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Review Paper: The revolution of superconducting materials for industrial utilization

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Abstract

The property of materials that is characterized by zero electric resistivity and ideally zero permeability has become a phenomenological revolutionary concern among scientist and engineers. However, with recent advances in sample growth superconductors, researchers are able to study the concept of high temperature superconductivity. This has now achieved impressive accomplishments in the field of power utilities, electronics, military applications, medicine and transportation. This paper reviews the concept of superconductivity, and the promise it offers in the realization of efficient system development for various industrial applications and sustainable national development. It shows how employing the technology in manipulating the superconductive materials becomes feasible for industrial application. As the research in the superconducting materials continues, the applications of superconductors would become extensive and unlimited.

Introduction

The theoretical understanding of superconductivity is extremely complicated and involving. However, it is known to involve the loss of all the electrical resistivity and the development of diamagnetic qualities in materials. Materials such as lead and aluminium become superconductors when they are cooled down to a low-temperature usually a few degrees above absolute zero. New materials have recently been discovered, which become superconducting at much higher temperatures. Among such materials include ceramic materials [1]. To exhibit superconductivity, these materials still require special cooling equipment using liquid nitrogen to exhibit superconductivity.

Superconducting Materials

The distribution of superconducting elements as shown in the periodic table is enumerated in [2]. Some elements do not become superconducting at all and others become so only under pressure. The magnetic elements Mn, Fe, Co and Ni do not become superconducting down to the lowest temperature available.

The superconducting elements are classified into two:

(i) **Non-transition elements:** these are Si, Ge, P, As, Sb, Bi, S, Se and Te, which are not superconducting under normal condition but under pressure.

(ii) **Transition elements:** These have unfilled 3d, 4d and 5d shells.

Hence, the crystal structure plays an important role in the superconducting state. Accordingly, superconducting materials are those used partly or wholly in the manufacture of superconducting devices. They perform their functions in the superconducting state that would be difficult or impossible to perform at room temperature, or that contain components, which perform such functions. The superconducting state involves a loss of electrical resistance and occurs in many metals and alloys at temperature near absolute zero.

Technology Status of High Temperature Superconductivity

Much of the research and development of high temperature superconductivity (HTS) is focused on the wire and the system development. High temperature superconductivity wire must be flexible, strong and capable of carrying large current in a magnetic field. HTS requires long length of wire and effective component.

The key to making HTS wire and, in turn, systems that are commercially viable, is to optimize critical current, operating temperature, field and cost. Critical current is the amount of current a given wire can carry without losing superconductivity. It is measured as critical current, I_c or critical current density, J_c. Critical current density is simply the total amount of critical current a wire can carry, divided by the cross-sectional area of the superconductor. Goals for critical current are 100-1000 amperes. Goals for critical current density are 10,000-100,000 amperes per square centimeter [3].

The anticipated range for HTS operating temperature, though depending on the application is 4.2K to 77K. Super-conducting devices also require tolerance to surrounding magnetic fields and are able to operate in fields of 2-5 tesla [3].

Superconductivity and the Future

Scientists had been intrigued with the concept of superconductivity since its discovery in the early 1900's but the extreme low temperatures the phenomenon required was a barrier to practical and low-cost applications. This notion changed in 1986 when a new class of ceramic superconductors was discovered [4]. The science of HTS was born, and along with it came the prospect for an elegant technology that promises to "supercharge" the way energy is generated, delivered and used.

High temperature superconductivity is a recent innovation from scientific research laboratories. The work of comercialization centers on the development of new products and engineering needed to implement the new technology. Application of new high-temperature superconductors will be in not too distant future. But still, time lags between the new discovery and the practical applications are often great. For example, the discovery of laser in the early 60's has only recently been appreciated through applications such as laser surgery; laser optical communications and compact disc players. The rapid progress in the field of superconductors led one to believe that applications of superconductors are limited only by one's imagination and time. While low temperature superconductors are expected to continue to play a dominant role in the field of scientific research, advances in high temperature superconductors is expected to enable the development of newer industries.

Figure 1 culled from International Superconductivity Industry Summit, (ISIS) [5], gives a rough breakdown of the various markets in which superconductors are expected to make contribution between the years 1995 and 2020.

It seems that this singular phenomenon in which electrical resistance becomes negligible in certain materials at extremely low temperatures could be about to revolutionize the delivery of electricity [6]. All of this is, of course contingent upon a linear growth rate. Should new superconductors with high transition temperature be discovered, growth and development in this exciting field could explode virtually overnight.

