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High Tc Superconductors - Background and Applications

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Presentation at DRIE, March 22nd 1988

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1. Introduction

In 1986 and early 1987, solid state physics gave a convulsive lurch into activity with the discovery by J.G. Bednorz and K.W.Muller of IBM Zurich and Paul Chu of the University of Illinois of what have become known as High Critical Temperature Superconductors [1,2].

Since that time an unprecendented amount of effort and money has been directed towards this phenomenon, optimistic predictions of economic impact have been made, and a new subject area has been formed in solid state physics and chemistry [3]. Interestingly enough, what has not yet emerged from this concerted effort is a clear explanation of the phenomena concerned.

This paper will review the phenomenon and its recent developments, and then describe the potential applications of the subject in electronics. It will close by trying to make a realistic assessment of the prospects for the use of high Tc materials along with time frames for implementation.

2. Background - Low Tc Superconductors

Superconductivity was discovered in 1911 in pure metals such as lead and tin [4]. The phenomenon has two significant features (Figure 1):

1. The electrical resistance falls to zero below a certain critical temperature Tc.
2. All magnetic flux is excluded from the material below Tc. This Meissner Effect is a unique property of a superconductor.

The flux exclusion occurs because of currents spontaneously generated in the surface regions of the material when the temperature falls below Tc. These currents interact with the external magnetic field to produce a repulsion which leads to the most common demonstration of high Tc superconductors. It is not an effect that you would expect if the electrical resistance simply became zero since flux is not expelled by a simple change in resistance. The Meissner effect is a specific quantum phenomenon which entails an addition to Maxwell's Laws [5]. Its most striking demonstration is when a magnet elevates above a high Tc material as its temperature drops below Tc. The flux penetration depth is a measure of the region over which the currents flow: in low Tc superconductors, the penetration length is of the order of a few millionths of a meter.

The initial explanation of superconductivity took forty years to achieve until J.Bardeen, L.N.Cooper and J.R. Schrieffer published the BCS theory for which they were awarded the Nobel Prize in the 1950's [6]. As seems to be common in this subject, the explanation is indirect and rather complex. I will consider first normal conductors, and then superconductors.

It is well established that certain rules describe the behaviour of the natural particles. Electrons have a property of spin 1/2 - Figure 2. Such quantum particles obey Fermi-Dirac statistics in which each particle must have a separate and distinct quantum state. In loose terms, each quantum state corresponds to a different energy for each electron. In a block of metal, we have roughly 10^{-24} electrons of which close to 1 electron/atom (10^{-22}) are free to carry current. The energy states of each electron are determined rather like filling a pail with water. Since water molecules cannot occupy the same physical space, as water (electrons) is (are) added to the pail, the level of the water rises and the potential energy of the whole collection extends from the bottom of the pail to the level of the surface. The surface (fermi energy) is where boats (electrons) can move around (enter a new state with kinetic energy) and in fact, only those electrons in a metal within jumping distance of the fermi energy (surface) carry current or interact with the outside world.

This distinct nature of electrons has other consequences in real metals. An early interest in describing the electrical properties of metals was to explain how the electrons avoided the lattice atoms (Figure 3). A conclusion of wave mechanics was that in a perfect periodic lattice, quantum states for electrons extend spatially over the entire volume of the material. The lattice atoms are then invisible to the electrons. Electrical resistance arises because of imperfections in periodicity. These may be due to thermally displaced atoms vibrating about their equilibrium positions, missing or misplaced lattice atoms, or impurities. The model to describe resistance is that of the scattering of electrons by such defects - that is, the motion of the electron in the field direction is randomised when it impacts a defect.

The BCS theory of superconductivity noted that a second class of fundamental particle exists. For particles with spin 0 or 1, their behaviour is described by Bose-Einstein statistics Figure 4. In this case, all the particles can, in principle, occupy or condense into the same quantum state which may have a lower energy than the single particle states . The energy difference is known as the superconducting energy gap. In the low energy state all particles are indistinguishable, currents are infinite, and superconductivity is explainable. The achievement of the BCS theory was to explain how electrons (fermions with spin ± 1/2) could be converted to bosons (spin 0 or 1).

In free space, it cannot be done; however, in a solid the lattice atoms bring about an interaction. Consider a negative electron passing though a lattice of positively charged atoms. As it passes, the negative charge of the electron and the positive charges of the lattice atoms attract each other. Since the mass of the atoms is about 2000 times that of the electrons, the movement of the atoms is small and is delayed by their inertia. However, the movement causes a dynamic accumulation of positive charge in the rear of the first electron. A second electron can be attracted by this charge and the two move as a 'Cooper pair' -the pairing interaction being facilitated by the lattice interaction.

BCS theory showed that pairs only occur between electrons having spins of +1/2 and -1/2, introduced the concept of a superconducting energy gap by which the energy was lowered when pairing took place, was able to make a reasonable computation of the temperature at which it occurred, and predicted the Meissner Effect. An important parameter of BCS theory is the correlation length, a measure of the distance separating the two electrons. In low temperature superconductors the correlation length is of the order of 10's of angstroms.

Some experimental conclusions are immediate (Figure 5):

1) since the electron interaction is the result of a dynamic shift of lattice atoms, the atomic mass should be important. In fact, the isotope effect in which Tc changes with the isotopic mass of the lattice atoms was an important experiment used to verify the BCS theory. 2) the pair may be broken by thermal energy and is therefore a low temperature effect (Tc is a measure of the pairing energy), 3) if the pair passes into a magnetic field, the magnetic interaction with the two electrons of opposite spin differs and the pair may be torn apart. The magnetic field which breaks the pair is called the critical field Hc, It may be externally applied or may be a consequence of the magnetic field generated by the flow of current. Thus we can also define a maximum current density Jc which can be carried by a superconductor.

current density Jc which can be carried by a superconductor. For metal semiconductors this is of the order of 10^6 A/cm^2.

One final definition may be made (Figure 6): The earliest superconductors were pure metals. These became known as

Type 1 superconductors. At Tc, their entire volume became superconducting and flux was excluded according to BCS theory. Critical currents and fields tended to be low.

Type 2 superconductors are alloys such as Nb_3-Sn. These have higher Jc and Hc which arise because the material tends to break up into interleaved normal and superconducting regions. Flux penetrates the material through the normal regions and superconductivity is retained to higher fields (currents). In this case we define two field parameters; Hc1 - the magnetic field at which flux penetration commences, and Hc2, the field at which superconductivity is fully quenched - Hc2>>>Hc1.

Type II superconductors have been the mainstay of commercial developments in superconducting magnets and can support fields up to 30 T [7]. However, even after vast efforts, the critical temperature for alloy superconductors has not exceeded 22 K so that liquid helium cooling is mandatory.

The applications of alloy superconductors include superconducting magnets for scientific, medical and industrial purposes, magnetic levitation and electronic devices [7]. In the case of large magnets, a significant feature is the mechanical strength required in the magnet windings to sustain the very high mechanical forces encountered. However, the technology can be defined as mature and capable of large scale engineering. The most significant investments have been in magnets for large particle accelerators [8].

3. High Tc Superconductors

In order to introduce the recent developments in what have become called High Tc (critical temperature) superconductors, it is of interest to mention efforts which were made in the 60's to develop organic superconductors (Figure 7). Recognising the need for and the mechanism of spin-pairing, efforts were made to develop long chain organic molecules in which conductivity along a central chain was modulated by charge movement in side chains [9]. It was hoped that this modulation would induce Cooper pairs at high temperatures. Dupont in Canada, for example, made considerable efforts in this area. However, these activities considerable efforts in this area. However, these activities were not successful in creating transition temperatures above the helium range. To everybody's surprise, success was left to be achieved by the ceramists in 1986.

Figure 8 shows the trend in Tc since 1911. After 50 years of 3 degrees per decade, an effective quantum jump took place in the early part of last year. The materials are copper-based oxides having a perovskite structure of compositions (Figure 9) with the Bi compound being the latest addition in January 1988. Superconducting analogs of these materials have been made in which various rare earths and alkali metals have been substituted. However, the role of copper seems to be vital, although some recent reports (as yet unconfirmed) may change this situation.

The phase diagram of the yttrium [123] compound (Figure 10) [10] shows the various compounds formed in this system. It is likely that virtually every compound represented by a point on this diagram has been synthesised by some laboratory somewhere in the world. The significant features of the structure are that the compounds are perovskite based layer structures, are non-stoichiometric in oxygen, and in terms of density are very poor as ceramics.

Figure 11 shows the structure of the yttrium based {123} compounds. Y.Lepage and W.R.McKinnon of the Chemistry Division at the NRC Laboratories have had a significant role in the definition of this structure and crystal model [11]. The structure involves layers of copper atoms, two of which are 'normal'involving a copper valence of II, while the third is unusual with valence states of I and III, the relative number of which is determined by the oxygen stoichiometry. It is this layer which is responsible for the superconducting properties.

Over the last two months, a related Bi-Sr-Ca-Cu-0 compound has been devised - and again the NRC laboratories have played a vital role in the evaluation of its structure [12]. The basic layer structure seems to be the same, but with a larger unit cell. It is clear that layer structures are destined to be a hot subject for attention over the next few years.

Finally it is of interest that the kind of ceramic we are discussing is really very poor. The microstructure is complex and poorly developed and consists of highly oriented crystallites with extensive porosity (Figure 12). From a ceramic viewpoint, the normal approach would be to densify the material by hot pressing or liquid phase sintering, but in general, superconductors processed in this way do not work. The reason for this seems to be the need to equilibriate all parts of the ceramic with oxygen -and the diffusion rate of oxygen in very dense ceramic is very slow. High porosity is necessary to enhance this diffusion. This slow diffusion has been significant in experiments to detect an isotope effect in high Tc superconductors. Initial experiments in which attempts were made to replace O-16 by O-18 by thermal diffusion appeared to show no effect suggesting that BCS-type models were not applicable. However, more recent studies at Argonne National Laboratories [13] using precusor oxides fabricated with O-18 show that an isotope effect does exist.

The gross microstructure is not the only factor which must be considered. The microstructure on a microscopic scale is also of extreme significance. High resolution microscopic studies (Figure 13) show complex twinning and long range structures which greatly affect the superconducting properties [14]. Currently it appears that the critical current is enhanced in structures in which the crystallites are small and uniform in size and are oriented with respect to the substrate. This can be explained through the pinning of flux lines by grain boundaries and crystallographic defects [15]. The highest critical currents have been achieved in thin film structures in which the film grows relative to the underlying substrate [16]. Such films can be grown as uniform crystal structures and studies of the exact role of film-surface interactions and the effects of grain boundaries are of obvious pressing importance.

4. Electrical Properties of High Tc Superconductors

We now may turn to the electrical properties of (123) superconductors. The processing of the compounds is outlined in Figure 14. The process is relatively standard for a ceramic, although the temperatures are relatively low and the step involving flowing oxygen is unusual.

Figure 15 shows R-T and I-V plots for an Y-Ba-Cu compound measured using a four-probe technique. The two graphs allow us to define the critical temperature Tc and the critical current Jc. The latter is taken as the point where the voltage across the sample departs significantly from zero. The effects of oxygen annealing on Tc and on the resistance above the transition are shown in Figure 16. The resistance drops to zero at 89-93 K over a temperature range of 1K or less. The precise temperature and range is determined by composition, processing, and most importantly, oxygen content. There is often evidence of 'bumps' on the curve which gives rise to excitement about higher Tc transitions. However, few of these results have been fully substantiated and the search for single phase, stable, higher Tc material still progresses.

Figure 17 summarises the electrical data for Type I and Type II metal superconductors, and for two types of ceramic material. The critical currents for the latter are smaller than those for the alloy materials (often by two orders of magnitude), but the critical fields are higher for the ceramics. As noted before, the reason for this for this seems to be closely connected with the respective microstructures in which flux lines can thread around the superconducting grains in the intergranular material.

