Syarahan Inaugural

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HIGH TEMPERATURE SUPERCONDUCTIVITY: PUZZLES & PROMISES

- 13 March 2004
- Dewan Taklimat Tingkat 1,
  Bangunan Pentadbiran Universiti Putra Malaysia

UNIVERSITI PUTRA MALAYSIA

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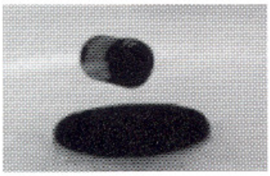
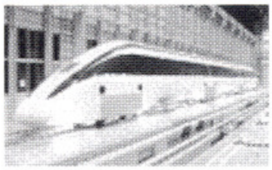




ABSTRACT

The discovery of high temperature superconductivity (HTS) in the non- inter-metallic compounds $La_{2-x}Ba_xCuO_4$ at 35 K (1986) and $YBa_2Cu_3O_7$ at 93 K (1987) has been ranked as one of the most exciting advancement in modern physics, with profound implications for technologies. Superconductivity is perhaps the most remarkable phenomenon that has been bestowed to mankind. Historically, superconductivity appeared only in metals and alloys, termed as low temperature or conventional superconductors, and only near liquid helium temperatures (~4 to 30 K), but within the past 16 years a very large family of superconductors have appeared in rather complex metallic cuprates, most of which are superconducting above liquid nitrogen temperatures (70 to 150 K). This discovery has raised hope that a wide range of applications would soon become a reality.

What makes superconductors so fascinating is their ability to carry electrical current without resistance; to shield out external magnetic fields and to exhibit quantum tunneling effect. The physics of low temperature superconductivity has been successfully explained by BCS theory, where electrons of opposite spins are ordered and form pairs termed as "Cooper pairs" via phonon couplings mechanism. These pairs travel in materials coherently without any resistance. It is believed that electron pairing is also behind the superconductivity of high temperature superconductors; however the prevailing thought has been that this pairing involves different physics, such as fluctuation of the magnetic spins of atomic nuclei, rather than electron-phonon coupling. Hence it remains one of the greatest puzzles in physics today.

Currently, the major superconductors practically used are still the metallic Nb-Ti or Nb_3Sn multifilament wires, which are cooled at liquid helium temperature. The disadvantage in the industrial viewpoint is that the available magnetic field is lower than 20T and the expensive cryogenic system required. The increasing demands in the twenty-first century for energy security and global responses to environmental problems, great hopes are being placed in superconductivity technology, which will bring the benefits in resources conservation and energy savings. HTS will certainly hold great promise for reducing energy consumption in practically any process that uses or transports electricity. Radar components, power transmission lines, communications satellites, and a host of electronic and electrical devices, for example, are good candidates for superconductor applications. A brief recount of the history; a summary of the present status; and a projection into the future of this exciting race for high temperature superconductivity will be highlighted.

INTRODUCTION

Superconductivity is characterized in three major phenomena of zero electrical resistance, perfect diamagnetism and Josephson effect. In 1919, H. K. Onnes, a Dutch physicist discovered the phenomenon of superconductivity when he compressed helium gas to produce liquid helium at 4K, which can cool the material close to 0K. In addition, he observed that the resistivity of Hg disappeared suddenly near 4.2K while Hg was being cooled (Fig.1). The property of which resistivity vanishes was called superconductivity. Another historic discovery related to the phenomenon of superconductivity was discovered by two German physicists, Meissner and Oshsenfelds, in 1933. They found not only the disappearance of resistivity but also the repulsion of magnetic field in the superconductor (Fig.2). This is now called the Meissner effect and has been recognized as one of the most fundamental characteristics of superconductivity. If a magnet is put on the superconductor, the magnetic field from the magnet penetrates into the superconductor. Since the superconductor tends to repel magnetic field, the magnet should levitate on it. This levitation process is quite remarkable. If the temperature increases the sample will lose its supeconductivity and the magnet cannot float on it.

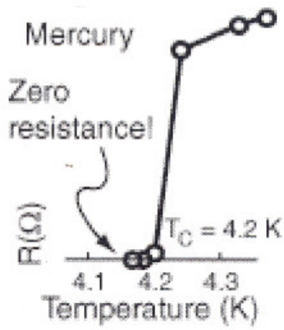


Figure 1. Zero resistance of mercury at 4.2K

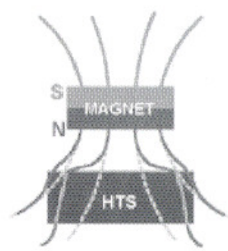


Figure 2. Magnetic Levitation

Since the discovery of 1911, little progress was made in developing a fundamental theory of their behavior until the 1957 publication of the microscopic theory, or BCS theory [Bardeen et al. 1957], by John Bardeen, Leon N. Cooper, and J. Robert Schrieffer, for which they were awarded the Nobel Prize in Physics in 1972. Electrons normally move through the material individually and lose energy by colliding with impurities. However, the BCS theory describes superconductivity in low-temperature metals, such as mercury and lead, based on an attractive interaction between electrons of opposite spins that results from their coupling to phonons (Fig.3).

In quantum mechanics, every Cooper pair can be described as a new particle, a "boson". The theoretical work of Einstein and Bose in the 1920's has shown that at low temperature a system of bosons condenses into a macroscopically coherent state whose quantum mechanical wave function extends over the entire system. In the condensed state, every boson can therefore move without resistance from one end of the system to the other. In 2001, three physicists received the Nobel Prize in physics for their experimental discovery of Bose-Einstein condensation in atomic systems. The bosonic Cooper pairs consisting of two electrons are charged, so that they can carry an electrical current through the entire material without resistance. Since the two electrons forming a Cooper pair are both are negatively charged, they repel each other. An attractive force counteracting this electrical repulsion is thus required for the formation of Cooper pairs.. In conventional superconductors this force is supplied by "phonon", that is, a coordinated motion of the positively charged nuclei in the solid. Phonons reduce or even neutralize the electrical repulsion between the electrons. However, the strength of this type of pairing force is only sufficient for superconductivity at very low temperatures, as observed in conventional superconductors. Most theorists now agree that the mechanism that leads to pairing in conventional superconductors, vibrations of the atomic nuclei cannot be responsible for HTS and hence the "glue" that keeps the pairs together in the HTS, however, is still mysterious.

Due to quantum mechanics, the energy spectrum of this Cooper pair possesses an energy gap, meaning there is a minimum amount of energy DE that must be supplied in order to excite the particle. Therefore, if DE is larger than the thermal energy of the lattice (given by kT, where k is Boltzmann's constant and T is the temperature), the Copper pair will not be scattered by the lattice. The Cooper pair is thus a superfluid, meaning it can flow without energy dissipation. Experiments have in fact demonstrated that currents in superconducting rings persist for years without any measurable degradation. This current is called 'Persistent current'.

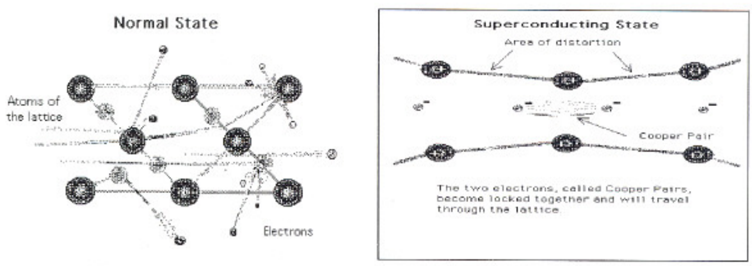


Figure 3. Electron behaviour in Normal and Superconducting state

From the application point of view, the present situation of HTS materials requires the optimization of the superconducting properties,
Today, reproducible preparation techniques for a number of HTS materials species are available which provide a first materials basis for applications.

