The high temperature superconductors (HTS) provides higher current densities in the presence of magnetic fields that are unachievable with LTS and generates magnetic fields above 15 T [52-55]. The ceramic materials $Bi_2Sr_2Ca_1Cu_2O_x$ (Bi-2212) and (RE)$Ba_2Cu_3O_{7-y}$ (REBCO), where RE stands for rare earth are the most prominent HTS for this applications. By using HTS for the generation of Large Hadron Collider (LHC) at CERN, the High Energy- LHC (HE-LHC) we can achieve a dipole field of 20 T that allows for beam energy of 16.5 TeV [56].

A high-temperature superconductor REBCO ($REBa_2Cu_3O_x$, where RE = Y, Gd) on a 30-micrometre-thick substrate [57],which makes the coil highly compact and capable of operating at the very high winding current density of 1,260 amperes per square millimetre, generates a magnetic field of 14.4 tesla inside a 31.1-tesla resistive background magnet to obtain a d.c. magnetic field of 45.5 tesla, the highest field achieved so far, for the last two decades .The 45.5-tesla test magnet is a witness for the predictions [58] of high-field copper oxide superconductor magnets by achieving a field twice as high as those generated by low-temperature superconducting magnets.

The superconductors of the form RE-Ba-Cu-O (where RE is a rare-earth element) which can be used for magnet applications can trap magnetic fields of several tesla at low temperatures [59,60] and magnitude of the trapped field is proportional to the critical current density and the volume of the superconductor [61,62]. Bulk RE-Ba-Cu-O superconductors have a complex structure, consisting of a $REBa_2Cu_3O_y$ matrix in which there are small particles of RE_2BaCuO_5 distributed. By using this magnet, various potential engineering applications like low friction in high temperature superconductor bearings, construction and performance test of a magnetically levitated transport system in vacuum, high output power reluctance electric motors with bulk high-temperature superconductor elements and in magnetron sputtering film deposition have emerged [63-71]. However, due to poor mechanical stability and low thermal conductivity of the bulk superconductors [72-75], the range of applications is limited. So to improve the mechanical properties, we need to do resin impregnation and wrapping the materials into the carbon fibre and to enhance the thermal stability and internal mechanical strength, we need to do a small hole drilled into the centre of the magnet that allows impregnation of Bi-Pb-Sn-Cd alloy into the superconductor and inclusion of an aluminium wire support. As a result, a magnetic field of strength 17.24 T could be trapped, without fracturing, in a bulk Y-Ba-Cu-O sample of 2.65 cm diameter at 29 K.

Power applications

The vision of electrical power applications had greatly changed from the discovery of HTS in 1986 by Bednorz and Müller [76] because of the significantly increased critical temperature, where the assignment of a more economical cryogen, liquid nitrogen becomes possible. The critical temperature was raised from 92 K in $YBa_2Cu_3O_x$ (YBCO) [77] to over 130 K in $Hg_2Ba_2Ca_2Cu_3O_y$ [78] in between 1987 to 1993. The Bi-2223 ($Bi_2Sr_2Ca_2Cu_3O_z$) and YBCO-123 based coated conductor are referred to as the "2nd generation conductor" due to high current capability. HTS conductors can be used to build electrical devices superconducting magnetic energy storage (SMES), magnetic bearings, fault current limiters and switches [79] with higher efficiency and higher power density. Furthermore, HTS offers environmental advantages such as oil free transformers and devices with low magnetic field leakage. Now we can discuss some power applications of HTS.

Cables

HTS cables have high current carrying capability and lower losses, which could be interesting for retrofit of existing underground cables to increase transmission capacity in a same way. Use of liquid helium cooled LTS cables into power grids in the 70's were technically successful [80] ,but it was economically viable only for power transfer > 5 - 10 GVA. This break-even point may be reduced to ~ 300 - 500 MVA by using LN_2-cooled HTS, if the cables can be retrofitted to already existing cable ducts and because of this , there is an increase of power transfer by a factor ~ 3 at a reduction of the voltage from ~

400 kV to ~ 100 kV [81]. Such a retrofit is especially attractive for metropolitan areas with high power demand.

Transformer

The major applications of HTS transformer lies in the potential for reduction (compared to conventional) in losses (<30%), volume (~50%), weight (~70%) and offers over-loadability without accelerated aging and possible integration of a fault current limitation function [82]. LN_2 is a much more pleasant coolant than oil used today due to risk of fire and environmental aspects. The major advantage of transformers is their potential for an operation at a power level exceeding the rated power by up to 100 % even over a period of several hours [83].

Motor

The potential applications of a HTS motor are similar to that of HTS transformer. A 50 % volume and loss reduction expected for large synchronous motors as compared to a conventional motor [84,85]. This is a very potential feature for the US navy since their new generation of surface ships is based on electric drives due to lower operating and support cost [86].

Fault Current Limiter

The fault current limiter (FCL) which prevents overloads from the grid components and enabled longer lifetimes and avoiding investment cost due to the usually practiced over dimensioning but there is a limitation of FCL which is based on the quench of a superconductor due to a current exceeding its critical current which result in a very rapid tremendous increase of its electrical resistance. The material problem to be solved is the spatial homogeneity of the local critical current density on the length scale of the thermal diffusion length. This homogeneity has been achieved by using Bi-2212 bulk [87], Bi-2223 tapes [88] and YBCO tapes [89] and YBCO thin films [90].

Cryocooler

There is a very few study of the cooling systems for commercial HTS applications. To attain the HTS system stable operation the cooling system is required enough cooling power to cool them below liquid nitrogen temperature. There are some cooling devices which can be used for a HTS application such as cryopumps, cryocoolers for MRI systems, or cryocoolers for laboratory equipment. The development of the refrigeration system which has commercial scale cooling power of 2 kW at 70 K for HTS applications was done [91].

By use of cryocoolers, the temperature can be attained from 100 K to 3 K which covers the temperature range for cooling superconducting applications [92,93]. Some cryogenic refrigerators are Joule-Thomson Gifford-McMahon (G-M), a Stirling, a pulse tube cryocooler, which has cooling power of several W–1 kW, are used in a study of HTS applications.

These different refrigerators have different principles for cooling to the LN_2 or even LHe temperature region. Joule-Thomson (“JT”) coolers has cooling power of 3 W at 77 K, based on the heat exchange during the expansion of a continuous gas flow and used for HTS SQUID cooling [94]. Stirling, Gifford-McMahon (“GM”) and Pulse Tube ("PT") coolers are all based on an oscillating gas flow and a regenerative heat exchange [95, 96].

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