5. Applications

While science and basic understanding is important, superconductivity will only attain the status of a viable technology if products and applications can be achieved. Figure 18 summarises various generic methods for material fabrication along with the various refinements required to develop a viable product. The methods include:

- bulk ceramic processing
- composite technology
- plasma spray
- thin film technology

These are summarised in the following sections.

a) Bulk ceramic processing

The current objectives focus on the enhancement of the critical current through controlled microstructure and grain orientation. Since microstructure seems to play a key role in the mechanism of conductivity, this may become of vital importance in future applications. In normal ceramics, it would be mandatory to increase the density to near theoretical. However in the (123) compounds both the slow diffusion of oxygen and the relative insensitivity of superconducting properties to density may make this of reduced importance unless the mechanical strength or chemical stability becomes a limiting factor.

Figure 19 shows potential applications of bulk ceramic in electrical power transmission, although the economic viability of such a use is probably limited more by overall engineering costs than by any material properties. Nearer term uses are likely as magnetic bearings using Meissner repulsion, or as demonstration 'Meissner motors' involving pulsed coils repelling superconducting discs attached to a rotor. Larger electrical machines based on homopolar generators in which the rotor is a large superconducting disc could be among the initial engineering developments. The overall requirement is for a tough, stable ceramic with high critical current. The market for bulk ceramic will overlap into that using powders in composite materials and the two uses are probably commercially inseparable.

b) Composite technology

The fact that the ceramic is electrically effective even with such low density is likely to be partly due to superconducting tunnel currents (See section 5(d)) across insulating grain boundaries. This suggests that a composite technology in which powder is distributed throughout a metal or polymer matrix may be equally effective. This would reduce processing costs to that of the powder and lead easily to shape fabrication, wire extrusion and cladding. Techniques such as explosive bonding have also been proposed for composite formation [17].

Wire and cables having Jc > 1000 A/cm2 have been reported from several sources although an initial objective for commercial use is closer to 10,000 A/cm2. The immediate applications reviewed in Figure 20 include large superconducting magnets for medical nuclear magnetic resonance facilities in which up to 40% of operating costs are currently spent in liquid helium refrigerants, mineral processing magnets, and an on-going demand for laboratory magnets. The development of large scale particle accelerators such as the super-collider in the USA would be considerably cheaper using high Tc magnets. If large static magnets can be fabricated with high field capabilities, an attractive development for power utilities would be short term energy storage to meet load interuptions from milliseconds to periods of minutes. While it may be cost effective to build such systems for local use, the magnetic field in the vicinity of such installations could rise to levels of several gauss. The medical effects of such fields will have to be established at an early stage. Finally, magnetic levitation for transportation is a long term market. However, it should be noted that such levitation is not the result of the Meissner effect, but an interaction with eddy currents induced in a metal track. The potential application of high Tc materials in this area awaits the development of a mature magnet technology in general.

c) Plasma spray

Plasma spraying involves the injection of a ceramic powder into a high temperature electric arc (Figure 21). This causes partial or complete melting of the powder which can then be condensed on surfaces ranging from ceramics to metals. This technology is well developed for ceramic powders in general, although its success with high Tc superconductors is somewhat surprising. The major application would be for magnetic shielding which would be effective at low frequencies - a range in which present magnetic shielding is less effective. Due to ac losses, the potential for higher frequency shielding is less assured, but material developments in this area could meet a large military and commercial market.

d) Thin Film Technology

Electronic applications almost by definition involve the fabrication of thin films (Figure 22). Current processes include magnetron sputtering, electron beam deposition and laser ablation. Chemical methods such as chemical vapour deposition and the pyrolysis of sol gel solutions are also being actively explored [18]. An interesting process for the fabrication of patterned films is the ion implantation of the constituent ions into a copper matrix followed by thermal annealing to develop the superconducting oxide [19].

A significant factor is that the highest critical current of $>10^{-5}$ A/cm^2 in high Tc superconductors has been achieved in thin films in which a substantial degree of grain orientation has been developed [16]. The substrates now necessary are relatively exotic -principally single crystal strontium titanate, but intermediate layers on silicon or glass substrates may solve the problems of interfacial strain.

The applications of thin films include:

- magnetic shielding
- conductors in integrated circuits (VLSI)
- Josephson junction technology

The uses in shielding are similar to the thick film applications discussed above. In integrated circuit design, device packaging is becoming limited by power dissipation in the copper interconnects. Superconductor equivalents would increase the possible packing density. Application in this area will require critical current densities of $> 10^{-5}$ A/cm^2 which appear achievable even on current technology. It may be noted that the use of superconductor interconnects will not necessarily increase the speed of computer logic. As shown in Figure 23, a pulse propagating on a conductor fabricated on a dielectric acts as a wave which penetrates the dielectric. The speed of propagation is therefore set by the wave speed in the dielectric $c = 1/\sqrt{\mu \varepsilon \varepsilon_0}$
.
This implies that development of dielectrics having low dielectric constant would be considerably more significant in the reduction of propagation times than superconducting interconnects.

A major area of electronic application is Josephson junction technology [20,21]. This is a quantum based phenomenon unique to superconductors which has already attained commercial products in metallic superconductors. The impact would be correspondingly greater if liquid nitrogen coolants could be implemented. The effects are illustrated in Figure 24 and include:

- high speed logic switches
  for computer applications
- magnetic field measurements
- voltage standards
- infrared and microwave detectors
- high frequency mixers and converters

The basic device is shown in Figure 24(a) and consists of two semiconducting slabs separated by a thin insulator (normally 40-100 A thick). The I-V characteristic of such a device is shown in Figure 24 (b). At low currents, a 'supercurrent' of Cooper pairs tunnels across the insulator so that current flows with no voltage developed across the device. Above a critical current Ic or if a magnetic field Hc is applied, the device becomes resistive and voltage appears. Since the effect is based on quantum tunnelling, transition speeds are, in principle, very high and very high speed computer logic could be implemented. A form of logic switch using the magnetic field generated by a control current in an adjacent superconducting control line is shown in Figure 25 [22]. Although Josephson logic was pursued actively for an extensive period by IBM in metal superconductors, a major project was cancelled in 1983 because of difficulties in reproducibility and stability. If these problems could be overcome in high Tc materials a significant area of application would be opened. In Canada, CTF Systems Ltd of Port Coquiltam B.C. has a $6M contract to develop such devices.

Other unique properties also exist. If a voltage greater than the threshold voltage is applied to a Josephson junction, a frequency w Hz is generated according to the relation h w = eV (Figure 24(c)). Since frequencies can be easily measured with high accuracy, this effect is now used as the international secondary voltage standard. In conjunction with a tuned LCR circuit, gain can be obtained and such a generator is called an 'RF Squid'. In the reverse effect, if a Josephson junction is illuminated by a source of microwave or infrared radiation, voltage steps appear on the I-V characteristic (Figure 24 (d)). Such steps can be used as a sensitive radiation detector.

Finally, the magnetic flux that can thread a superconducting loop is quantised in units of h/2e, where h is Plank's Constant and e is the charge of the electron (Figure 24 (e)). Flux can enter the loop through a 'weak link' such as the Josephson junction illustrated in Figure 23 (a). Such a device is called a 'SQUID', or superconducting quantum interference device (Figure 26) [21]. The value of the flux quantum is 2 x 10-7 gauss and the magnetic field is detected by a variation in the critical current of the junction as each flux line enters the loop. This effect can be used as a very sensitive measure of magnetic field and this sensitivity can be improved even further by transformer techniques developed for low temperature metallic squids. The technology is already mature for measurements of the earth's magnetic field using a 'squid magnetometer' and a tremendous market in medicine could be opened by sensing the changing magnetic fields associated the operation of various body organs. A liquid nitrogen cooled technology would open this field to widespread use.

A prediction of the markets for high Tc superconductors over the next 15 years is given in Figure 27 [23].This includes both helium and nitrogen cooled superconductors. It is noticeable that in the near future the big markets are in electronic and medical applications and NOT in the large scale transportation or energy storage equipment so often referred to in popular reports.

6. Industrial Consortia and Research Groups in Canada

Figure 28 summarises the major industrial and scientific consortia currently being considered in Canada. The Canadian University Industry Council on Advanced Ceramics has organised a consortium concerned with ceramic processing. Six companies will contribute $50,000 per year for three years and this will be matched by NRC/NSERC funding. The research will be carried out in four university laboratories at McMaster, Queens, British Columbia and the Technical University of Nova Scotia. This work complements NSERC strategic grants at McMaster University and University of British Columbia, and a number of smaller programmes at other universities.

Atomic Energy of Canada, Canada Wire and Cable, Hydro Quebec have a major proposal for the development of wire and cable.

A consortium to examine a wide range of scientific experiments is being developed by the Ontario Centre of Materials Research.

On the industrial scene, CTF Systems Ltd have a multi-million dollar contract with the Department of National

Defence to develop a thin film technology. Almax Industries Ltd is manufacturing and selling to Canadian and international markets, ceramic powder, sputtering targets and other shaped ceramics, along with a set of demonstration and teaching kits concerned with the properties and use of high Tc superconductors. The industrial situation in the United States has been reviewed well in a article in High Technology Business News [24].

Ontario Hydro has taken a leading role in examining the use of superconducting technology. An invaluable service has been the publication of a monthly newsletter on superconductivity [25]. Copies of this publication can be obtained by contacting Dr. Frank Chu at Ontario Hydro. A American publication of similar value is 'Superconductivity News' [26].

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CHARACTERISTICS OF SUPERCONDUCTIVITY