JOSEPHSON EFFECT

Brian Josephson came up with idea for the Josephson effect while he was still a graduate student at Cambridge. It is one of those rare instances when theory predicted a completely new phenomenon and experiment later confirmed it. Usually experiment comes first and then the theorists figure it out. The Josephson effect is a remarkable consequence of the rigidity in phase of the superconducting wavefunction. If two superconductors are placed next to each other separated by a thin insulating layer called the 'weak link', the phase difference (Fig.4, Eq.1) between the two superconductors will cause a current of superconducting Cooper pairs to flow between the superconductors. This is Josephson tunneling and the tunnel junction is called a Josephson junction or weak link. The effects of pair tunneling include the DC Josephson effect and the AC Josephson effect. In the DC Josephson effect a DC current flows across the junction in the absence of any electric or magnetic field. The current J flowing from side 1 to side 2 across the weak link, is proportional to , or equivalently, to.

$$J = J_C \sin \delta = J_C \sin(\theta_2 - \theta_1) \qquad (1)$$

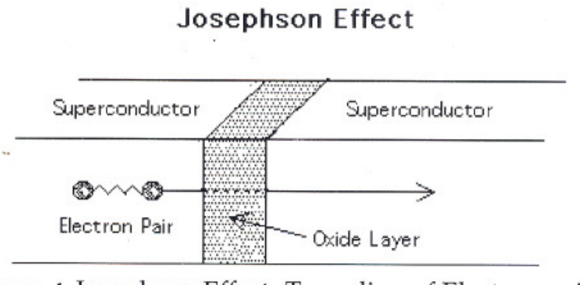


Figure 4. Josephson Effect- Tunneling of Electron pairs

Thus the phase difference between the superconductors leads to current flow. Current flows without batteries or a power supply attached! J_C is the maximum zero voltage current that can be passed by the junction. This phenomenon has been utilised in sensitive device called **S**uperconducting **Qu**antum **I**nterference **D**evices (SQUIDS). Josephson device absolutely required a high-grade thin film technology.

CLASSIFICATION OF SUPERCONDUCTORS

TYPE I SUPERCONDUCTORS

Very pure samples of lead, mercury and tin are examples of Type I superconductors. Figure 5 shows the linear response of induced magnetic field in the superconductor as the applied in increased. This behaviour is termed as perfect diamagnetism. This class of material has very low critical field of about 800 gauss. The earth magnetic field is about 0.5gauss. Today a small neodymium-iron-boron (NdFeB) magnet has field strength of about 16 kilogauss. Hence, a pure Type I superconductor in the presence of NdFeB magnet would easily be quenched to normal state and its practical application is very limited. Type I superconductors are poor carriers of electrical current since current can only flow in the outer surface since the magnetic field can only penetrate the surface layer.

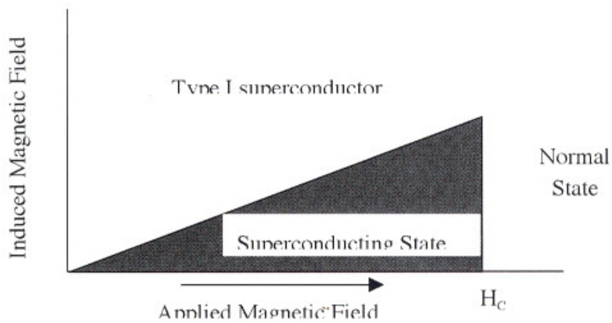


Figure 5. Type I superconductor

TYPE II SUPERCONDUCTORS

Except for the elements vanadium, technetium, carbon and niobium, the Type II category of superconductors is comprised of metallic compounds and alloys (Figure 6). When a type II superconductor is placed in a magnetic field $Hc_1 < H < Hc_2$, where Hc_1 and Hc_2 are the lower and upper critical fields, respectively, the magnetic vortices that penetrate the material should form a uniform triangular lattice (Abrikosov vortex lattice) with a lattice spacing determined by the strength of H. If H is increased, the vortices become more closely spaced and their cores start to overlap. At Hc_2 the vortex lattice and the pairing of the electrons disappear and the material becomes normal. However, within the family of high-temperature superconductors, the vortices have been found to be capable of forming a number of exotic new phases of matter besides the triangular lattice. The weak pinning of the flux lines of high-temperature superconductors gives rise to energy dissipation in these materials at finite currents, which limits the maximum value of the critical current (the current required to destroy superconductivity) and, hence, a variety of applications of the high-temperature superconductors. Knowing how the vortices move and arrange themselves under various temperature and magnetic-field conditions, as well as how these phenomena are influenced by the physical properties of the material, will be critical in controlling the flux motion and maintaining the supercurrent flow in these materials. The first superconducting Type II compound, an alloy of lead and bismuth, was fabricated in 1930 by W. de Haas and J. Voogd. This new category of superconductors was identified by L.V. Shubnikov at the Kharkov Institute of Science and Technology in the Ukraine in 1936 when he found two distinct critical magnetic fields known as Hc_1 and Hc_2.

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 II group. They achieve higher Tc's than Type I 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 Figure 9). 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 one consider that by 1985 known Tc's had only reached 23 K. To date, the highest Tc attained at ambient pressure has been 138 K. One theory predicts an upper limit of about 200 K for the layered cuprates (Vladimir Kresin, Phys. Reports 288, 347 - 1997). Others assert there is no limit. Either way, it is almost certain that other, more-synergistic compounds still await discovery among the high-temperature superconductors. But, was not recognized as such until later, after the Meissner effect had been discovered. 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 (Table 1).

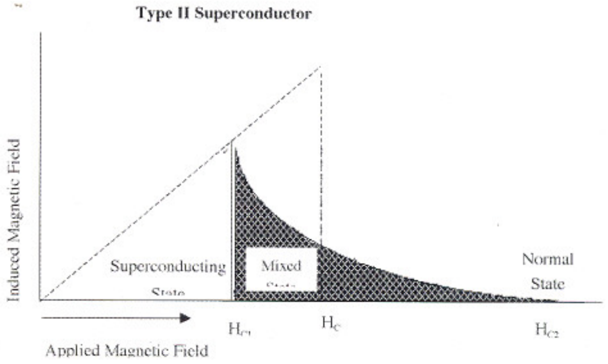


Figure 6. Type II superconductor

Type II 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 II 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 II superconductors are listed below by similarity and with descending Tc's. Where available, the lattice structure of the system is also noted.

Table 1: Type II superconductors

Non Cuprate		
MgB_2	39 K	Highest Tc observed in conventional type –II superconductor. Discovered by Jun Akimitsu in 2001
$Ba_{0.6}K_{0.4}BiO_3$	30 K	(First 4th order phase compound)*
$PuCoGa_5$	18.5 K	(First SC transuranic compound)
A15 Compounds		
Nb_3Ge	23.2 K	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.
Nb_3Si	19 K	
Nb_3Sn	18.1 K	
Nb_3Al	18 K	
V_3Si	17.1 K	
Ta_3Pb	17 K	
V_3Ga	16.8 K	
Nb_3Ga	14.5 K	
V_3In	13.9 K	
$Nb_{0.6}Ti_{0.4}$	9.8 K	(First superconductive wire)
$MgCNi_3$	8 K	(First all-metal perovskite superconductor)
NbN	16.1 K.	(After NbTi, this is the most widely used low-temperature superconductor
$Sr_{.08}WO_3$	2-4 K	(Tungsten-bronze)
$Tl_{.30}WO_3$	2.0-2.14 K	
$Rb_{.27-.29}WO_3$	1.98 K	
These four are the only elemental Type 2 superconductors. C=Fullerene, Nb=BCC, Tc=HEX, V=BCC		
C_{60} , K_xC_{60}	15 K , 19 K	Hebard et al. 1991 as highly-aligned, single-walled nanotubes
Nb	9.25 K	
Tc	7.80 K	
V	5.40 K	
Rare ferromagnetic superconductors.		
$ErNi_2B_2C$	10.5 K	Borocarbide
$YbPd_2Sn$	~2.5 K	Heusler compound
UGe_2 $CeCu_2Si_2$, UBe_{13}, $CeAl_3$	~1K	Heavy fermion
$URhGe_2$	~1K	
$ZrZn_2$	~1K	
$AuIn_3$	50 mK	

SOME BASIC PROPERTIES RELATED TO SUPERCONDUCTIVITY

Penetration depth, l

- The magnetic fields penetrate the superconducting surface to a small extent, about 100 nm.
- Within this layer the magnetic field decreases exponentially from its external value to zero. $B(x) = B_o e^{-x/\lambda}$ and $\lambda = (m/\mu_o ne^2)^{1/2}$, n is the superconducting electrons.
- Typical value of λ is ~ 10 to 100 nm.
- Penetration depth varies with temperature according to the empirical formula;
  $\lambda(T) = \lambda_o [1 - (T/T_c)^2]$, λ_o = penetration at 0 K.
- λ becomes infinite as T approaches. Hence the magnetic field penetrates more deeply into the sample

Magnetization, M

- In the superconducting state, its magnetization opposes the external magnetic field. $M = \chi H$, where $\chi = -1$; χ = magnetic susceptibility.
- Type I superconductor is a perfect diamagnetic substance.
- Penomenological equations for Type I (Fritz and London) based on equilibrium thermodynamics,
  $E_s + (B_c^2 / 2\mu_o) = E_n$,
  E_s = energy per unit volume of the superconducting state
  E_n = energy per unit volume of the normal state
  B_c = critical field
- For $E_s < E_n$ the material becomes superconducting.
- London theory also gives temperature dependence of E_s and $B_c(T)$ and understood as;
  - At some $T < T_c$ magnetic field appear.
  - Superconductor will act to exclude the field.
  - The energy decrease of the magnetic field appears as increased enegy of the electrons that make up the superconducting current.
  - As H increases, the energy acquired by the superconductor also increases.
  - At H_c the energy of the superconducting state becomes higher than the energy of the normal state and so the material becomes normal.

