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New Superconducting Material MgB_2 and the Trends in Research and Development

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7.1 Introduction

The discovery of the superconductivity of magnesium diboride (MgB_2) by Professor Jun Akimitsu's group of Aoyama Gakuin University was announced for the first time to the participates at a study meeting in Sendai (January 10, 2001), and the news spread all over the world before the report appeared in the scientific magazine Nature (March 1, 2001). Since then, intensive research has been made worldwide and fundamental data are being published in succession.

The superconducting critical temperature of MgB_2 is 39K, which is higher than the temperature range of 20 to 30K that has been considered to be the limit for metallic superconductors.Therefore, it is very likely that it can be used at temperatures relatively easily attainable using refrigerators (about 20K)*[1], and its practicality is attracting researchers' attention.

This paper outlines the past research and development in superconductivity, and then reviews, relating to MgB_2, the characteristics and possibilities of application that have been elucidated, and the situation of domestic and overseas research and development.

7.2 Trends in past research and development on superconductivity

7.2.1 History of the discoveries of superconducting materials

In 1911, the physicist, Kamerlingh Onnes, discovered superconductivity (mercury, critical temperature 4K) for the first time. Since then, critical temperatures of metallic superconductors (generally having low critical temperatures and referred to as low temperature superconductor LTS) have been raised over many years and reached 23K (Nb_3Ge) in the 1970s. NbTi used for the magnetic resonance imaging apparatus (MRI) is one of the LTSs.

On the other hand, the high temperature super conductor (HTS) was discovered by Bednorz and Muller of the IBM Zurich Laboratory in 1986, and the critical temperature was raised up to 130K (mercury compounds) within several years. No material having a critical temperature higher than

Chart 1: Superconducting materials that have been discovered recently

1980	D. Jerome and co-workers of University Paris-Sud found the superconducting organic material, $(TMTSF)_2PF_6$
1986	Bednorz and Muller of the IBM Zurich Laboratory found an oxide high temperature superconductor.
1991	A. F. Hebard and co-workers in University of Florida found the superconductivity of a fullerene (C_{60}). (C_{60} doped with potassium)
November 2000	B. Batlogg's group of Bell Laboratories announced that they had discovered the superconductivity of C_{60} having a field-effect transistor (FET) structure (critical temperature: 52K). At the same time, it was reported that polycycle aromatic hydrocarbons such as anthracene, pentacene, and tetracene as well as polymer, polythiophene show superconducting transition.
March 2001	J. Akimitsu's group of Aoyama Gakuin University officially announced that MgB_2 undergoes transition to superconducting state at 39K.
April 2001	S. Uji and colleagues of the National Institute for Materials Science reported that λ-$(BETS)_2FeCl_4$ showed the magnetic-field-induced superconductivity in the magnetic field of 18T or higher.

Prepared by the Science and Technology Foresight Center that has been found since then. High temperature superconductors that are being developed aiming at practical use at the liquid nitrogen temperature of 77K are mainly the bismuth compounds (critical temperature: 110K) and the yttrium compounds (critical temperature: 92K).

Search for the superconductivity of organic materials began on a full-scale in the 1970s, and $(TMTSF)_2PF_6$ was the first organic material to be found as a superconductor. Since then, many superconducting organic materials have been synthesized and the highest critical temperature that has been attained so far is 12K. Then, the superconductivity of fullerenes was discovered in 1991, and the present highest critical temperature is 33K of $PbCs_2C_{60}$. Recently, the C_{60} having a field-effect transistor structure has become the focus of attention due to its superconductivity transition at the critical temperature of 52K.

7.2.2 Research on applications

Research works on applications of LTS and HTS materials are being conducted mainly for the following uses.

(1) Electric power system

For energy saving and stabilization of electrical power systems, electrical power cables, transformers, superconducting magnetic energy storage system(s) (SMES), and superconducting bearings for the flywheel electrical power storage system are being developed using superconducting materials.

(2) Superconducting magnet for MRI and NMR (nuclear magnetic resonance)

Products using LTS wires made of NbTi and Nb_3Sn are on the market, and LTS and HTS wires required for superconducting magnets used for NMR under 20T or higher are being developed.

(3) Information device and filter

The single flux quantum (SFQ) device, which is expected to contribute to the information technology devices of the next generation that realize fast operation, and superconducting receiving filters used for receiver front ends for base stations of portable telephone systems are being developed.

(4) Sensor

It is being studied to apply SQUID*2 using LTS to high-sensitivity magnetic flux meters, high-resolution X-ray analyzers, and high-sensitivity mass spectrometers used for LSI inspection, etc.

(5) Magnetic separation

Magnetic separation and purification equipment used for water purification and removal of environmental hormones are being developed making use of strong magnets of HTS bulk material and superconducting magnets.

Hopes are set on HTS materials for their high performance and economical merits. As a strategy taken in the actual research projects on the application of HTS materials, however, equipment is first developed using LTS materials available at the time of development and then the LTS materials are replaced by HTS materials when they become available.