1. THE ELECTRICAL RESISTANCE FALLS TO ZERO BELOW A CRITICAL TEMPERATURE T_C.

2. ALL MAGNETIC FLUX IS EXCLUDED FROM THE MATERIAL BELOW T_C.

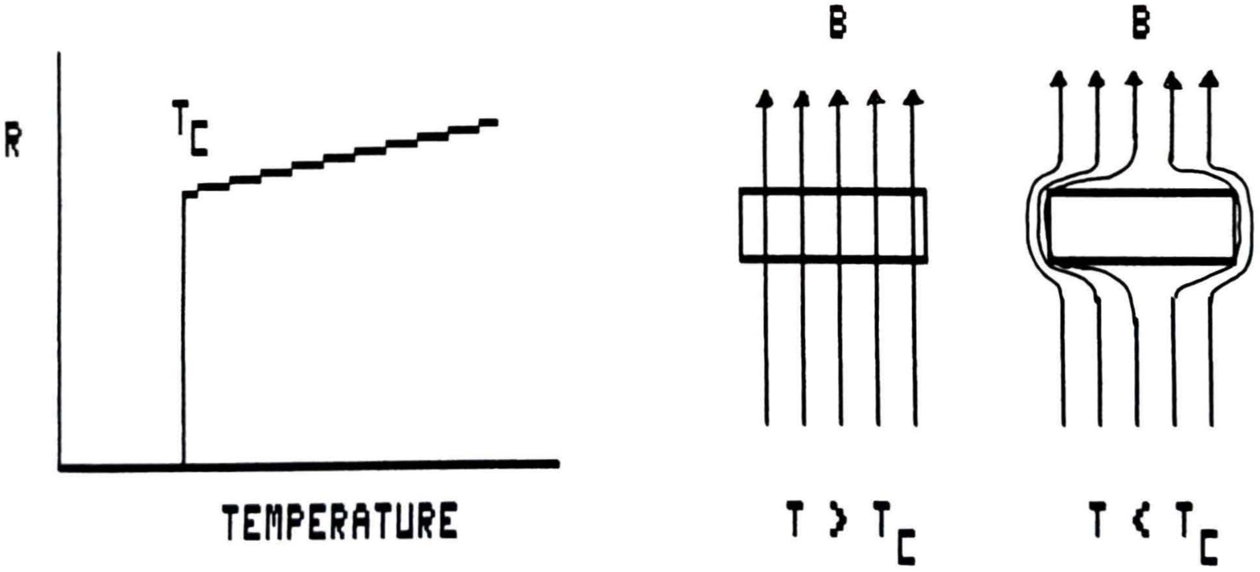


figure 1: Characteristics of Superconducting Behaviour

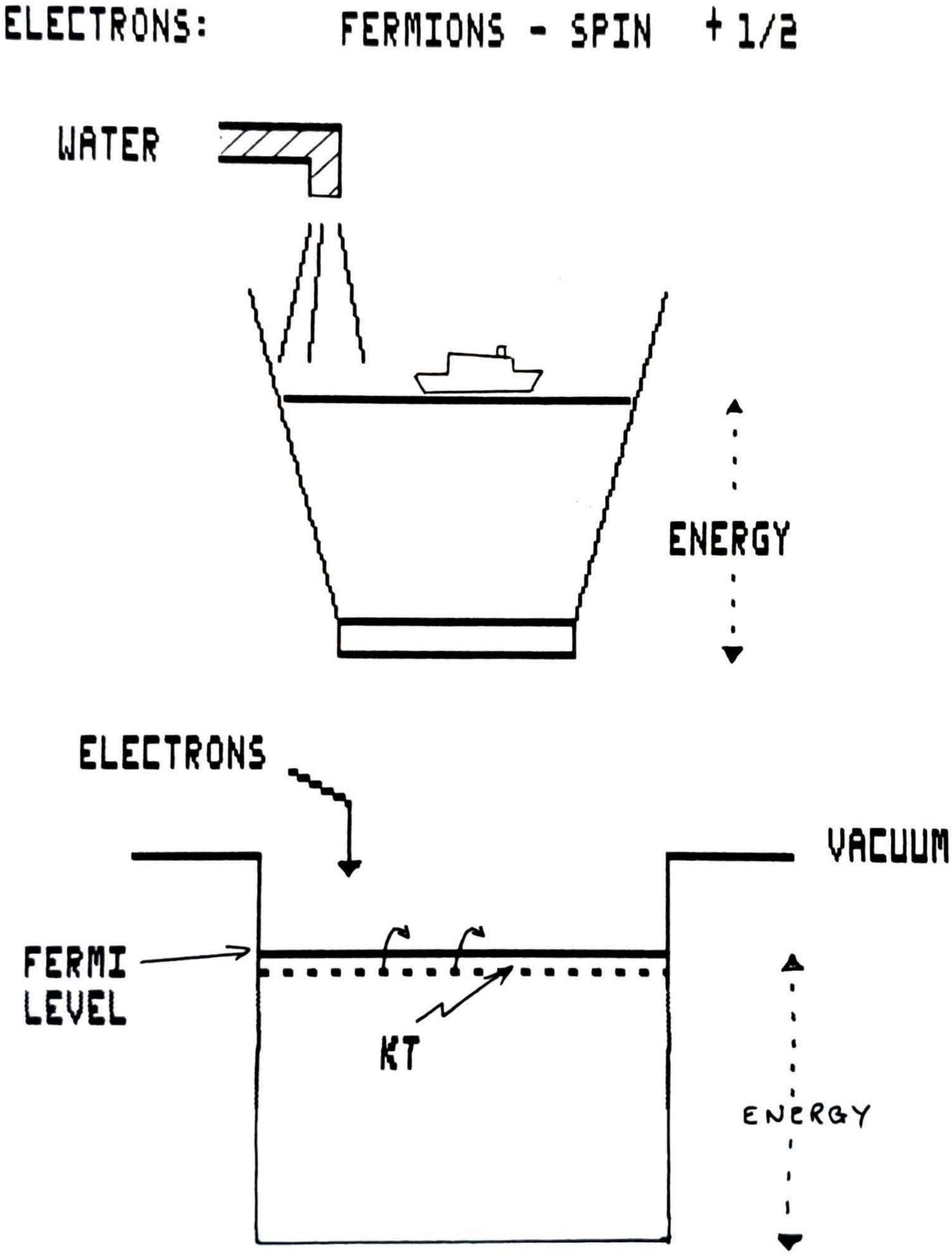


Figure 2: Energy states for Fermions

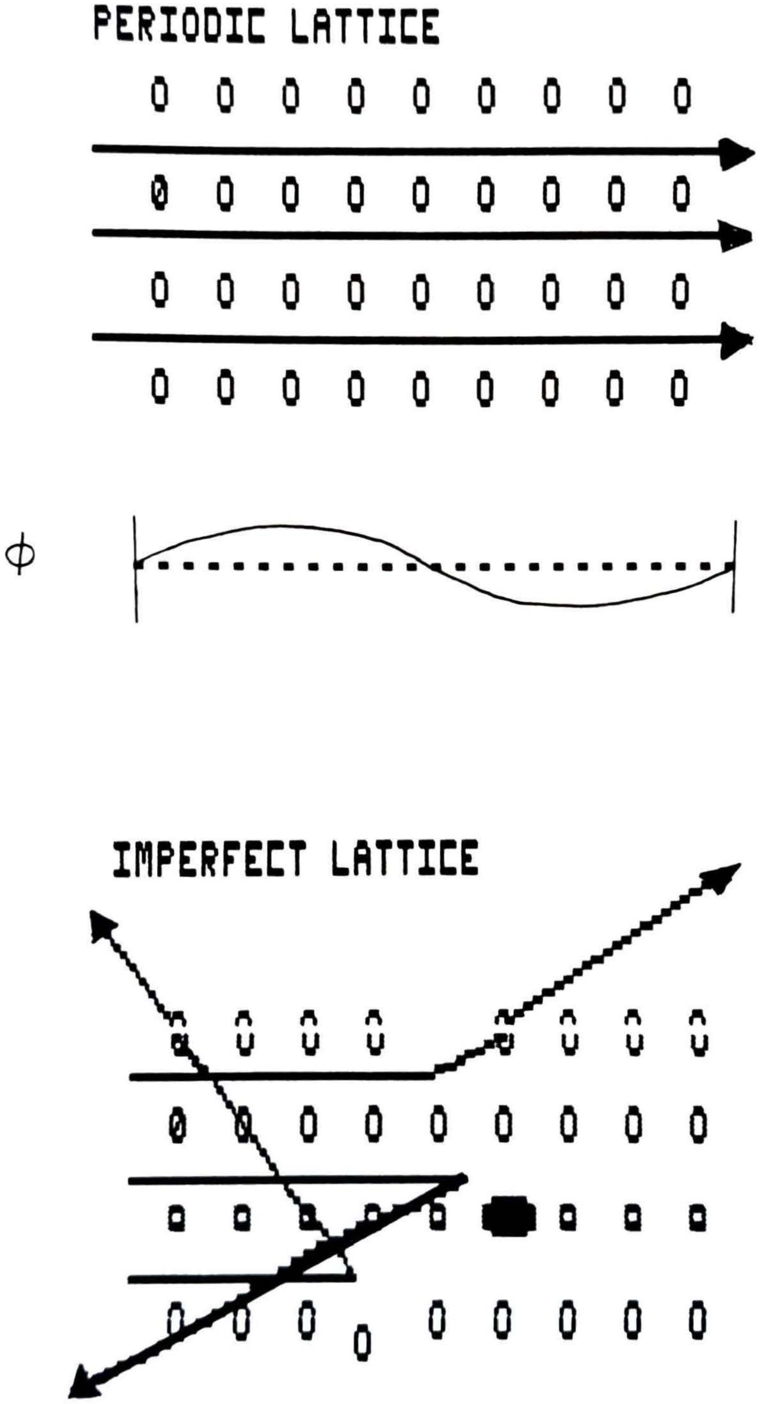


Figure 3: Electron motion in periodic and imperfect lattices