Flux Magnetization

- Superconductivity is fundamentally a quantum phenomenon.
- Consider the superconducting ring with trapped flux. Fritz London suggested that the trapped magnetic flux should be quantized in units of h/e.
- In hollow cylinders, the flux quantum is $F_o = h/2e = 2.0679 \times 10^{-15}$ Tm^2. This is the magnetic flux quantum.

Coherence length, ξ

- It is the smallest dimension over which superconductivity can be established or destroyed.
- It is the characteristic length scale over which Cooper pairs are correlated.
- Typical values are 10's of nm.
- A superconductor is type I if $\xi < \lambda$.
- An increase of λ/ξ favours type II.
- Both ξ and λ depend on the mean free path of electrons in the normal state.
- Adding impurities to a metal can reduce the mean free path which causes the penetration depth and the coherence length to decrease.
- If the superconductor is not pure, the coherence length is degraded by the scattering of electrons from impurities.

Persistent Currents, I_p

- Because the dc resistance of a superconductor is zero below T_c once a current is set up in the material, it persists without any applied voltage.
- These persistent currents have been observed to last for years with no measurable losses. Experimental evidence shows the decay time exceeds 10^5 years.

Energy gap, E_g

- The stability of the superconducting state is critically dependent on strong correlation between Cooper pairs.
- E_g equals the binding energy of the Cooper pair.
- BCS theory predicts $E_g = 3.53k_BT_c$.
- Thus, superconductors with large E_g have high T_c.

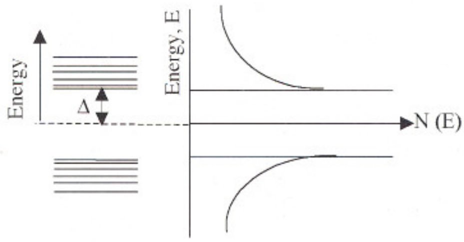


Figure 7. Energy gap

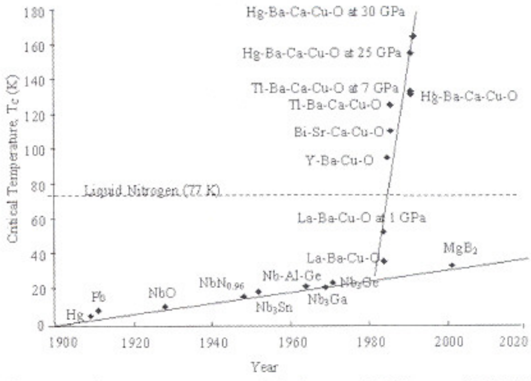


Figure 8. Evolution of critical temperature, T_C from 1911 until 2004.

HIGH TEMPERATURE SUPERCONDUCTORS

What is a high temperature superconductor? In April 1986, two researchers at IBM in Switzerland, K. Alex Muller and George Bednorz, detected superconductivity in $(La\text{-}Ba)_2CuO_4$ with a Tc up to 35 K, in contrast to the previous record of 23 K for which they were subsequently awarded the Nobel Prize. By the end of 1986, superconductivity research achieved revolutionary advances with the effort of Paul C. W. Chu and colleagues at the University of Houston. Signs of superconductivity above 77 K were repeatedly observed in poorly-characterized samples during the period, strongly affirming the belief in the existence of superconductivity in the liquid nitrogen temperature range. The scientific world knew that the textbooks had to be rewritten after January 1987, when the Houston group in collaboration with M. K. Wu, Chu's former student, achieved stable and reproducible superconductivity above 90 K in $Y_1Ba_2Cu_3O_{7-d}$ (Y123), with Tc close to 100 K. Since then HTS based on cuprate family with different compositions were discovered (Figure 8).

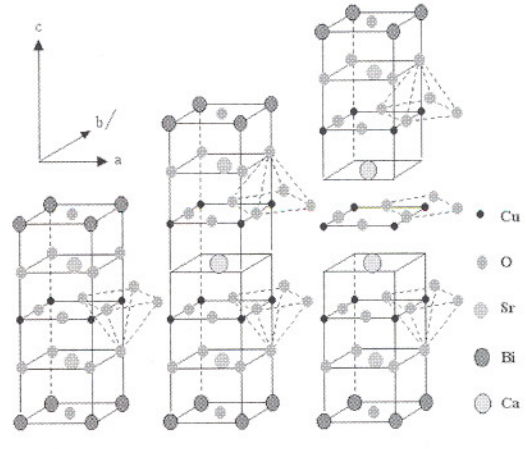


Figure 9. Crystallographic structure of $Bi_2Sr_2Ca_nCu_{n+1}O_{2n+6+d}$ system with n = 0, 1, and 2. (Debsikdar, 1989; Bourdillon *et al.*, 1993).

ATOMIC STRUCTURE AND CLASSIFICATION

The structural element of HTS compounds are stacks of a certain number n = 1,2,3É of CuO_2 layers which are glued on top of each other by means of intermediate Ca layers, see Fig. 9. Counterpart of these 'active block' of $(CuO_2/Ca)_{n-1}CuO_2$ are'charge reservoir blocks' $EO/(AO_x)_m/EO$ with m = 1,2 monolayers of a quite arbitrary oxide AO_x (A =Bi, Pb, Tl, Hg, Au, Ca, B, Cu, Al, Ga) wrapped on each side by a monolayer of alkaline earth oxide EO with E = Ba, Sr. The HTS structure results from alternating staking of these two block units. The choice of BaO and SrO as 'wrapping' layer is not arbitrary but depends on the involved AO_x since it has to provode a good spatial adjustment of CuO_2 to the AO_x layers. The general chemical formula $A_mE_2Ca_{n-1}Cu_nO_{2n+m+2+y}$ is conveniently abbreviated as A-m2(n-1)n- (e.g $Bi_2Sr_2Ca_2Cu_3O_{10}$: Bi-2223).

At this point in time, there is only one class of materials that exhibit high temperature superconductivity. That is the class of rare earth copper oxides with various kinds of dopants. Table 2 lists some of the cuprate perovskite that exhibit superconductivity. These are all layered materials consisting of CuO_2 planes, with the Cu atoms forming a square lattice and O atoms between each nearest-neighbor pair of Cu atoms. The rest of the atoms, rare earth atoms, dopants and excess copper and oxygen, lie in charge reservoir layers separating the square planar CuO_2 layers. These charge reservoir layers control the oxidation state of the planar coppers, which is either Cu^{2+} or Cu^{3+}. The Cu^{2+} state has a single unpaired 3d electron while, in the Cu^{3+} state, all the 3d valence electrons are paired. The copper oxide superconductors are highly anisotropic materials containing two-dimensional copper oxide planes as a key structural element. Fig.9 shows the crystallographic structure of $Bi_2Sr_2Ca_nCu_{n+1}O_{2n+6+d}$ system with n = 0, 1, and 2. (Debsikdar, 1989; Bourdillon *et al.*, 1993). The other components of these materials determine the overall structural anisotropy, chemical complexity, and ultimately the superconducting transition temperatures Tc of these materials. For example, the $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$ (BSCCO) family of materials (n = 1-3) have a high degree of structural anisotropy due to weakly interacting Bi-O double layers. In fact, crystals of $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$ can be easily cleaved between the Bi-O double layers like the quasi-two-dimensional materials mica and graphite.