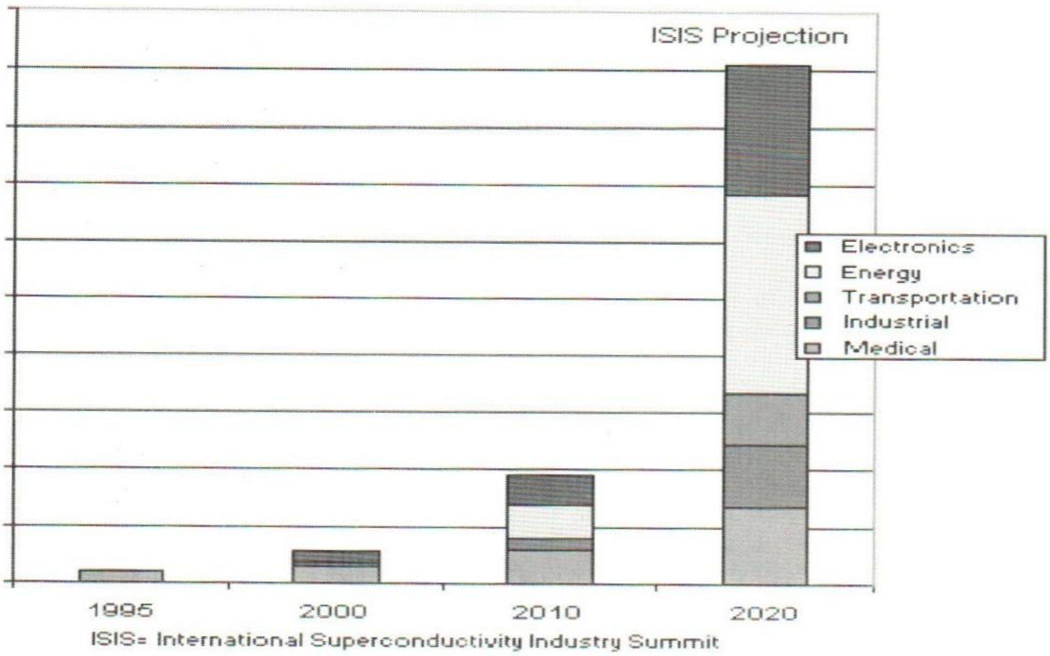

Fig 1: Rough breakdown of the various markets in which superconductors are expected to make contribution. (Source: energy efficiency and renewable energy network, EREN website). [5]

AREAS OF APPLICATIONS OF SUPER-CONDUCTIVITY

Power Utilities:

Electric power generation has emerged as one of the most promising areas of application of superconductivity.

Electric generators made with super-conducting wire are far more efficient than conventional generators wound with copper wire. In fact, their efficiency is above 99% and their sizes about half that of conventional generators [5]. These facts make them very attractive ventures for power utilities. General Electric of USA is currently developing 100 MVA prototypes to confirm the viability of the use of superconductors.

Recently, power utilities have begun to use superconductor-based transformers and "fault limiters". For instance, the Swiss Swedish company ABB has developed 6.4MVA fault current limiter- the most powerful in the world.

In one-instance 113.398 kg (250 pounds) of superconducting wire replaced 8164.663 kg (18,000 pounds) of vintage copper cable, making it over 7200% more space efficient.

An idealized application for super-conductors is to employ them in the transmission of commercial power to cities. However, due to high cost and impracticability of cooling miles of superconducting wire to cryogenic temperature this has only happened with short "test runs".

Superconducting Microchips

Various universities and professional organizations in developed world are currently trying to develop "petaflop" computer [7, 8]. A petaflop is a thousand trillion floating-point operations per second. Today's fastest computing simulator is reportedly running at 35.6 teraflops per second [8]. It has been conjectured that devices of the order of 50 nanometers in size along with unconventional switching mechanisms, such as Josephson junction associated with superconductors will be necessary to achieve these blistering speeds. Researchers have quantified this further by predicting that 100 billion Josephson junctions on 4000 micro-processors will be necessary to reach 32 petabit speeds. These Josephson junctions are incorporated into field effect transistors, which become part of the logic circuits within the processor [9]. Recently, it was demonstrated that the tiny magnetic fields that penetrate type 2 superconductors could be used for storing and retrieving digital information. It is however envisaged that computer of the future will be built around superconducting devices.

In late February 2000, Irvine Sensors Corporation received a contract to research and develop a superconducting digital router for high-speed data communications [10, 11]. Since internet traffic is increasing exponentially, superconductor technology is capable of meeting this need.

In the area of electronics industry, ultra high performance filters are now being built. Since superconductivity wire has near zero resistance, even at higher frequencies many more filter stages can be employed to achieve desired frequency response [12]. This translates into an ability to pass desired frequencies and block undesirable frequencies in applications such as in cellular telephone systems.

Military Applications

Superconductors have also found widespread applications in the military. The US navy is using HTS SQUIDs (Super-conducting Quantum Interference Devices) to detect mines and submarines. Also, significantly smaller motors are being built for navy ships using superconducting wire and tape. In mid July 2001 [13], American superconductor unveiled a 5000-horse power motor made with superconducting wire [14].