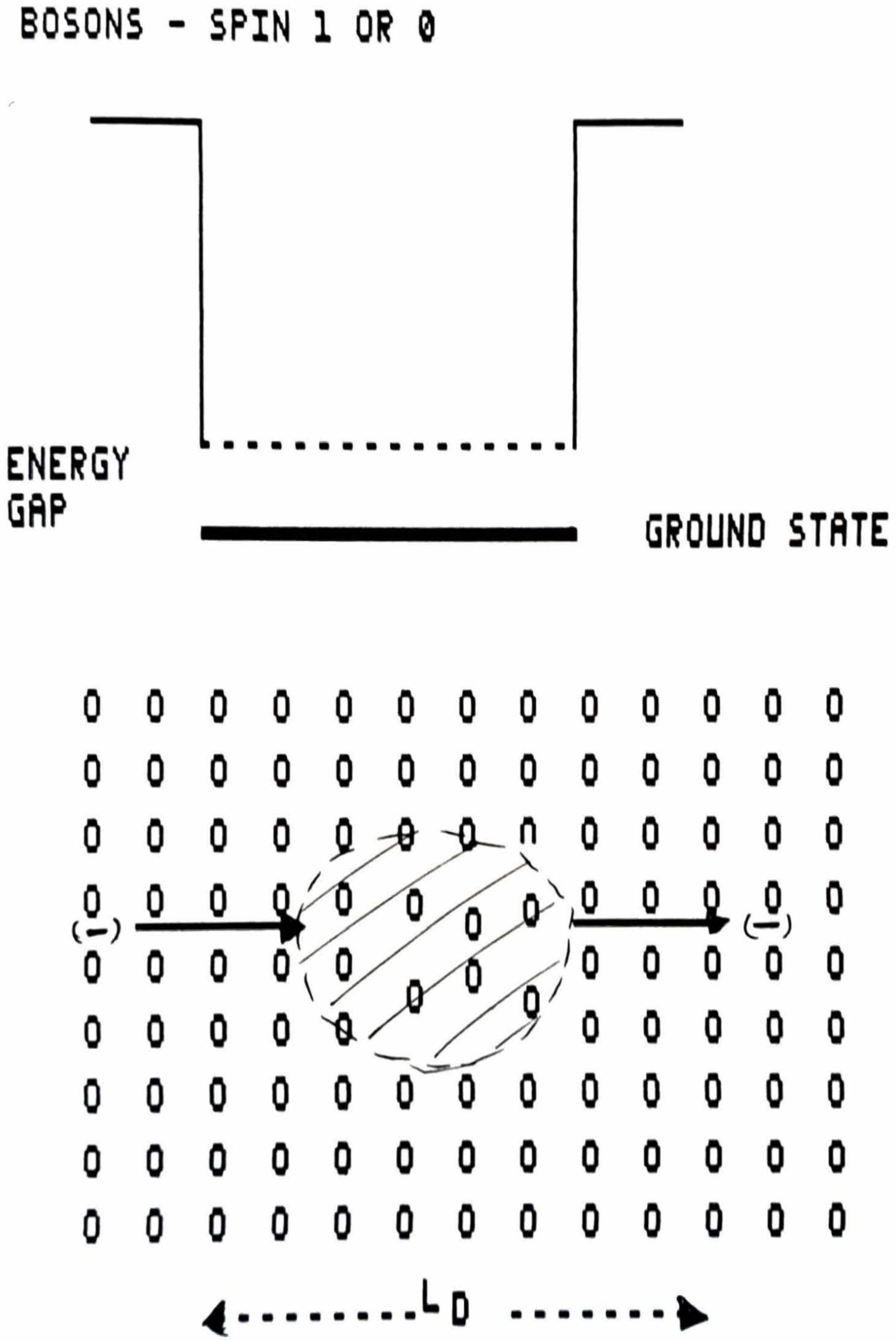


Figure 4: Energy States for Bosons and the formation of Cooper Pairs

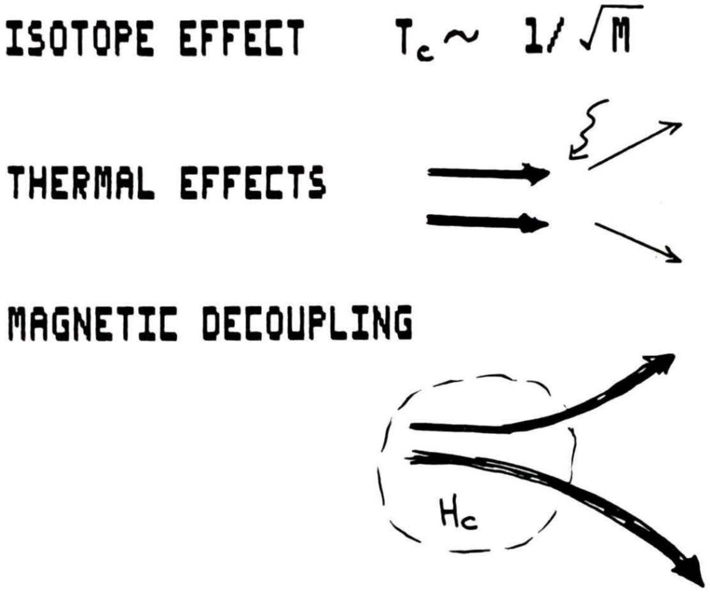


Figure 5: Factors influencing the coupling of Cooper Pairs

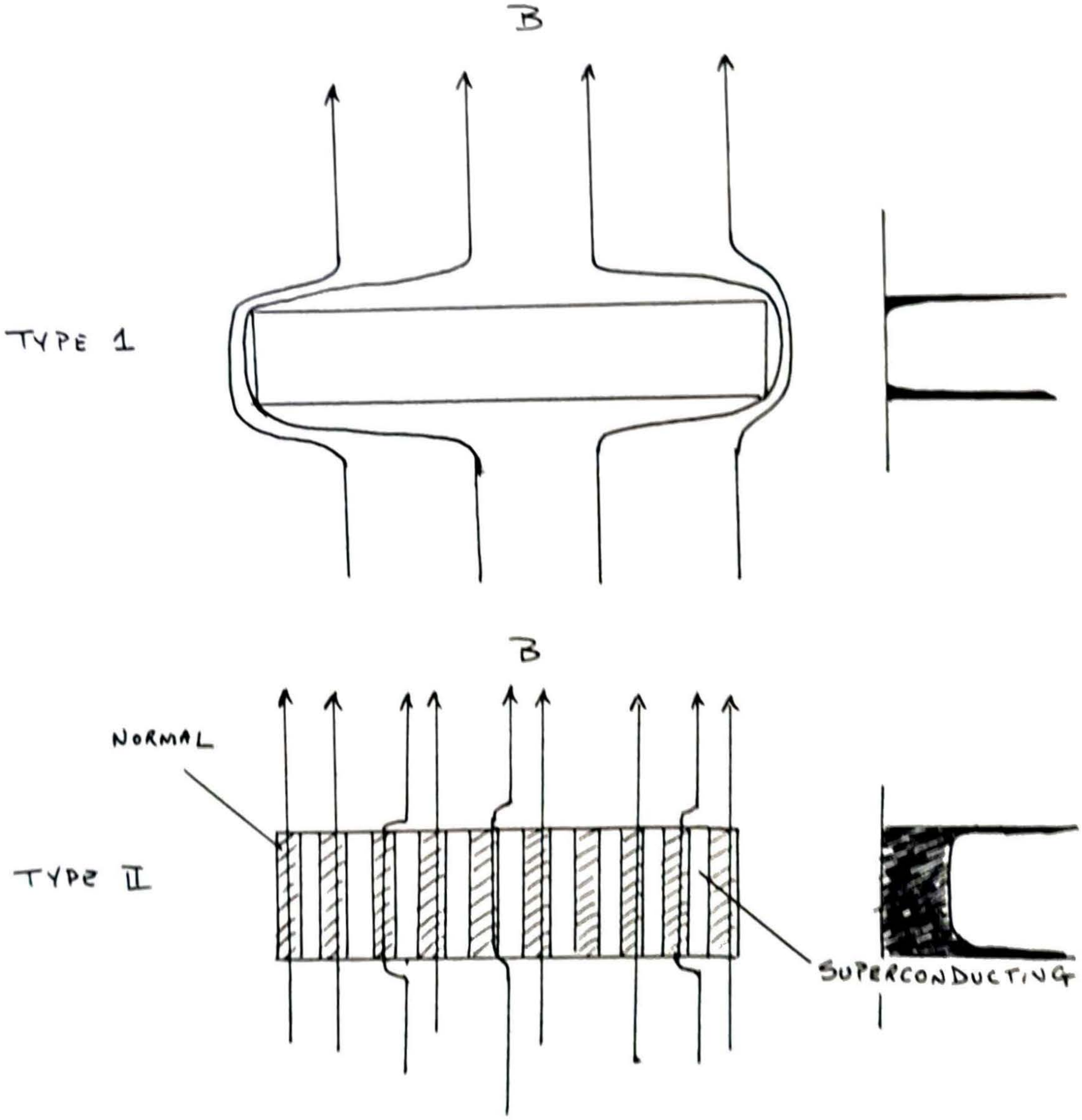


Figure 6: Flux exclusion in Type 1 and Type 2 Superconductors
Type 2 involves the formation of normal and superconducting domains.