Table 2 Various Types of Cuprate Perovskites

CUPRATE PEROVSKITES		
(Mercury –based)	**Lattice: TETRAGONAL**	
$Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}$	138 K	**Record-holder to date**
$HgBa_2Ca_2Cu_3O_8$	133-135 K	Schilling et al. 1993
$HgBa_2Ca_3Cu_4O_{10+}$	125-126 K	
$HgBa_2Ca_{1-x}Sr_xCu_2O_{6+}$	123-125 K	
$HgBa_2CuO_{4+}$	94-98 K	Putilin et al. 1993
(Thallium –based)	**Lattice: TETRAGONAL**	
$Tl_2Ba_2Ca_2Cu_3O_{10}$	127-128 K**	
$Tl_{1.6}Hg_{0.4}Ba_2Ca_2Cu_3O_{10+}$	126 K	
$TlBa_2Ca_2Cu_3O_{9+}$	123 K	Sheng, Z.Z. & Hermann 1988(First to report)
$Tl_2Ba_2CaCu_2O_6$	118-120 K	
$TlBa_2Ca_3Cu_4O_{11}$	118 K	
$Tl_{0.5}Pb_{0.5}Sr_2Ca_2Cu_3O_9$	112 K	
$TlBa_2CaCu_2O_{7+}$	103 K	
$Tl_2Ba_2CuO_6$	95 K	
(Bismuth –based)	**Lattice: ORTHORHOMBIC**	
$Bi_{1.6}Pb_{0.6}Sr_2Ca_2Sb_{0.1}Cu_3O_y$	115K	(thick film on MgO substrate)
$Bi_2Sr_2Ca_2Cu_3O_{10}$***	110 K	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.
$Bi_2Sr_2CaCu_2O_9$***	110 K	Maeda et al. 1988(First to report)
$Bi_2Sr_2Ca_{0.8}Y_{0.2}Cu_2O_8$	95-96K	
$Bi_2Sr_2CaCu_2O_8$	91-92K	
$Ca_{1-x}Sr_xCuO_2$	110K	(Highest Tc ternary/quaternary compound)
YBCO lattice: TETRAGONAL		
$In_{0.5}Sb_{0.5}Sr_2ScCu_2O_7$	101-103K	
$TmBa_2Cu_3O_7$	90-101 K	
$GdBa_2Cu_3O_7$	94 K	
$YBa_2Cu_3O_7$	93 K	Comment: "1-2-3" superconductors actually have the 1-2-1-2 structure. Thus, the formula for YBCO could be written CuBa2YCu2O7. [Wu et al. 1987] (First to report)

$Y_2Ba_4Cu_7O_{15}$	93 K	
$Yb_{0.9}Ca_{0.1}Ba_{1.8}Sr_{0.2}Cu_4O_8$	86 K	
$YbBa_{1.6}Sr_{0.4}Cu_4O_8$	78 K	
(Rare-Earth –based))	**Lattice: TETRAGONAL**	
$La_2Ba_2CaCu_5O_{9+}$	79 K	(Saurashtra Univ., Rajkot, India - 2002)
$(Sr,Ca)_5Cu_4O_{10}$	70 K	
$Pb_2Sr_2YCu_3O_8$	70 K	
$GaSr_2(Y, Ca)Cu_2O_7$	70 K	
$(La,Sr,Ca)_3Cu_2O_6$	58 K	
$La_2CaCu_2O_{6+}$	45 K	
$(Eu,Ce)_2(Ba,Eu)_2Cu_3O_{10+}$	43 K	
$La_{1.8}5Sr_{0.15}CuO_4$	40 K	
SrNdCuO	40 K	First ceramic superconductor discovered without a non-superconducting oxide layer.
$(La,Ba)_2CuO_4$	35-38 K	
$(Nd,Sr,Ce)_2CuO_4$	35 K	
$Pb2(Sr,La)_2Cu_2O_6$	32 K	
$La_{1.85}Ba_{.15}CuO_4$	30K	**First HTS ceramic SC discovered** [Bednorz & Muller 1986]
Rare ferromagnetic superconductors		
$RuSr_2(Gd,Eu,Sm)Cu_2O_8$	~58 K	Ruthenium-oxocuprate

Comment: All of the above are cuprate perovskites, even though their metal-to-oxygen ratios are not exactly 2-to-3. The best performers are those compounds that contain one or more of the electron-emitters BaO, SrO or CaO, along with a Period 6 heavy metal like Mercury, Thallium or Bismuth.

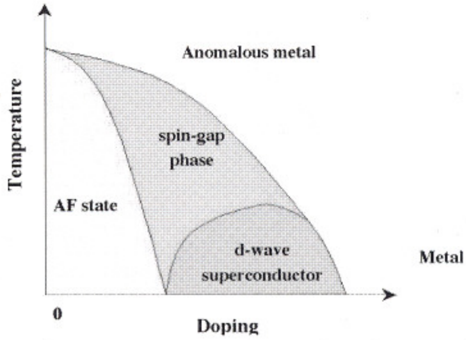


Figure 10. Phase diagram of CuO_2 superconductor (Batlogg and Varma 2000) Spin-gap phase is important in understanding HTS

High temperature superconductivity occurs when the "undoped parent compound", which is an insulating antiferromagnetic material, is "doped with holes" (Figure 10). In the undoped parent compound, all of the planar coppers are in the Cu^{2+} state, with one unpaired spin per site. These unpaired spins then order antiferromagnetically, so that neighboring spins are antiparallel. The insulating character of this state is thought to result, not from the antiferromagnetism directly, but from the strong on-site Coulomb repulsion, which is the energy cost of putting an extra electron on a Cu atom to make Cu^{1+}. This Coulomb energy for double occupancy suppresses conduction, in systems with an average density of one electron per site, by creating a kind of collective Coulomb blockade. The result is called a "Mott insulator." Removing electrons or equivalently adding holes to these materials both destabilizes the antiferromagnetic spin order and relieves the electronic congestion, turning them from insulators to conductor.

There are two basic types of high-temperature superconductors that have been studied since the mid-1980s-the "electron doped" type that contains added electrons in its lattice-work, and the "hole-doped" type that has open slots for electrons. The holes in HTS form pairs below Tc with a total spin S=0, and the pairing state has an angular momentum L=2, i.e. d-pairing. Magnetic pairing mechanism has long been predicted to give rise ta a d-pairing, although causes of non-magnetic origin have also been proposed. Table 3 high lights the similarities and differences of HTS and conventional superconductors.

Table 3. Properties of Conventional and High Temperature Superconductors

Properties	High Temperature Superconductor	Conventional Superconductor
$\rho = 0$ (when $H<H_{c1}$)	yes	yes
Meissner state (when $H < H_{c1}$)	yes	yes
Charge carrier	Cooper pairs	Cooper pairs
Ginzburg-Landau theory	applicable	applicable
T_c	< 164 K	< 25 K
coherence length	~10^{-7} cm	10^{-5}cm
carrier concentration	~10^{21}cm^{-3}	~10^{23}cm^{-3}
Penetration depth	long	short
Type	II	I & II
Energy gap	Exist	Exist
Material	Cu-O based	Metals/alloys
structure	~2D	3D
anisotropy	large	small
Magnetic properties	complex	Less complex
BCS	?	applicable

CURRENT STATUS OF HIGH TEMPERATURE SUPERCONDUCTORS

Some highlights of the current status of HTS research are given below under various categories and types of cuprates.

BULK MATERIALS

Bulk materials for all the systems belonging to yttrium, bismuth, thallium, and mercury based cuprate oxide have been studied quite extensively over the last 17 years since the great discovery of HTS by Bednordz and Muller. Various techniques have been adopted. These include the solid state oxide, coprecipitation, sol-gel, melt-textured, crystal growing and mechanical alloying. Melt-textured YBCO pellets with good superconducting properties (J_c (77 K, I T) > 10 kA/cm^2, J_c (50 K, 10 T) > 100 kA/cm^2) can be grown reproducibly in sizes up to a diameter d = 6 cm even in complex shapes comparable to what has been achieved in NdFeB permanent magnets. The present production cost of > 1000 EUR / kg (including quality control) is still a factor of ~ 10 higher than for NdFeB but it can be expected to come closer this cost level once a production of several tons per year can be established here as well. Sizes up to d = 10 cm have been realized but joining of smaller size pellets with good superconducting properties of the connections seems to be a more practical solution. For larger pellets full oxidation becomes increasingly difficult even though it is not based on oxygen bulk diffusion but on oxygen transport along micro cracks [Yamada et al. 2002]. Numerous procedures have been reported in obtaining bulk samples with high purity and hence a good superconducting properties. Saleh et al. (1999) and Hamadneh et al. (2002)(Figure 11) have prepared high quality Bi-2223 via sol-gel and coprecipitation techniques respectively. The quality of the samples was well-observed using ac susceptibility measurements where the response of χ' showed an almost perfect diamagnetic behaviour [Halim et al. 2000]. Abd-Shukor, R. (1993) has reported the optimization procedure for the preparation of Bulk $Tl_2Ba_2CaCu_2O_{8-d}$ (2212).