The military is also looking at using super-conductive tape as a means of reducing the length of very low frequency antennas employed in submarines. Normally, the lower the frequency, the longer the antenna.

However, inserting a coil of wire ahead of the antenna will make it function as if it were much longer. Unfortunately, this loading coil also increases system losses by adding the resistance in the coil's wire. Using superconductive wire can significantly reduce losses in this coil as well as making possible the use of an even-shorter length of antenna wire.

The most ignominious military use of superconductors may come with the deployment of E-bomb. These are devices that make use of strong, superconductor-derived magnetic fields to create fast, highintensity electro-magnetic pulse (EMP) to disable an enemy's electronic equipment [13].

Biomedical Application

An area where superconductors can perform a life-saving function is in the field of biomagnetism. The concept of magnetic resonance imaging (MRI) that was discovered in 1940 has only recently become an indispensable medical tool with the development of powerful computers to quickly process a large volume of data in determining what is going on inside the human body.

Transportation

Magnetic levitation is an application where superconductors perform extremely well. Transport vehicles such as trains can be made to "float" on strong superconducting magnets, virtually eliminating friction between the train and its track.

Figure 2 depicts a summary of the present and potential application of HTS. It could be obversed from the figure that the application of superconductors is only just beginning.

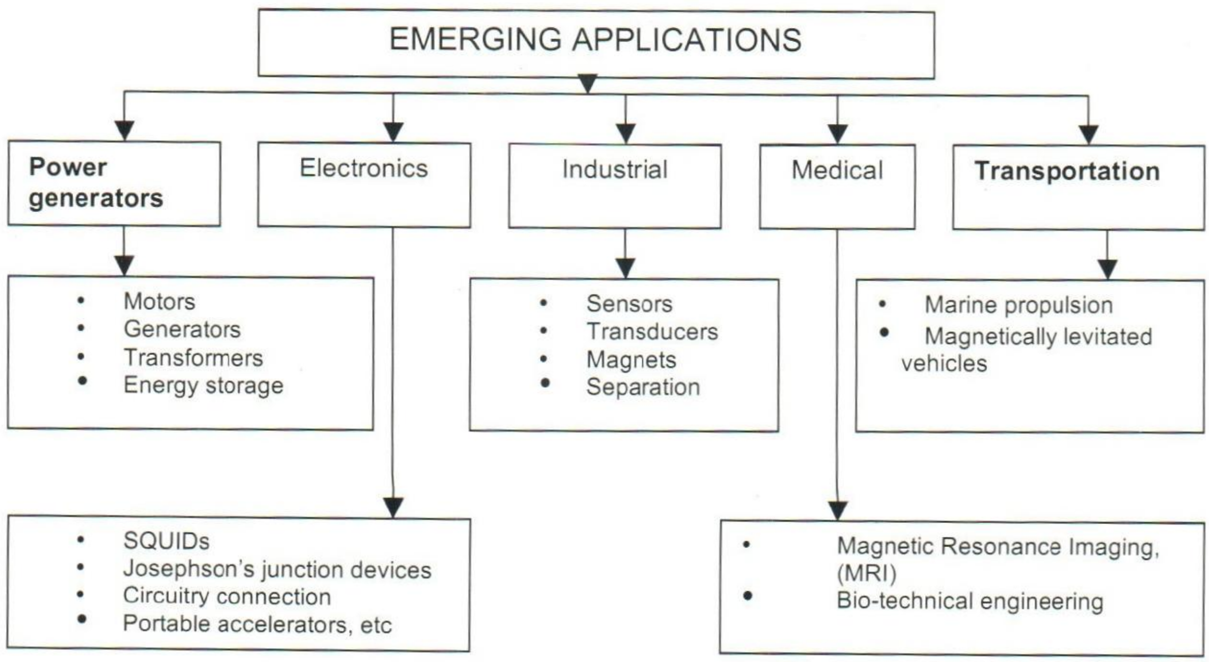

Fig. 2: **Present and Potential Applications of High Temperature Superconductivity**

Superconductivity for Electric System

At the heart of high temperature superconductivity lies a promise of transmitting electrical energy with near perfect efficiency and much higher capacity. Associated benefits include:

(i) More electricity would reach consumers and perform useful work.
(ii) Has non-greenhouse gas: hence is environmentally friendly
(iii) Improves energy reliability and capacity
(iv) Cuts transmission losses by half

(v) Electrical equipment could be reduced in size dramatically, which opens more potential site applications [15].

(vi) Improved efficiency for the performance.

Conclusion

As our understanding of the properties of superconducting materials improves, applications such as power transmission, superconducting magnets in generators, energy storage devices, particle accelerators levitated-vehicle transportation, rotating machinery and magnetic separators will become more realistic and practical. Superconductors however, may even play a significant role in Internet communications soon. However, should the trend continue, then most of the books in electrical engineering would have to be re-written.

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