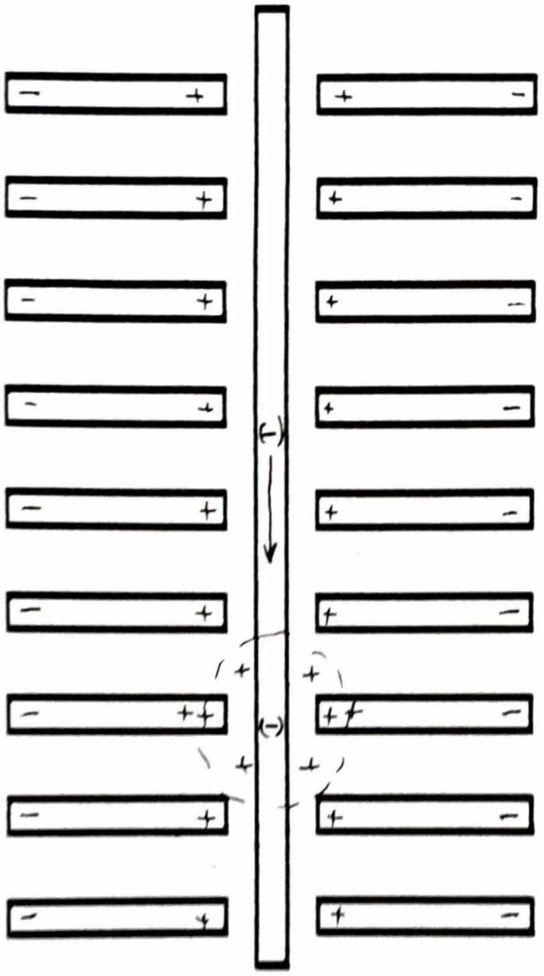


Figure 7: Proposed model for organic superconductors

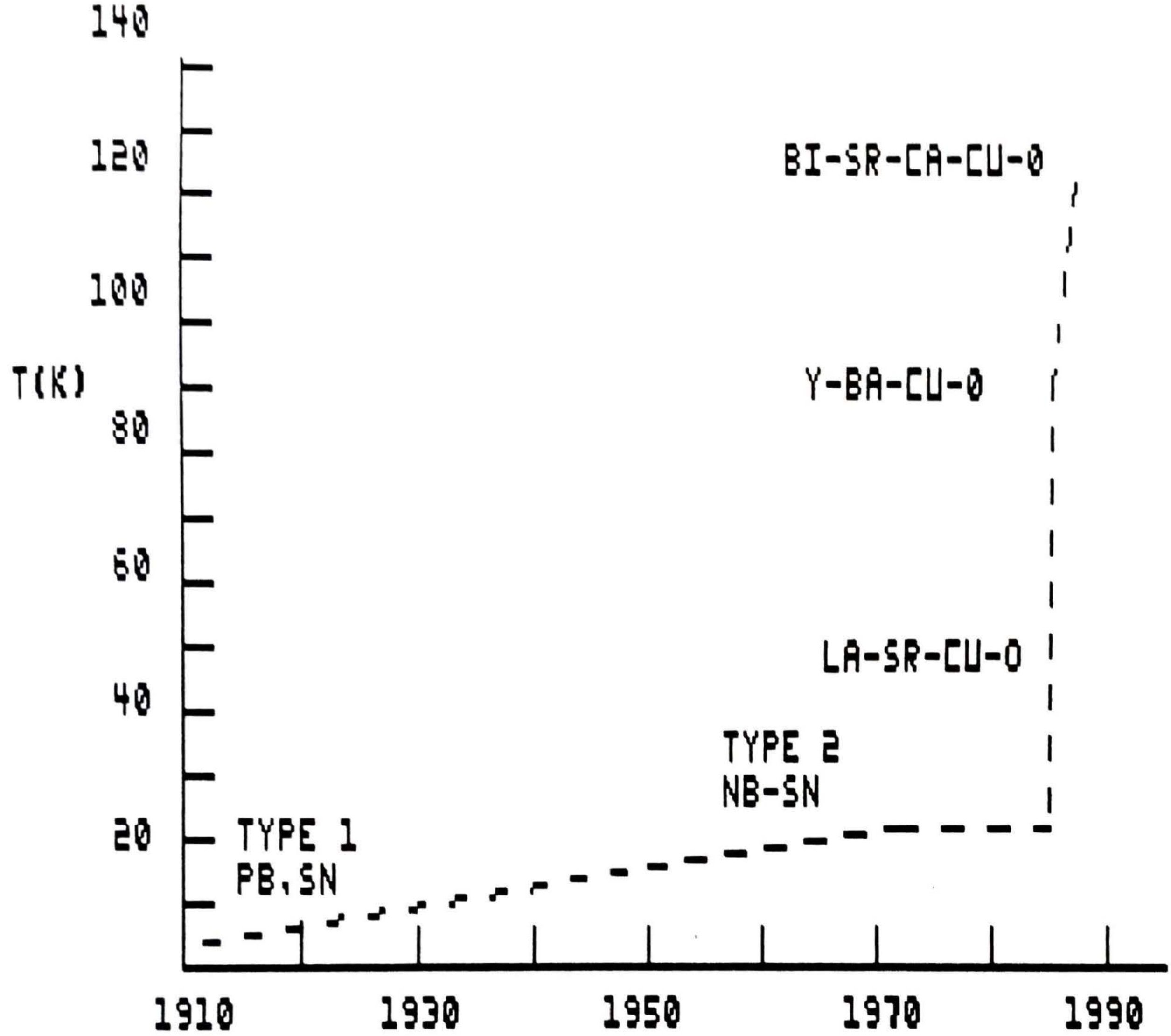


FIGURE 8 : TREND IN CRITICAL TEMPERATURE WITH TIME

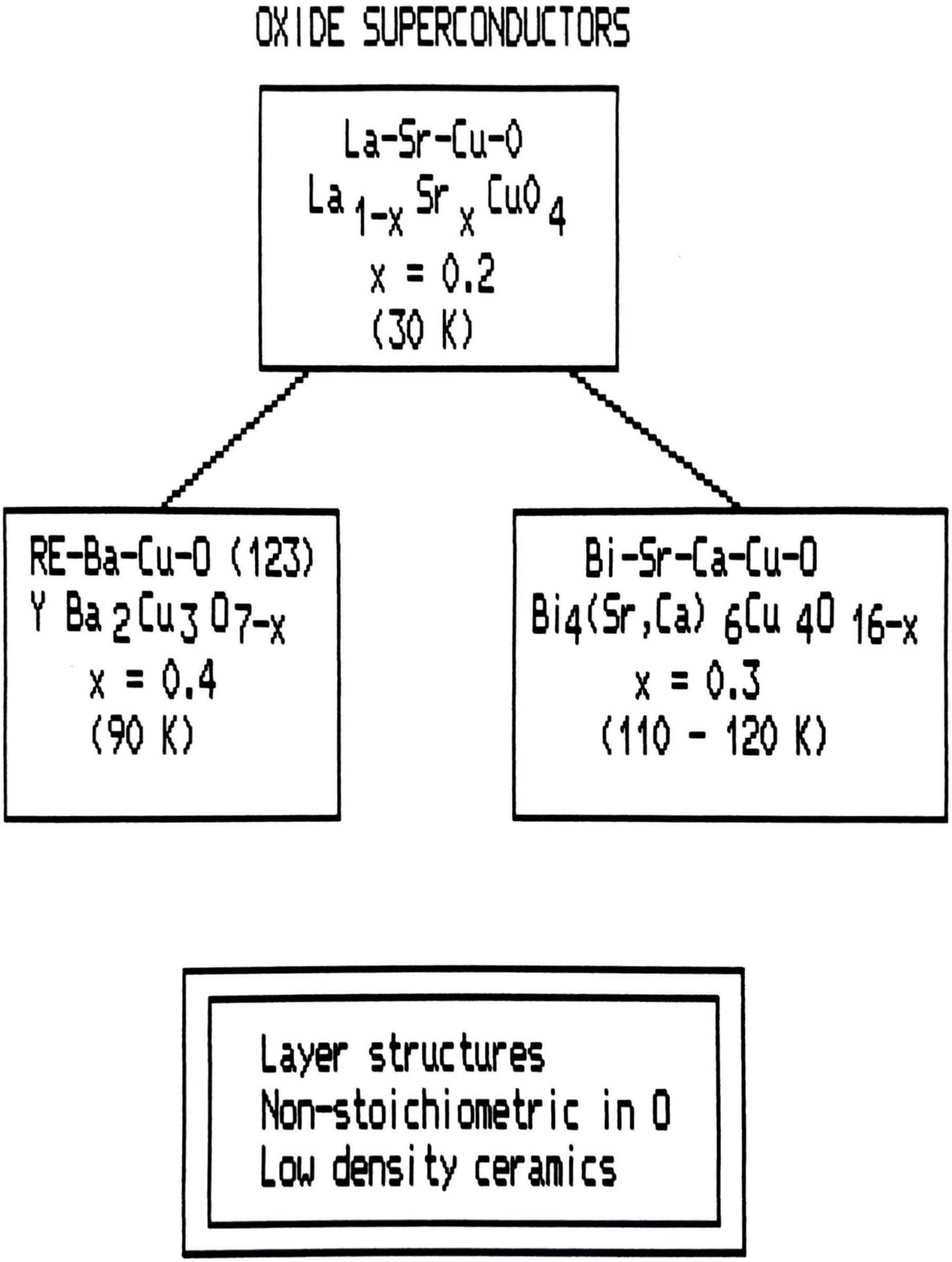


Figure 9: Classes of Superconductors

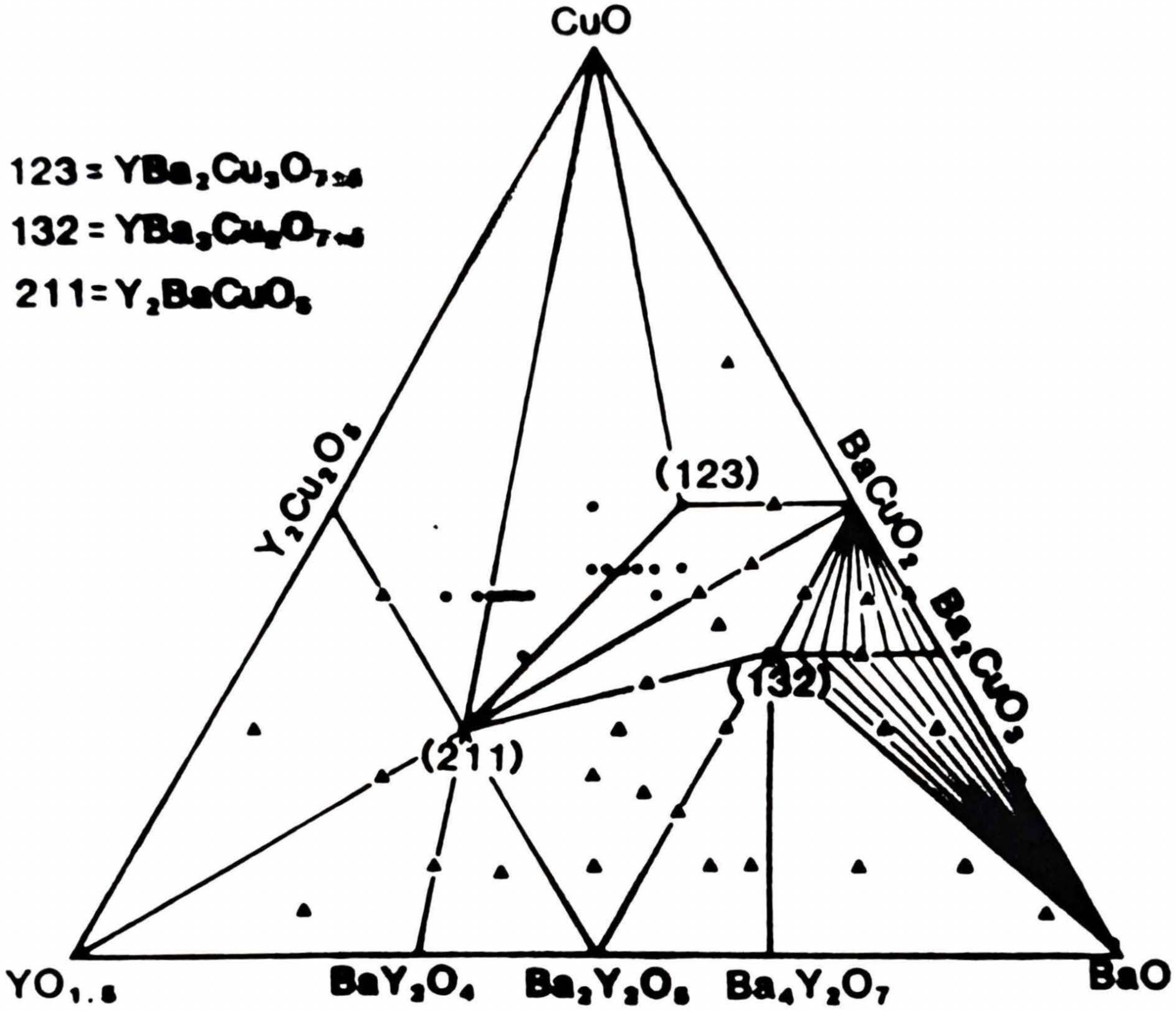


Figure 10: Phase Diagram for the Y-Ba_Cu-0 System [10]

$YBa_2Cu_3O_{7-\delta}$

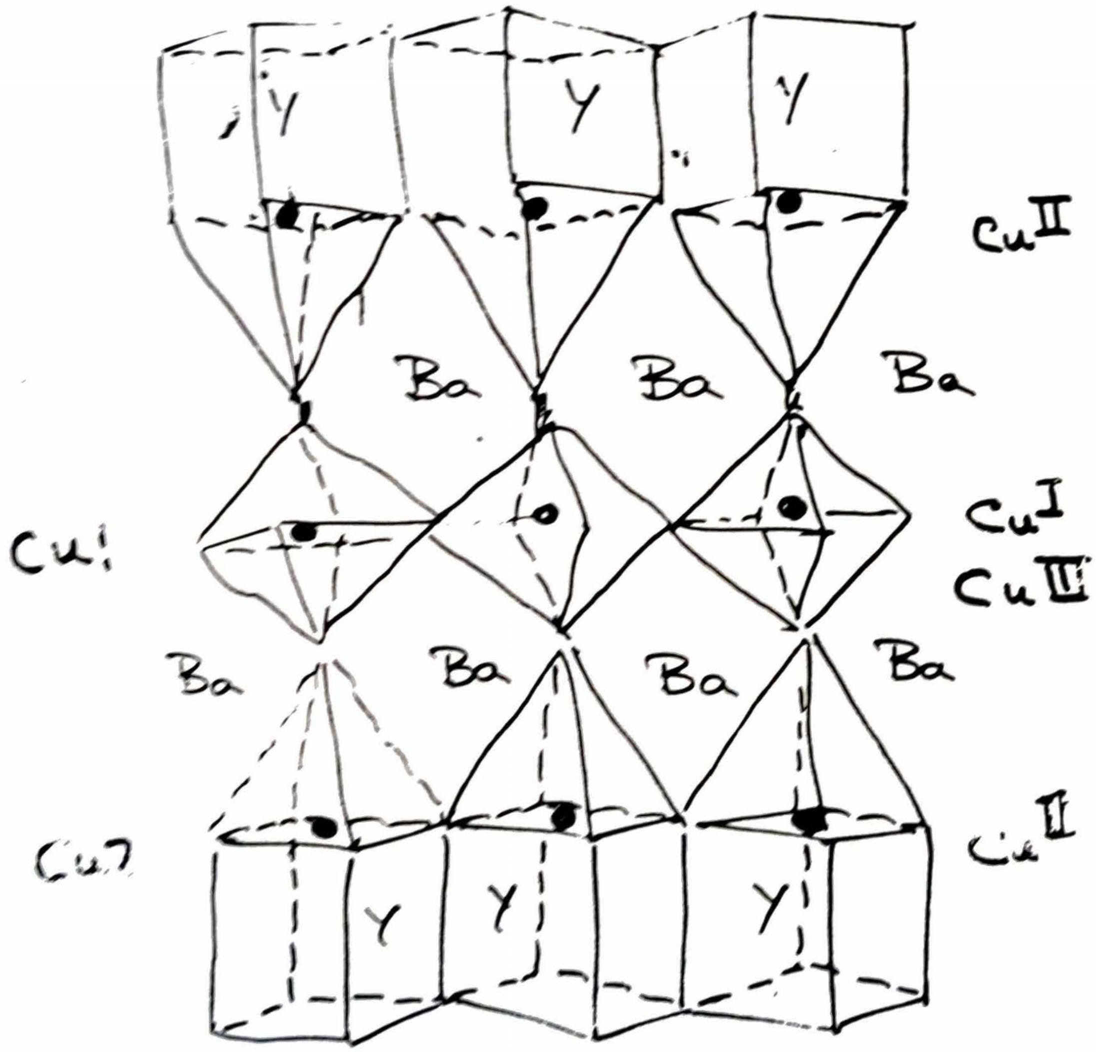


Figure 11: Illustrative structure of Y-Ba-Cu-O based on the NRC model [11]