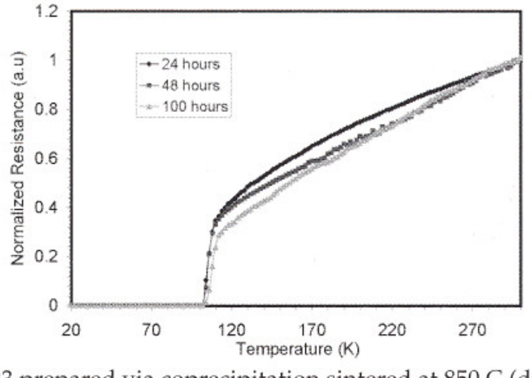


Figure 11. Pure Bi-2223 prepared via coprecipitation sintered at 850 C (different sintering time) (Hamadneh et al, 2002)

THIN FILMS FOR HTS ELECTRONICS

Several deposition techniques have been developed for the fabrication of HTS films. For each HTS compound, the deposition route gas to be optimized individually for satisfying the pre-requisites for commercial use of film-based applications. So, far all known deposition techniques allow to reach j_c values above $5x10^5 A/cm^2$ at 77 K, 0T, for thickness below 1mm. Laser ablation and pulsed laser deposition are widely used. This method can also be used to prepare long tapes. Ion beam Sputtering and Thermal Co evaporation (also on Inclined Substrate) are particularly suited and cheap for uniform films over large area. YBCO films on substrate as large as 20x20 cm^2 have been reported with $j_c \sim 2x10^6 A/cm^2$ at 77 K, 0T. Magnetron sputtering, MOCVD and Molecular Beam Epitaxy have been shown to produce high quality films suitable for multilayers and hybride structures devices. Very recently, high j_c values were also obtained for Spray Pyrolysis, a relatively simple technique with high technical promise.

WIRE AND TAPE CONDUCTORS

The key to making HTS wire and tape, that are commercially viable, is to optimize critical current, operating temperature and field. Fig. 12 shows the critical surface phase diagram for superconductors. Critical current is the amount of current a given wire/tape can carry without losing superconductivity. It is measured as critical current (Ic) or critical current density (Jc). Goal for critical current are 100-1000 while goals for critical current density are $10^4 – 10^6$ Acm^{-2}.

HTS wires/tapes must also be able to carry current at relatively high temperature to decrease the difficulties associated cooling. The anticipated range for HTS operating temperature is 4.2 K(-269° C) to 77.3(-196.2° C) K. Superconducting devices also require tolerance to surrounding magnetic fields and be able to operate in the field of 2-5 Tesla.

Improvements to critical current, operating temperature and magnetic field tolerance will result in cost-effective HTS wire, the goal being $0.01/ampere-meter.

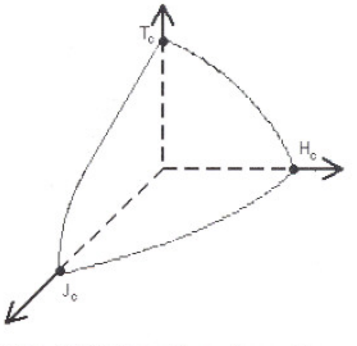


Figure 12. Critical surface phase diagram

The two leading technologies for practical and robust HTS wire/tape are multi-filamentary wires/tapes and coated conductors. Both are composite of HTS and metal. [Malozemoff et al 2003]. Multi-filamentary HTS tapes composites (MFC) fabricated by oxide-powder-in tube deformation process are typically composites of silver or silver alloy and one of the HTS are either Bi-2212 or Bi-2223. Bi-HTS/Ag tapes were the first practical HTS conductors [Heine et al. 1989] and have already reached a commercial stage: Tapes with cross sectional areas of ~1 mm^2 are available that can transport critical currents I_c (77 K,0 T) up to 130 A [Masur et al. 2001] over km lengths. In the "Powder-in-Tube" (PIT) fabrication, Ag tubes are filled with Bi-HTS precursor powder and are subject to various thermo-mechanical processing steps where the tubes are flattened out to tapes that include Bi-HTS material as thin filaments.

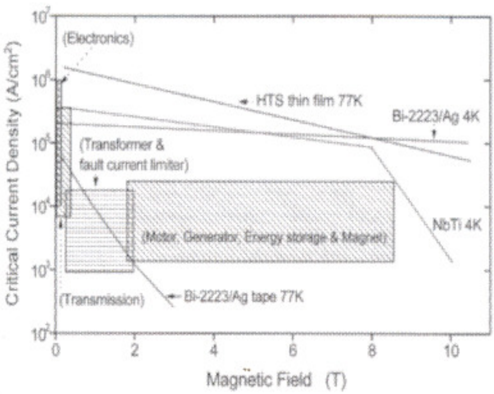


Figure 13. Performance of HTS for different applications

The fragility of the Bi-22(n-1) n grains along neighbouring Bi-oxide planes is the physical starting-point for the successful mechanical alignment of the Bi-HTS grains by means of rolling or pressing which orients the grains preferably with the ab-planes parallel to the tape surface. Silver is the only matrix material that is chemically not reacting with HTS compounds and allows for sufficient oxygen diffusion. The common melting of Ag and Bi-HTS around ~ 850°C gives rise to a close mechanical and electrical contact that helps to bridge non-superconducting regions by means of low-resistivity shorts. However, the cost and the softness of Ag are critical issues for technical applications. MFC wire is expected to reach a price/performance of $50/kAm (at 77 K, self field)

Between the two "practical" Bi-HTS systems Bi-2212 and Bi-2223, Bi-2212 has the advantage of a much better control of the chemical phase development [Funahashi et al. 1997]: Bi-2212 forms from a single-phase precursor whereas Bi-2223 requires a multi-phase starting mixture. Today, a quite homogeneous superconductive connection of the HTS grains can be achieved in B-2212 filaments with *engineering critical current densities* (calculated with respect to the total conductor cross section J_{eng} (4.2 K, 0 T) > 70 kA/cm^2 over several 100 m conductor length. By clever arrangement of Bi-2212 tapes, J_{eng} (4.2 K, 24 T) . 20 kA/cm^2 has been achieved in a practical wire conductor independent of the direction of the applied magnetic field. By new processing techniques Bi-2212 tapes have been fabricated with *superconducting critical current densities* J_c (4.2 K, 10 T) . 500 kA/cm^2 (calculated with respect to the HTS Part of the conductor cross section) already close to the limit of epitaxial thin films [Kitaguchi et al.1999]. This demonstrates good perspectives for Bi-2212 conductor with respect to applications in high magnetic fields at low temperature (Figure 13).

Bi-2223/Ag tapes were for a long time in the center of interest of HTS conductor development since their $T_c > 100$ K allows operation at LN_2 temperature [Fujikami et al. 2002]. However, since the phase evolution of Bi-2223 is much more complicated compared to Bi-2212, the pronounced percolative superconductive current flow in the B-2223 filaments could not yet be overcome. Moreover, the upper field limit of ~ I T at 77 K restricts the LN_2 operation of Bi-2223 tapes to low-field applications such as cables [Li et al. 1997] or transformers. For operation at technically interesting magnetic field levels of several Tesla, Bi-2223 windings have to be cooled to $T_{op} < 30$K. However, in this temperature region Bi-2212 conductors may be competitive due to simper processing and thus lower fabrication cost [Kitaguchi et al.1999]. Ag/Bi(2223) square and round shape wires show its J_c value of 11kAcm^{-2} at 77 K and 0 field [Su et al. 2002]. Monofilament Ag/Bi-2223, with powders prepared via coprecipitation, show J_c of 13.4 kAcm^{-2} at 77 K and 0 field[Ismail et al. 2004].

Coated conductors composites (CCC) consist of a nickel-based alloy substrate and one or more micron-thick layers of the HTS materials, RBCO, where R is yttrium or other rare earth element. However, the transfer of YBCO thin film techniques to such a conductor fabrication has taken a lot of efforts since biaxial texture without any interruption is required over the whole conductor length. Usually a metal passivation and stabilization layer is deposited on top. The combination of the metal substrate and the thin RBCO layer allows critical strains in the range as the MFC-BSCCO tapes. Meanwhile, J_c (77 K, 0 T) ~ 2.4 MA/cm^2 is achieved over a length of ~ 10 meters which allows first practical demonstrations. This status of conductor length development is comparable to the situation of Bi-HTS conductors 10 years ago. Cost arguments have always been in favour of HTS coating of simple robust metal carrier tapes.