As for the developments of superconductivity technologies by private companies, venture businesses play an important role in the U.S., and large companies are at the center of development in Japan. In Europe, both large companies and venture businesses are involved.

7.2.3 Trends in research and development in Japan

At universities, search for new superconducting materials and development of devices, wire making technology, and equipment related to electrical power systems are being conducted. At the National Research Institute for Materials (now reorganized as the National Institute for Materials Science), development of Nb_3Sn wires used for generating a high magnetic field of 10T or more and search for bismuth compound HTS are being carried out, and the HTS wire technology and the first 900MHz-MNR in the world are aimed at in a multi-core project sponsored by the Ministry of Education, Culture, Sports, Science and Technology (former Science and Technology Agency).

At the International Superconductivity Technology Center (ISTEC), jointly established by the Ministry of Economy, Trade, and Industry (former Ministry of International Trade and Industry) and private companies, research and development on basic physical properties, electrical power systems, information devices, and bulk materials are being carried out.

For these 10 years, superconducting wires have been developed under the leadership of electric cable manufacturers such as Furukawa Electric Co. and Kobe Steel. Recently, however, tests conducted on 100m long HTS power transmission cables have been started jointly by the Central Research Institute of Electric Power Industry, Tokyo Electric Power Co., and Sumitomo Electric Industries.

Among the progressing developments of superconductivity devices carried out mainly by electrical and communication companies are: HTS Josephson device by Toshiba Corp., HTS magnetic sensor by Sanyo Denki Co. and Sharp Corp., AD converter using a single flux quantum (SFQ) device operating at 100GHz by Hitachi.

The present large market for superconducting products is that of superconducting magnets used for NMR and MRI. LTS materials such as NbTi and Nb_3Sn are used for this application, and the market value is estimated at ¥10 billion per year[*3]. Although the quality of LTS wires produced in Japan is at the top level of the world, price competition is very keen.

7.3 Superconductivity of magnesium diboride (MgB_2)

The news of the super conductivity of MgB_2 attracted the attention not only of superconductivity researchers but also of the mass media. The critical temperature of MgB_2 is not so high as those of copper oxide superconductors referred to as yttrium compounds and bismuth compounds, which are 90K to 110K. However, it is worthy of note that a superconducting material, which has a relatively high critical temperature, has been found in addition to copper oxides.

7.3.1 Basic physical properties of MgB_2 and mechanism of superconductivity

Research to clarify why MgB_2 has relatively high critical temperature is being conducted intensively worldwide. It has important meaning to consider whether similar materials having higher critical temperatures exist.

MgB_2 was first called a "metallic superconductor" because its superconductivity was attributed to the BCS mechanism, which is brought about by the interaction between the lattice vibration and electrons in the same way as metallic superconductors (LTSs), such as NbTi that has been put to practical use. For the BCS mechanism, the upper limit of the critical temperature has been considered to be 20 to 30K. It is now the focus of discussion, therefore, whether the superconductivity of MgB_2 is on the extension of the BCS mechanism or attributed to the magnetic interaction mechanism used for the explanation of HTS, or it is attributed to a new mechanism.

If the BCS mechanism is assumed, the critical temperature is considered to decrease as the result of the decrease in the vibration energy of lattice when the ^{10}B is replaced by the isotope of

Chart 2: Position of MgB_2

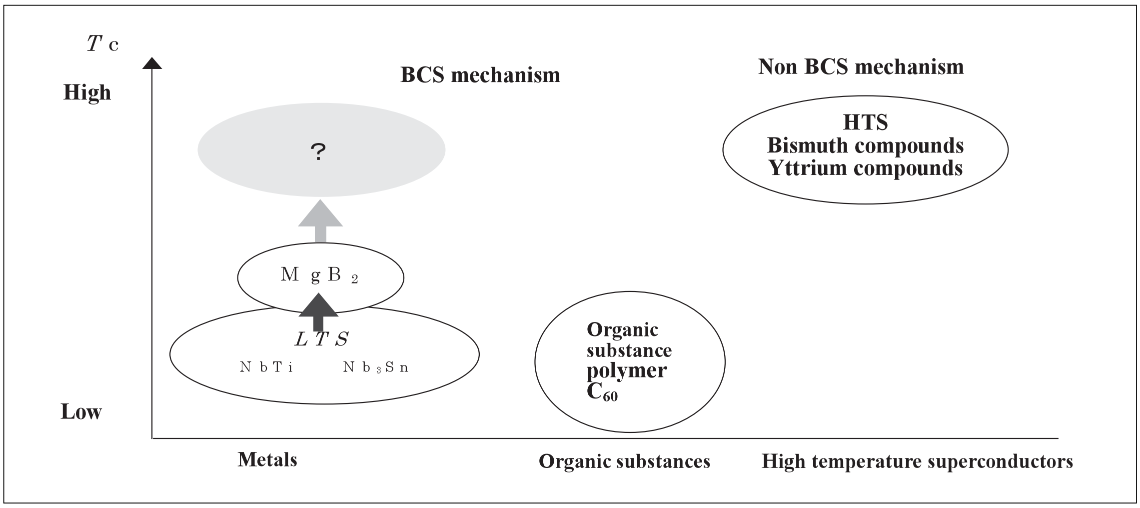

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Chart 3: Applications of superconductivity and materials used