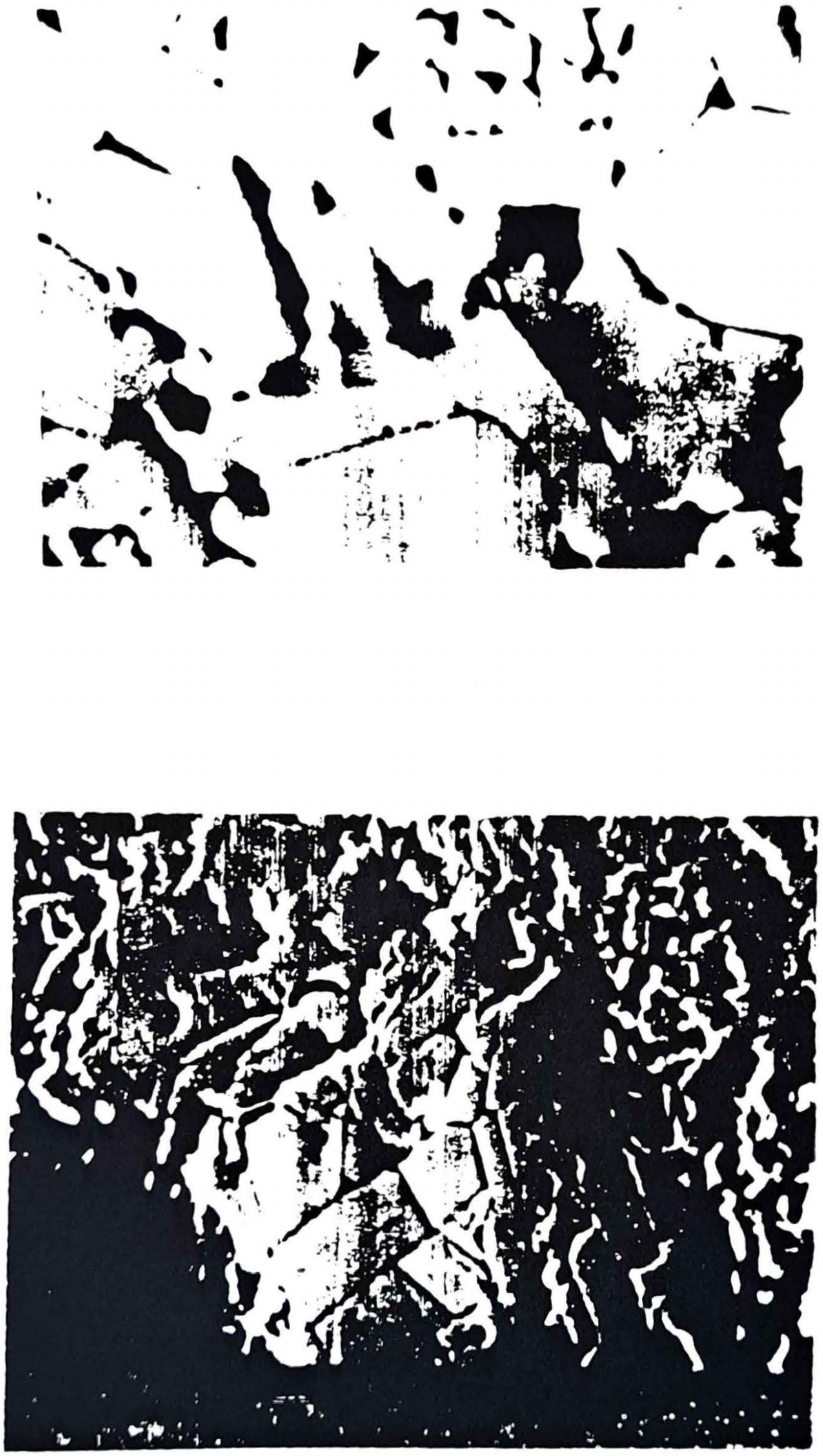


Figure 12: Gross Microstructure of Y-CuBa-O

High resolution electron micrograph along [100] or [010] projection typical of large extended regions of this material. In the regions of the defects, all horizontal mirror planes (seen in the undistorted region at the bottom of the image) disappear. This is evidenced by the arrowed traces of the prominent crystallographic planes in the image; only the vertical one represents mirror symmetry. [14]

Figure 13: Microstructure on the atomic level in Eu-Ba-Cu-O

e

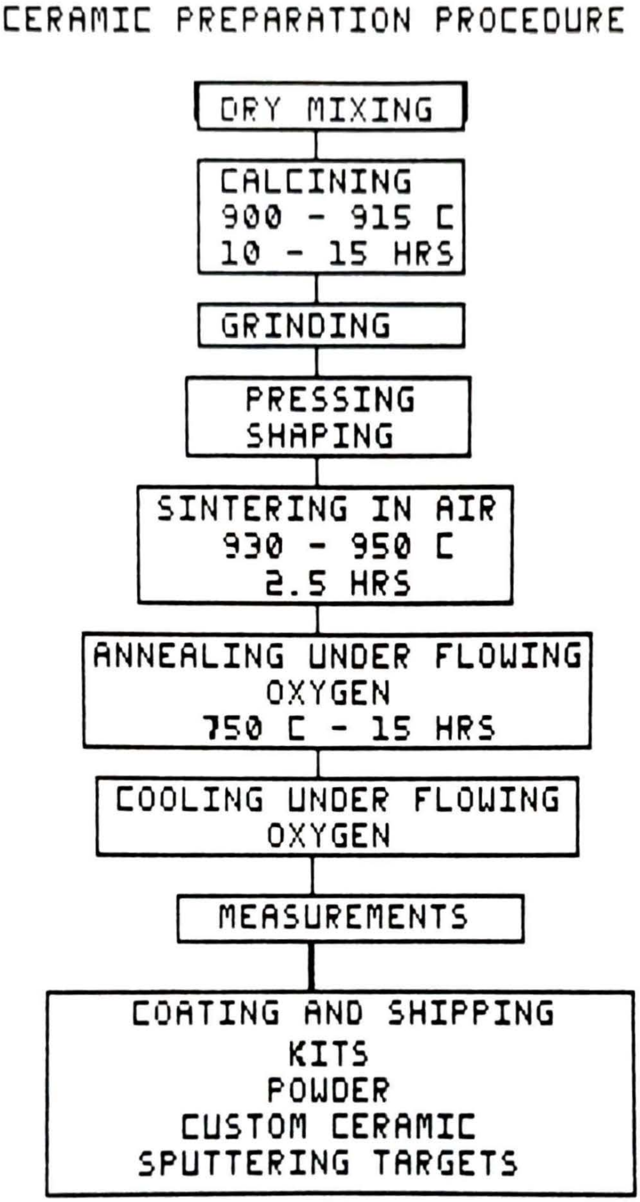
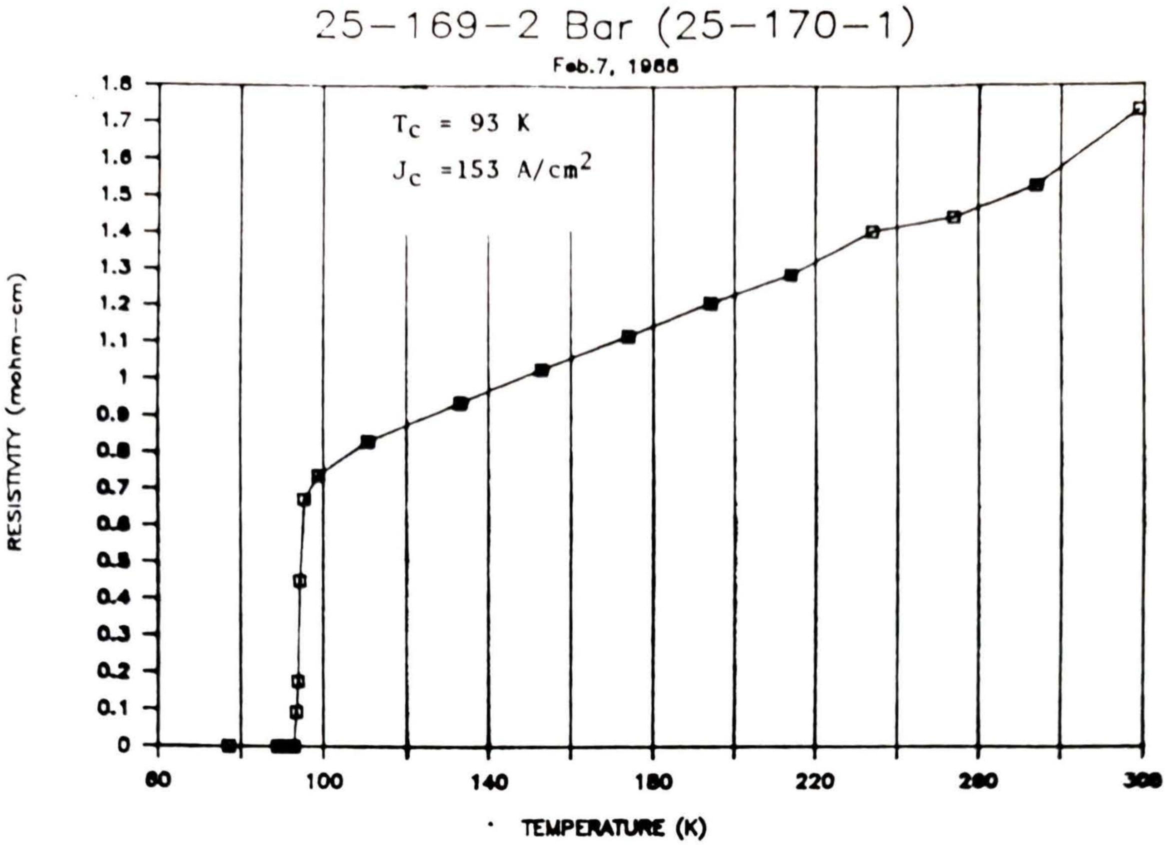