TI-1223 [Bhattacharya et al. 2002] and Hg-1212 [Wu et al. 2002] are under investigation with respect to HTS coatings with $T_c > 100$ K. However, the difficulties of the required thin film techniques suggest that these HTS are at present no practical alternatives to YBCO. Earlier efforts with respect to a fabrication of T1-1223 conductors by means of processing techniques developed for Bi-HTS conductors have also not been successful. Currently, the performance of the best MFC and CCC tapes would be about comparable. Some of the confusion about this has come from the fact that the local 77K critical density Jc of CCC-RBCO is much higher, typically >1 MA/cm^2 in CCC, as compared to 50 kA/cm^2 in MFC. Since the superconducting fill factor (f) of MFC is much higher than for CCC, the two effects compensate in determining the overall or engineering density $J_e = fJ_c$.

$Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$ (Bi-2212; n =2) materials

The representative n = 2 compound, Bi-2212, consists of two-dimensional repeat units containing 2-BiO, 2-SrO, Ca and 2-CuO_2 layers. Bi-2212 tape conductors with a HTS fill factor of up to 60% can be produced by simple surface coating of Ag bands. By improved processing ("Pre-Annealing and Intermediate Rolling", "PAIR") tapes with J_c (4.2 K, 10 T) > 500 kA/cm^2 have been fabricated. Trade-off between J_c and the thickness of the Bi-2212 layers limits the expectations for J_{eng} (4.2 K, 20T) of optimized long tapes to 50 – 60 kA/cm^2 [Aoki et al. 2000].

As practical demonstration, such tape conductor was assembled in a cable similar to a "Rutherford cable", the standard conductor for accelerator magnets: It consisted of 427 Bi-2212 filaments in a AgMgSb alloy outer sheath to allow for higher stress tolerance compared to pure Ag. This wiere exhibited excellent I_c (4.2 K, self-field) = 285 A and J_c (4.2 K, self-field) – 340 kA/cm^2 and a room temperature tensile strength of 180 MPa. For a full cable I_c (4.2 K, self-field)= 3500 A was obtained in a short sample, I_c (4.2 K, self-field) > 2700 A in 17-m-long sections cut from a continuous 80-m-long cable. Beside a possible application for next generation accelerator magnets, the cable is also investigated with respect to its use in Superconducting Magnetic Energy Storage devices ("SMES").

By clever arrangement of differently oriented Bi-2212 tapes, a wire conductor with high J_{eng} (4.2 K, 24 T) > 20 kA/cm^2 independent of the direction of the applied magnetic field has been constructed which is suitable for the fabrication of conventional solenoid magnets ("Rotation-Symmetric Arranged Tape-in tubë wire", "ROSATwire") [Sato et al. 2001]. The Bi-HTS fill factor could be increased to ~ 40% .

This development aims at insertion magnets for 30 T class magnets where the Bi-HTS coils have to generate an additional field of several Tesla in a background field of ~ 20 T [Wakuda et al. 2001]. The most ambitious goal is the use of such magnet systems for high-field NMR; the extreme requirements of temporal stability can probably only be fulfilled in a superconducting magnet system operated in persistent mode which relies on an extremely slow decay of the super currents [Hase et al. 2000]. However, the demonstrated decay times are still not yet sufficient to achieve this goal.

$Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$ (Bi-2223; n =3) materials

Bi-2223 Powder-in-Tube (PIT) tapes have seen for more than ten years a continuous performance increase. The critical current densities in the HTS filaments were raised up to J_c (77 K, 0 T) ~ 70 kA/cm^2 in short samples. Better understanding of the mechanical deformation process and of the Bi-2223 phase development during thermal annealing helped to establish a production of several 10 km of such tape conductors with J_{eng} (77 K, 0 T) ~ 15 kA/cm^2 at a total conductor cross section of ~ 1 mm^2 . Locally, Jc (77 K, 0 T) up to 180 kA/cm^2 has been observed, but this seems to be the upper limit for Bi-2223/Ag tapes.

Multi-core tape composites with various filaments have been made by a tape-in-tube (TIT) process and J_c (77 K, 0 T) ~ 16 kA/cm^2 was measured [Kovac et al. 2001] The reason are non-superconducting inclusions and pores in the HTS filaments leading to a percolative supercurrent flow along the Bi-2223 grains which are well connected but make up at most only ~ 2/3 of the filament cross-section [Dhalle et al. 1997]. With an HTS fill factor of high-Jc Bi-2223 conductors of at most 35% an intrinsic limit J_{eng} (77 K, 0 T) ~ 60 k!/cm^2 has to be expected which is still comparable to the limit of ~ 100 kA/cm^{2}estimated for YBCO coated conductors (assuming a future development of J_c (77 K, 0T) ~ 1 MA/cm^2 in 5 m thich YBCO coatings on 50 m thick metal carrier tapes).

However, for applications in higher magnetic field a substantially lower operating temperature is required with the additional benefit of a J_c increase of up to a factor of 7 compared to 77 K (J_c(T, 0 T) Å J_c (77 K, 0 T) [7 – T/13 K] [Kaneko et al.1999]. Another economical disadvantage with respect to YBCO coated conductors is the mandatory use of silver as matrix material. Previous cost estimations of 10 $/kA m for full-scale production levels (at present: 200 – 300 S/kA m) have turned out to be too optimistic and are meanwhile adjusted to 25 – 50 $/kA m in 2006. Moreover, while the good electrical contact of the HTS filaments with the Ag matrix is helpful in bridging disconnected HTS regions by means of low resistance shorts [Peterson et al. 1997], frequent use of this current rerouting prevents persistent-mode operation of Bi-2223 coils.

Bi-2223 conductors have overcome many problems on the way to a technical HTS material. The problem of the softness of the Ag matrix has been solved by applying dispersed MgO in the Ag matrix or by adding a thin layer of stainless steel reinforcement to both sides of the tapes which enables the tapes to withstand a tensile stress of 300 MPa and a tensile strain of 0.45%ta 77 K [Masur et al. 2001]. Promising approaches have been developed to tackle the problem of ac losses which arise from electromagnetic coupling of the HTS filaments and are of concern for all power applications since they determine the necessary cooling power [Yamashita et al. 2001]: Insulating BaZrO3 or SrCO3 barriers around the HTS filaments and higher resistive Ag alloys such as AgAu or AgPd as matrix material as well as twisting of the filaments reduces these coupling currents. A novel wire arrangement of horizontal and vertical stacks of Bi-2223 tapes reduces the I_c-anisotropy with respect to the orientation of an external magnetic field [Graso et al. 1997].

In conclusion, Bi-2223 conductors have arrived at a practical level of technical applicability, however, still at a quite high cost level. At present, the biggest psychological handicap for Bi-HTS conductors is the great expectations for a soon arrival of a cheaper and better YBCO coated conductor.

YBCO

YBCO-coated metal tapes are promising with respect to lower-cost HTS conductor operating even at LN_2 temperature in magnetic fields up to several Tesla. J_c (77 K, 0 T) = 1 – 2 MA/cm^2 has been achieved in short samples by a number of YBCO coating methods choosing different routes to biaxial YBCO texture. One route is the deposition of a textured buffer layer on (untextured) metal with the assistance of an *ion beam* that *introduces orientation-selective growth*. With stainless steel as attractive choice for the metal, 10 m long high-J_c tapes have been demonstrated. Another route is the use of *cube-textured metal bands*. Buffer layers (CeO_2, Y-stabilized ZrO_2 (YSZ), $Gd_2Zr_2O_7$ (GZO), In-Sn oxide (ITO) have to be applied here as well in order to compensate the lattice mismatch and to prevent poisoning of superconductivity in the YBCO coating by in-diffusion of metal atoms. Ni and Ni alloys are used here as metal substrates that show the required cube-texture after appropriate metallurgical and heat treatment.

Most of the tested buffer materials are insulators with the consequence that a disruption of the superconducting current path cannot be bridged by a low-resistance short via the metal tape as in the case of Bi-HTS/Ag tapes. Practical solutions of this problem are the deposition of a Au layer on top of the YBCO coating or use of metallic oxide buffer layers.