Figure 14: Ceramic Fabrication for Y-Ba-Cu-O



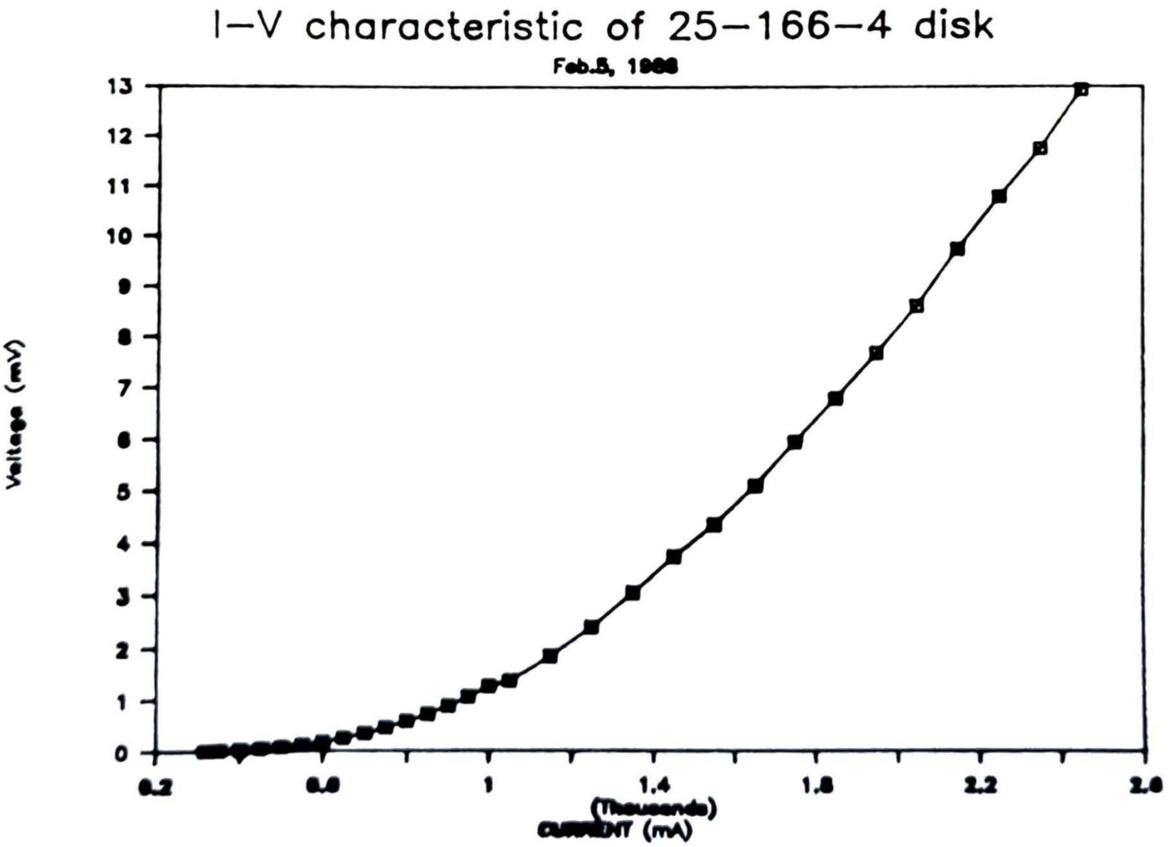


Figure 15: Resistance-Temperature and I-V Plots for Y-Ba-Cu-O

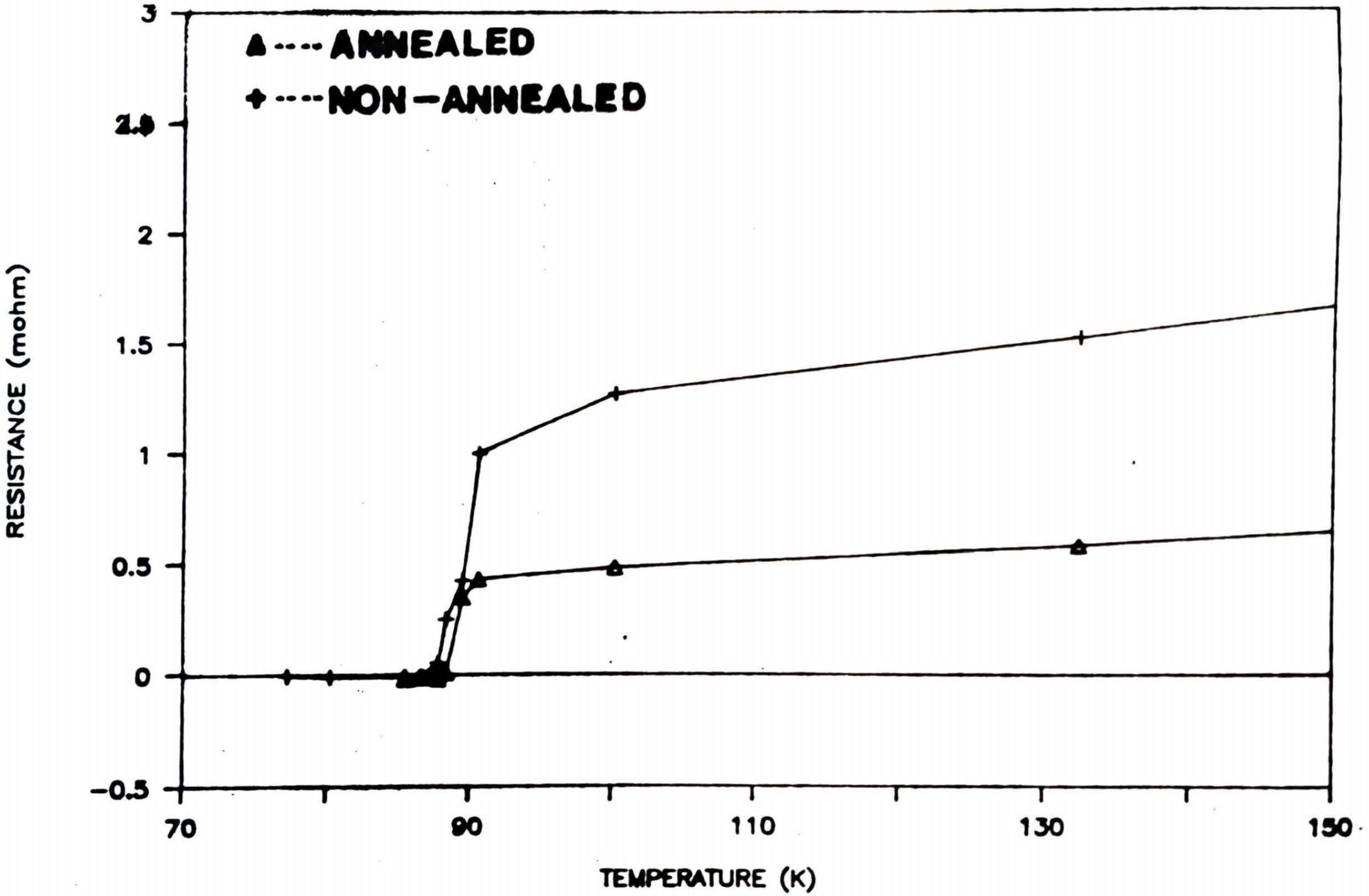


Figure 16: Effects of Annealing in oxygen on Y-Ba-Cu-O

SUPERCONDUCTING PROPERTIES

MATERIAL	FORM	T K	JC(A/CM^2)	HC (T)
TYPE I METALS SN/PB	BULK	7	10^5	0.1
TYPE II ALLOYS NB SN	BULK	20	$> 10^6$	10
Y-BA-CU-0	CERAMIC	93	10^2-10^4	50
	ORIENTED FILM	90	10^5	50
BI-SR-CA-CU-0	BULK	120	10^3	150

JC DECREASES WITHG INCREASING TEMPERATURE

Figure 17: Summary of superconducting properties for different types of superconductors

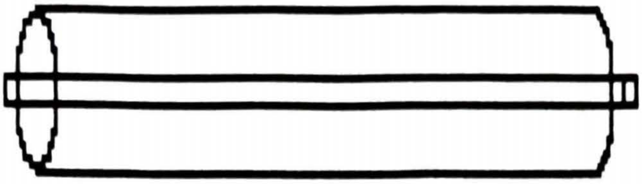
FABRICATION METHODS

METHOD	REFINEMENT
CERAMIC PROCESSING	DENSIFICATION GRAIN ORIENTATION CONTROLLED MICROSTRUCTURE BULK DEVICES
COMPOSITE TECHNOLOGY	METAL/CERAMIC POLYMER/CERAMIC WIRE EXTRUSION AND CLADDING ROLLED PRODUCTS EXPLOSIVE BONDING
PLASMA SPRAY	THICK FILM COMPONENTS LARGE AREA COATINGS R.F. SHIELDING
THIN FILM TECHNOLOGY -MAGNETRON SPUTTERING -LASER ABLATION -ION IMPLANTATION	VLSI INTERCONNECTS ELECTRONIC DEVICES (JOSEPHSON LOGIC) SQUIDS VOLTAGE STANDARDS

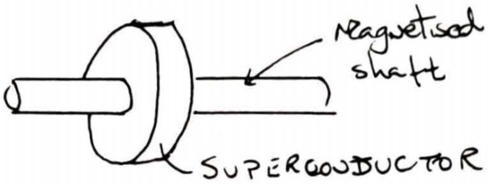
Figure 18: Fabrication Methods

APPLICATIONS : BULK CERAMIC

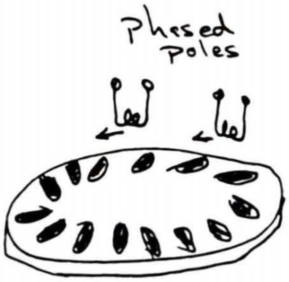
1. BULK CONDUCTOR - POWER TRANSMISSION

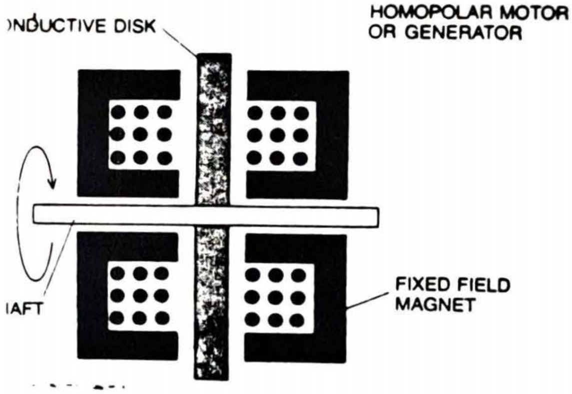


2. MAGNETIC BEARINGS - MEISSNER REPULSION



3. MOTOR STATORS AND ROTORS - GAIN OVER METAL ALLOYS?





REQUIREMENT: TOUGH, STABLE CERAMIC WITH HIGH JC
POWDER/COMPOSITE TECHNOLOGY

Figure 1·9: Applications of bulk superconductors

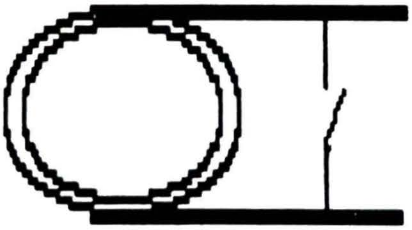
APPLICATIONS : WIRE AND CABLE

REQUIREMENT: FLEXIBLE, MECHANICALLY STRONG WIRE HAVING HIGH JC AND HC

PROBABILITY: METAL/CERAMIC POWDER COMPOSITE, POSSIBLY CLAD AND DRAWN. STABILITY AGAINST O LOSS REQUIRED.

INTEREST: MAGNET CABLE (1000A/CM2 - 10,0000A/CM2)

- NMR SCANNER COILS (40% OPERATING COST IN COOLANT)
- MINERAL PROCESSING MAGNETS
- LARGE FACILITIES FOR POWER STORAGE



- POWER TRANSMISSION CABLES *
- LEVITATION (EDDY CURRENT) *
- PARTICLE ACCELERATOR MAGNETS

Figure 20: Applications for wire and cable

MAGNETIC SHIELDING

METAL/SUPERCONDUCTOR OR POLYMER/SUPERCONDUCTOR SHEET

PLASMA SPRAYED PLASTIC

--- EXCELLENT FOR LOW FREQUENCIES

--- POORER FOR VHF DUE TO SKIN DEPTH AND AC LOSSES IN SUPERCONDUCTOR

--- IMPROVEMENTS POSSIBLY OBTAINED BY ALIGNED MICROSTRUCTURE.

MARKET: 1988/89 £5M - LARGE VOLUME PRODUCT

Figure 21: Applications for sheet products in shielding

APPLICATIONS: ELECTRONICS

REQUIREMENT: HIGH QUALITY THIN FILMS OF CONTROLLED COMPOSITION

FABRICATION: MAGNETRON SPUTTERING
ELECTRON BEAM DEPOSITION
PLASMA SPRAY/SOL GEL/CVD
ION BEAM IMPLANTATION

APPLICATIONS:

1. MAGNETIC SHIELDING

2. VLSI INTERCONNECTS

3. JOSEPHSON JUNCTION TECHNOLOGY

    A) LOGIC SWITCHES
    B) HIGH SPEED COMPUTERS

    C) MAGNETIC FIELD MEASUREMENTS
    D) VOLTAGE STANDARDS

    E) IR DETECTORS
    F) HIGH FREQUENCY MIXERS AND CONVERTERS

Figure 22: General Applications in Electroncs

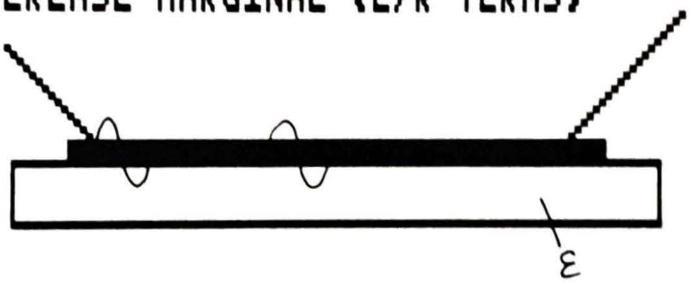
VLSI AND COMMUNICATIONS

THIN FILM TECHNIQUES - MAGNETRON SPUTTERING
- CHEMICAL DEPOSITION

A) POWER DISSIPATION/ LINE SHARPENING

- NEED HIGH JC MATERIALS
- CURRENT MATERIALS MARGINAL

B) SPEED INCREASE MARGINAL (L/R TERMS)