J_c(77 K, 0 T) ~ 1 MA/cm^2 is obtained in YBCO coatings with a thickness of up to ~ 3 m. [Usoskin et al 2001]. For ~ 100 m thick metal carrier tapes this results in a HTS fill factor of only ~ 3%. The engineering current density J_{eng} calculated with respect to the total conductor cross-section of J_{eng} (77 K, 0 T) ~ 30 kA/cm^2 is therefore still close to what is achieved in present commercial Bi-2223/Ag tapes. 50 m thick metal carrier tapes are available. Ca doping and optimization of the grain architecture may help to transfer the high intra-grain J_c (77 K, 0 T) ~ 5 MA/cm^2 into macroscopic current densities even for the case of a grain alignment of only 10°.

By *Ion Beam Assisted Deposition* {"IBAD"} [Jia et al. 2002] tapes with J_c (77K, 0 T) = 2.2 MA/cm^2 (I_c (77K, 0 T) = 78 A) measured over a length of 10 m and J_c (77 K, 0 T) = 0.5 MA/cm^2 over a length of 46 m have been fabricated. The deposition of the required ~ 1m thick YSZ buffer under assistance of an additional ion beam selecting the required biaxial texture is painfully time-consuming. This problem can be overcome by MgO-IBAD- buffering where a buffer thickness of ~ 10 nm is already sufficient for biaxial texture . Meanwhile, J_c (77K, 0 T) = 0.9 MA/cm^2 (I_c(77K, 0 T) = 144.4 A) has been achieved with this technique over a length of 0.8 m. This renders again the YBCO laser deposition as the time-limiting fabrication step at present coating rates of up to 60-70 nm x m^2/h. The cost of the laser deposition is an economical issue: IBAD-YBCO tapes are still more expensive then Bi-2223/Ag tapes.

Inclined Substrate Deposition ("ISD") achieves biaxial alignment of the YSZ buffer without assistance of an additional ion-beam using a high rate laser deposition and appropriate inclination of the metal substrate with respect to the laser plume. This mates the YSZ buffer deposition by a factor 10 faster than IBAD. However, the degree of biaxial alignment is not yet sufficient: J_c (77 K, 0 T) ~ 1 MA/cm^2 has been achieved up to now only in short samples.

In *Rolling-Assisted-Biaxially-Textured-Substrates ("RABiTS")*, cube-texture of a Ni (alloy) substrate tape is generated by conventional rolling with heavy deformation (. 95 %) to a roll textured tape, followed an annealing step which results in a recrystallization into the desired biaxially textured cubic phase [Goyal et al. 2001]. Sophisticated buffering techniques have been tested in order to avoid or remove the oxide layer from the tape surface since it destroys the unique biaxial orientation of the substrate and may blast the YBCO coating due to the volume expansion accompanying the oxidation. With a CeO_2/YSZ/CeO_2 buffer system J_c (77 K, 0 T). 1 MA/cm^2 has been achieved in small samples, but only J_c (77 K, 0 T) ~ 0.6 MA/cm^2 over 0.8 m tape length.

"Surface-Oxidation Epitaxy" ("SOE") is a similar approach where cube-textured pure Ni tape is used which is oxidized under controlled condition to form cube-textured NiO. The actual texture "seen" by the YBCO coating is here not the Ni texture but the texture of the NiO which is suitably lattice matched to YBCO/ J_c (77 K, 0 T) ~ 0.1 MA/cm^2 demonstrated in short samples with additional MgO buffering is not yet satisfactory.

Biaxially textured Ag-substrates are investigated for YBCO coating as well [Doi et al. 2002]. However, the use of expensive and soft Ag carrier tapes in combination with the low HTS fill factor of the tape coating approach is not very promising. Moreover, the achieved degree of textured grains is still well below the level of nearly 100% which is already obtained for Ni and Ni alloy tapes [Kursumovic et al. 2003].

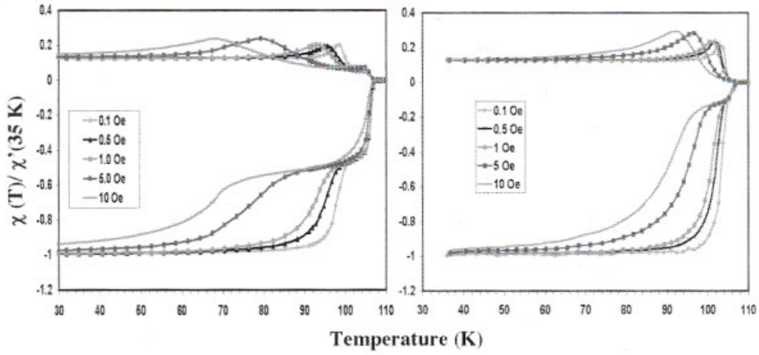
Substantial cost-reduction can be expected if less costly deposition methods than the technically successful but expensive vacuum physical vapour deposition approaches can be employed. Recent progress in *solution-based* YBCO *coating* (dip coating, spray pyrolysis, sol-gel) with first J_c (77 K, 0 T) ~ 1 MA/cm^2 samples is most promising. Recently, MOD-YBCO coated tapes with I_c (77 K, 0 T) = 140A over 7.5 m tape length have been reported. *Liquid Phase Epitaxy* is another promising option [Izumi et al 2002].

PROBING THE MAGNETIC PROPERTIES

The magnetic properties of superconductors are at least as fascinating as their extremely high electrical conductivity. There is a need to scrutinize magnetic fields inside these materials and internal magnetic fields are hard to measure. A new technique using cold muons can probe these fields within nanometers of a material's surface. A muon is a heavier, short-lived sibling of the electron, and by virtue of its spin, the muon is sensitive to magnetic fields. In the technique called muon spin rotation (mSR), slow muons plow into a sample and get stuck inside. When they expire after 2 microseconds, they beget electrons, and by carefully observing these electrons, a precise picture of the magnetic field at the site where the muons took their last breaths can be obtained. Jackson *et al.* 2000 at Paul Scherrer Institute in Switzerland have measured the profile of the magnetic field beneath the surface of a superconductor with a few nm resolutions by using muons of energies between 3 to 30 keV to probe a HTS to a depth of 152 nm. Hence they were able to confirm the assumption made in 1930 that the internal magnetic field strength decreases exponentially with increasing depth. This work will pave ways to further understand the internal magnetic fields as a consequent of the superconducting mechanism.

AC SUSCEPTIBILITY – Determination of J_c across Weak link

It is well established that ceramics HTS comprise a collection of tiny, randomly oriented anisotropic grains that are connected to each other by a system of so-called 'weak links' or 'matrix'. Ac susceptibility is intimately tied to the ac losses. Measurements of complex Ac susceptibility as a function of temperature and AC field amplitude have been carried out on by many workers. Halim et al.(1999c), Muhammad (1999), Azhan (2000), Imad et al. (2002), Malik et al. (1999), (2000), Ali et. al. (2003) have measured c on the rectangular bar-shaped $Bi_{1.6}Pb_{0.4}Sr_2(Ca_{1-x}M_x)_2Cu_3O_d$;(M = Ba, Zn, Sn, Cd, Nd, Sm, Gd, Dy, and Ni, and x= 0 – 0.1), superconducting samples prepared by the solid-state reaction method. The onset of diamagnetism was well observed at 110 K for pure sample. The effect of substitution by various elements on the Bi–(Pb)–Sr–Ca–Cu–O system has also been investigated. It was found that as the amount of doping content increases, the transition temperature decreases. Temperature-dependent critical current density was deduced from AC susceptibility data. The complex susceptibility written as $c = c' - ic''$ shows a measure of diamagnetism c' and hence the transition temperature T_c and also c'' displays the coupling loss which allows the determination of Josephson critical current, J_c. The peak (near $T_{c(onset)}$) is the manifestation of the field penetration into the grains or indication of hysteresis loss for the motion of intragranular Abrikosov vortices inside the grains.



a) b)

Figure 14. Temperature dependence of Ac magnetic susceptibility for Bi-2223 prepared via a) conventional powder method and b) coprecipitation technique(Hamadneh et al. 2002)

In type II superconductors, there are various loss mechanism [Civale et al. 1991]: a) Eddy-current losses, b) bulk-pinning and surface pinning hysteretic losses which are frequency independent but magnetic field dependent and c) flux-line cutting losses. A typical display of c is as shown in figure 14 [Hamadneh et al. 2000]. Applications of HTS are currently limited by the low transport critical current density, j_c, due to the granular nature of sintered HTS. Inter- and intra-granular pinning properties, field and temperature dependence and substitution effect have been studied by many workers [Civale et al. 1991, Halim et al.1999a, 1999b, 1999c; Malik et al. 1999, Azhan et al. 1999, Celebi et al. 2002, 2004]. The weak-links in samples with Bi-2223 dominancy is probably of the S-N-S type, whereas in the low Tc phase (Bi-2212), S-I-S junctions seem to dominate [Halim et al. 1999a].

TECHNOLOGICAL APPLICATIONS OF SUPERCONDUCTIVITY

Superconductivity is exciting both because it is strange and because it has the potential to improve our lives. It has enormous applications in the electrical industry, electronics, transportation, medicine and energy by the year 2020[Figures 15 and 16][Chu 1997].

- Of the many possible application of superconductivity, the grandest is the magnetic levitation (MAGLEV). MAGLEV can reach speeds of over 300mph. This method of transportation could be used to connect cities, relieving congested highways. The superconducting magnetic coils on-board the train and on the sidewalls of the guide way provide levitation, keep the vehicle in the center of the guide way and propel the MAGLEV along the track.

- Superconductors may play a role in Internet communication soon, such as microwave filters (e.g., for mobile phone base stations). There are ongoing projects to research and develop a superconducting digital router for high speed data communications. Since Internet data traffic is doubling every 100 days, superconductor technology is being called upon to meet this super need. Should new superconductors with higher Tc be discovered, growth and development in this exciting field could explode virtually overnight. Steady progress is also being observed in the commercialization of HTS SQUIDs in various specialty markets, such as non-invasive testing or geophysical exploration. The development of scanning SQUID microscopy and its successful commercialization portends promising commercial opportunities for applications in semiconductor chip quality control.

- Superconductors have also found wide spread applications in the military. HTS SQUIDS are being used by the US NAVY to detect mines and submarines. Significantly smaller motors are being built for NAVY ships using superconducting tape and wires.

- Fault current limiters- based on electrical bridge, inductive and resistive concept. a prototype has reached a power of 20 kVA.

- Tiny magnetic fields that penetrate Type II superconductors could be used for storing and retrieving digital information. Computers for the future will be built around superconducting devices with the usage of Josephson junctions on microprocessors.

- Since superconducting wire has near zero resistance, even at high frequencies, many more filter stages can be employed to achieve a desired frequency response. This translates into an ability to pass desired frequencies and block undesirable frequencies in applications such as cellular telephone systems.

- Electric generators, transformers and electric power transmission cables made with superconducting wire are far more efficient than conventional generators wound with copper wire. In fact their efficiency is above 99% and their size is about that of conventional generators. These facts make them very lucrative ventures for power utilities.

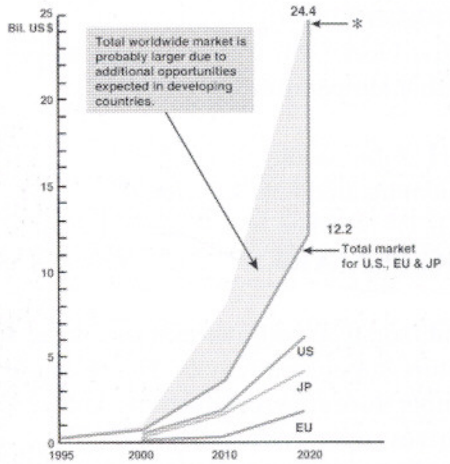
- In medical applications, the superconducting magnet has been used to observe the inner structure of the brain with an MRI (Magnetic Resonance Imaging). At the present time, the superconducting wire is cooled by using liquid He, but if a high Tc superconductor is used, the MRI can be operated at considerably low cost by cooling with liquid nitrogen. Together with the development of NMR, there is a worldwide market of approximately $2 billion [ISIS 1998]. As for future medical applications of superconductor electronics technology, efforts to develop magnetoencephalography (MEG) and magnetocardiography (MCG) using superconducting quantum interference devices (SQUIDs) are also showing exciting progress. These technologies provide non-invasive methods for diagnosing diseases that cannot be identified by any other available method. MEG systems have gone beyond the basic research stage, and a number of units are already being used clinically. MCG is expected to become available as a clinical diagnostic instrument in the very near future.

- Performance of particle accelerators in high energy physics studies is very dependent on high field superconducting magnets (such as beam-steering magnets). Superconducting Super Collider (SSC) illustrates the political ramifications of the application of new technologies.

Overview of Maglev R&D

A super high-speed transport system with a non-adhesive drive system that is independent of wheel-and-rail frictional forces has been a long-standing dream of railway engineers. Maglev, a combination of superconducting magnets and linear motor technology, realizes super high-speed running, safety, reliability, low environmental impact and minimum maintenance.

- In 1970: R&D of Maglev, which adopts superconducting technology, has been underway at RTRI of JNR.
- In 1987: The manned two-car vehicle registered a speed of 400.8 km/h on Miyazaki Maglev Test Track.
- April 3, 1997: New test line called the Yamanashi Maglev Test Line opened. Maglev vehicle in a three-car train set achieved world speed records, attaining a maximum speed of 531 km/h in a manned vehicle run.
- December 12, 1997: A maximum speed of 550 km/h in an unmanned vehicle was achieved.
- March 18, 1999: A five-car train set attained a maximum speed of 548 km/h.
- April 14, 1999: The five-car train set surpassed the speed record of the three-car train set, attaining a maximum speed of 552 km/h in a manned vehicle run.
- December 2, 2003: The three-car train set attained a maximum speed of 581 km/h in a manned vehicle run.



* This forecast includes the expected expansion of sales by 100% into outside U.S., EU & JP, as predicted by the World Bank.

Figure 15. Superconductivity Sales Opportunities (unit: Bil.US$)

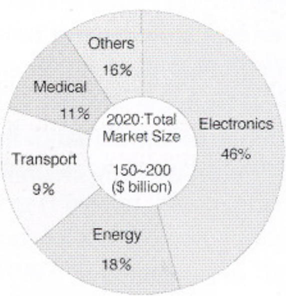


Figure 16. Worldwide Market Forecast for Superconductivity

CHALLENGES

Inspite of the impressive progress made in HTS, some critical issues remain unanswered. In its science the following questions are asked,

- Is the electrical charge system in cuprate HTS truly abnormal, thus suggesting a non-fermi liquid behaviour?
- What is the pairing mechanism responsible for such unusual material?
  -Many theoretical models have been proposed, in an attempt to account for the occurrence of HTS. The pairing mechanisms involved are in general either pnononic or magnetic in nature.
- What is the effect of dimensionality on HTS, and does HTS take place only in a truly 2D electron system?
- Does Cu- or (CuO_2) layer necessary for HTS?
- What is the microscopic HTS theory?
- Can we find less anisotropic HTS?
- Can we find HTS with higher Tc?
- Can one modify the active block (AB) or their charge-reservoir block (CRB) in order to excite the pairing at higher temperature?
- What is beyond HTS?

Some of these questions are remained to be answered.

CONCLUDING REMARKS

This paper briefly highlights some of the important issues regarding the current status of research in high temperature superconductivity. Hence one would ask, 'What are the burning issues in high temperature superconductivity today?' The most important issue is the mechanism: What drives superconductivity at 150K? Could it equally well work at 300K? How do strong correlations, i.e. electrons trying to stay out of each other's way, manage to stabilize d-wave superconductivity? On the fundamental side, one can say that the essence of the challenge is to solve the strong correlation problem; the 'glue' problem. What should be clear from this special issue is that there are many competing candidate mechanisms, and a broad range of experimental probes that can be brought to bear on this problem to distinguish them. These are very difficult questions but the payoff is also very large for good answers and clever experiments and how close are we in the quest for a room-temperature superconductor? Aside from the expected excitement in the future, one equally exciting unexpected spin-off from the study of HTS is the growth of mesomaterial engineering due to the vast knowledge accumulated in the synthesis and characterization of perovskite and related oxides. It is an exciting challenge!

ACKNOWLEDGEMENT

Firstly, Praise is to ALLAH. Then the author would like to thank Universiti Putra Malaysia, Faculty of Science and Environmental Studies and the Department of Physics for all the support rendered throughout his career. He also extends his acknowledgement to all his graduate students. Finally he would like to convey his heartfelt gratitude to his wife and all his family members for their endless support, sacrifice, patience and love.

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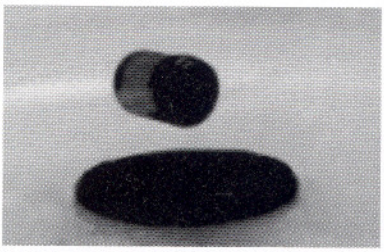

A neodymium-iron-boron magnet floats above a disk of YBCO superconductor, prepared via coprecipitation method, with a critical temperature $T_{C(R=0)}$ = 91 K. (Halim et al. unpublished)

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