$$C = \frac{1}{\sqrt{\mu_0 \varepsilon \varepsilon_0}}$$

SPEED SET BY DIELECTRIC CONSTANT OF SUBSTRATE ε

Figure 23: Factors influencing transmission speed in VLSI

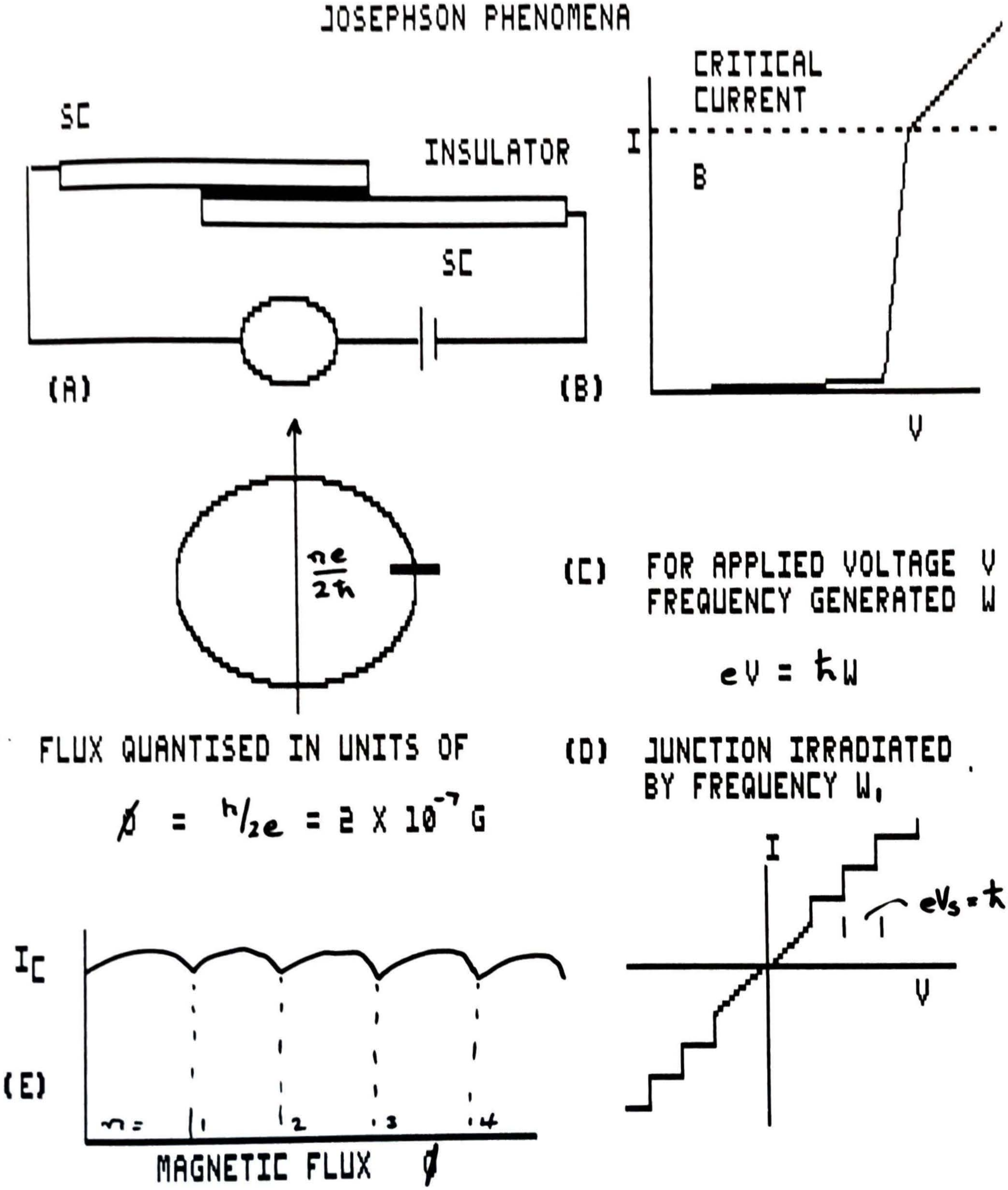
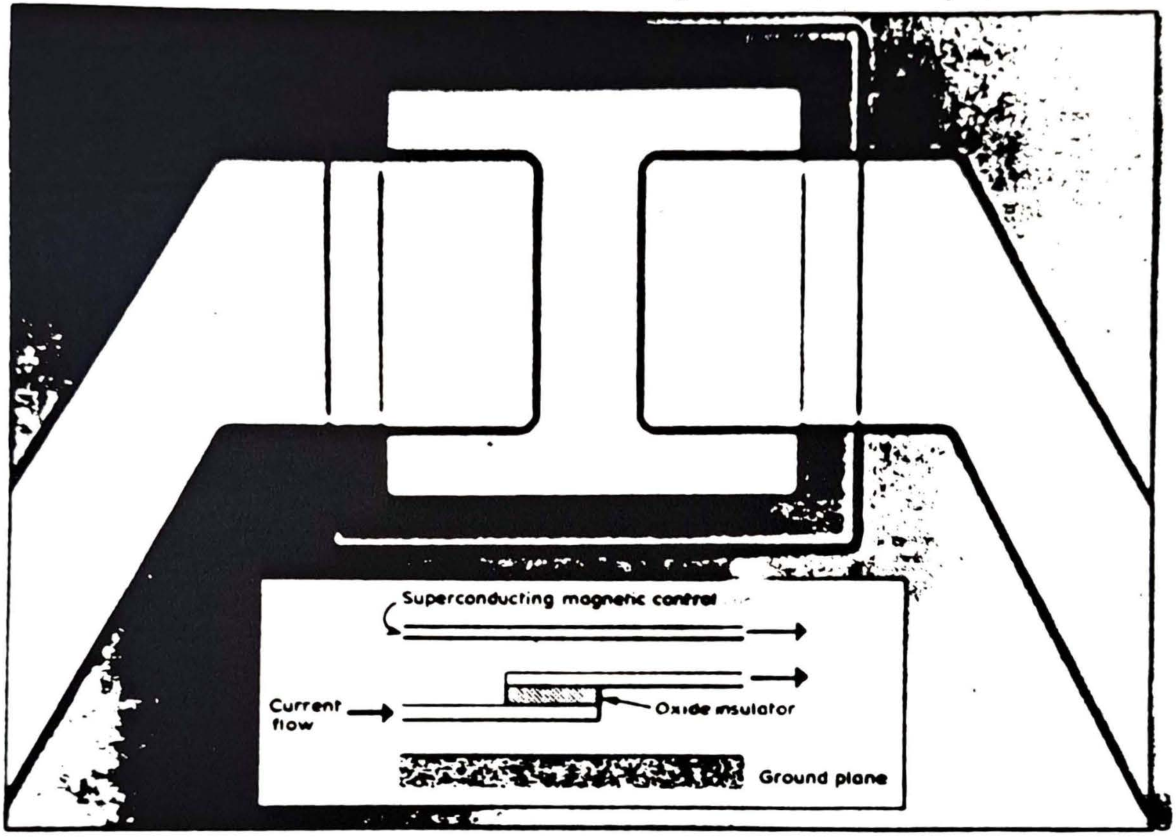


Figure 24: Electronics based on Josephson Junction technology



Inside a 25-micron square Josephson junction: when you apply a current to the electrodes, pairs of electrons tunnel through an insulating layer of oxide. Providing the temperature is low enough, the electrons create a superconductive current at the junction

Figure 25: Josephson logic junction (from reference 20).

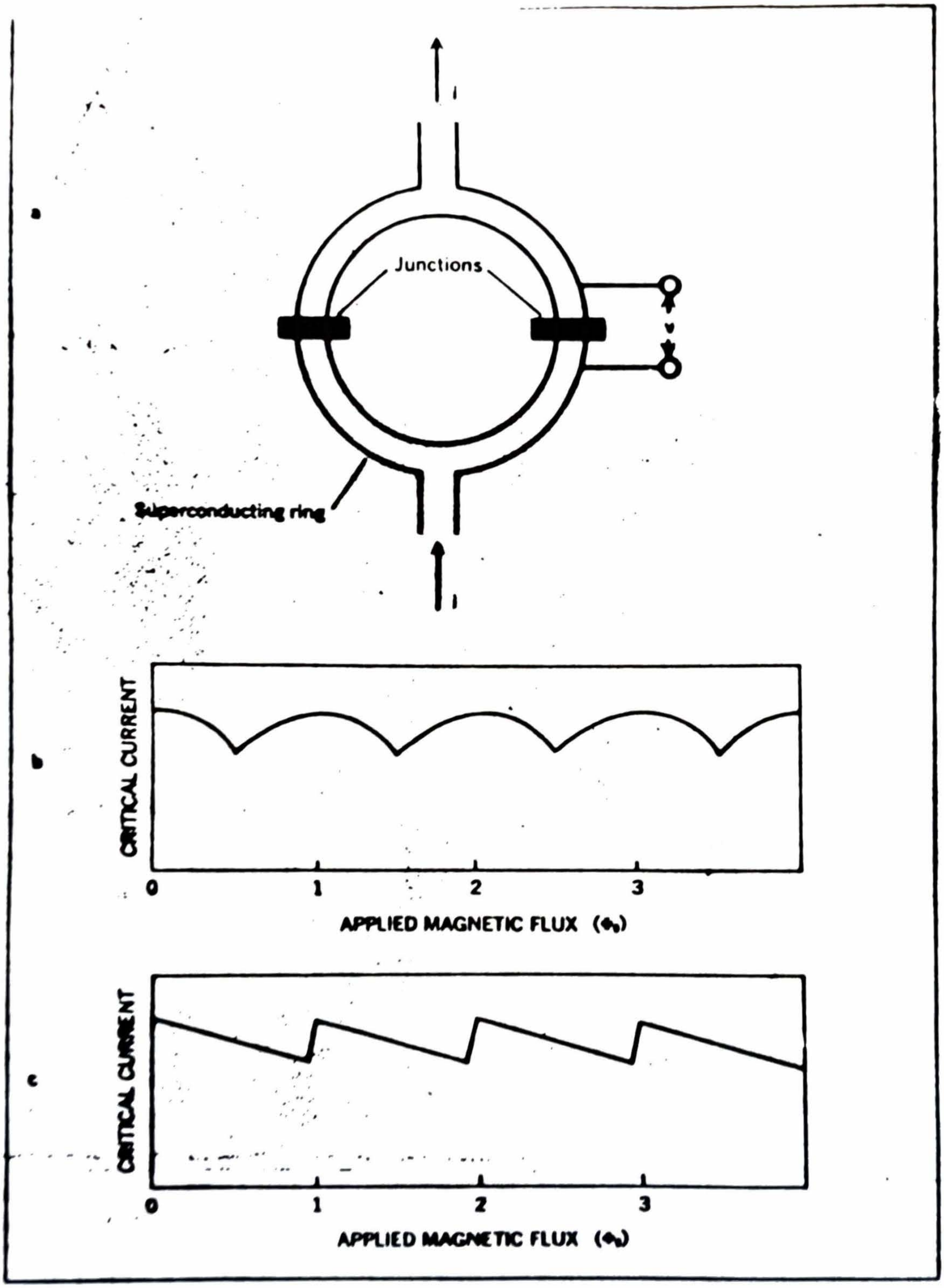


Figure 26: Superconducting Quantum Interference Device (SQUID)

WORLD MARKETS FOR SUPERCONDUCTORS: 1987-2002*

($ Millions)

	1987	1992	1997	2002
Integrated Circuits	$25	$75	$225	$400
Laboratory Instruments and Sensors	<5	25	125	200
Medical Diagnostics	150	300	500	750
High-Energy Physics	25	150	150	200
Electrical Power	5	10	20	40
Transportation	—	<1	5	10
Magnetic Separation	5	25	60	175
Total	$215	$586	$1085	$1775

*Source: *High-Tech Materials Alert*. Forecasts are for nitrogen- and helium-cooled superconductor electronic devices and/or magnets, including cooling systems.

Figure 27: World Markets for low and high Tc Superconductors

CONSORTIA AND RESEARCH GROUPS

CANADIAN UNIVERSITY INDUSTRY COUNCIL ON ADVANCED CERAMICS

ALCAN
ALMAX
SHERRITT GORDON
MAGHEMITE
CTF SYSTEMS
ONTARIO HYDRO
(50K EACH+ GOV'T MATCHING FUNDS)

MCMASTER
QUEENS
UBC
TUNS

- CERAMIC DEVELOPMENT/COMPOSITES
  THIN AND THICK FILMS

AECL/CANADA WIRE AND CABLE/IREQ ($6M)

- WIRE AND CABLE

ONTARIO CENTRE FOR MATERIALS RESEARCH

- SIX PROJECTS, PROPOSAL OUT FOR 10 COMPANIES AT 15K EACH+ GOV'T MATCHING

- BASIC SCIENCE

INDUSTRY

CTF SYSTEMS LTD - SQUID TECHNOLOGY
DEFENCE APPLICATIONS
BIOMEDICINE

ALMAX - EDUCATIONAL KITS
SPUTTERING TARGETS
CUSTOM POWDER

Figure 28: Consortia, research groups and industrial activities in Canada in 1988.