Applications of superconductivity	Materials (use temperature)		
Power cable		HTS (77K)	
SMES	LTS (4K)	HTS (77K)	MgB_2 (20K)
Magnet for MRI	LTS (4K)		MgB_2 (20K)
High field magnet for NMR	LTS (4K or lower)	HTS (4Kor lower)	
Magnet for accelerator and nuclear fusion	LTS (4K)		MgB_2 (4K)
Linear motor car		HTS (77K or lower)	MgB_2 (20K)
Information technology device	LTS (4K)		MgB_2 (20K)
Sensor	LTS (4K)		MgB_2 (20K)
Bulk material (magnet)		HTS (77K)	

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^{11}B. Experimental results have shown that the critical temperature decreases by about 1K, which is half the expected value. Taking some other experimental results into consideration, many researchers so far consider that the superconductivity of MgB_2 is attributed to the BCS mechanism.

7.3.2 Possibilities of applications

Chart 3 summarizes the applications of superconductivity that already exist or are under development and materials used for the applications. Possible applications for MgB_2 are also listed. It is shown in the chart that MgB_2 has possibilities for application in a wide range of fields. The reasons why MgB_2 is the focus of attention are: i) it may be possible to use at the temperature of 20K, which is attainable by refrigerators; ii) production cost is significantly low compared to HTS wires that require silver sheaths to compensate for the brittleness and to align the direction of HTS crystals; and, iii) wires with high strength are expected. Due to these favorable characteristics, applications to SMES, to which a large stress is applied, accelerators, and magnets used for nuclear fusion are expected.

Important characteristics required in the applications are: critical temperature (T_C); critical magnetic field (B_{C2}); and, critical current density (J_C). If the value of J_C reaches 100kA/cm^2 in a magnetic field, it can be used as a material for electromagnets.

In July of this year, the National Institute for Materials Science announced that they had developed superconducting wires. According to the report, the wires were formed after filling a stainless steel tube with MgB_2 powder, and the value of J_C in a magnetic field (1T) was about 450kA/cm^2 at 4K and about 100kA /cm^2 at 20K without giving heat treatment. Since B_{C2} and J_C are improved by the method of fabrication and the addition of trace elements, the properties of MgB_2 are expected to be improved.

7.4 Trends in research on MgB_2 in Japan and overseas

Immediately after the discovery of the superconductivity of MgB_2 was announced at a meeting, many papers on the superconductivity of MgB_2 began to be published by registering to the print servers[*4] of Los Alamos National Laboratory, Iowa State University of the U.S., and Aoyama Gakuin University. The number of papers published only through the server at Iowa State University has been confirmed as 202 by the end of May. Among theses papers, the number of those sent from Japan accounts for 10% to 20%, which is low compared to the situation after the oxide superconductivity was found in 1986.

7.4.1 Research and development in Japan

(1) Research on superconductivity characteristics

Search for superconducting materials mainly by adding third elements to MgB_2 and by studying related borides and boron carbides, and studies on the superconductivity characteristics are being conducted by many universities and the National Institute for Material Science.

(2) Research and development on wire production

The National Institute for Material Science is conducting research on wire production. Although Japanese wire producers are conducting research on wire production technology, they are rather conservative about the actual use because MgB_2 can not be used by cooling with liquid nitrogen and the characteristics (J_C and B_{C2}) are somewhat inferior to those of LTS and HTS[*5].

(3) Research on superconducting devices

NEC has started to develop single flux quantum devices (SFQ) using MgB_2. The reason is that MgB_2 is favorable in operation cost because it can be used at higher temperatures compared to the SFQ devices that use LST niobium.

Since the superconductivity characteristics are better than those of HTS, the performance is expected to be improved, and, in addition, the quality of thin films will be easily improved due to its simple crystal structure.

7.4.2 Overseas research and development

(1) Research on superconductivity characteristics

Studies on superconductivity characteristics, wire production, and production of thin films are being made in earnest.

High-quality thin films and improvement of superconductivity characteristics by the addition of oxygen have been reported by Pohang University of Korea and Wisconsin University of the U.S., respectively. Papers on basic studies including superconductivity characteristics have been published mainly from universities in the U.S. and Europe, and some from Korea, China, etc.

(2) Research and development on wire production

Noteworthy results relating to the characteristics of wire have been reported by Ames Laboratory, Agere Systems[*6] of Lucent Technologies, and Imperial College of U.K. in Europe. U.S. wire producers have started to develop the technology to produce wires of borides for MRI and SMES, considering the possibility of new superconducting borides that surpass MgB_2 in performance, but they are still taking a prudent attitude about commercialization. The technologies to produce wire including the one that has been developed for the production of brittle oxides are considered to be possibly applicable to boride materials[*5].

(3) Research on superconducting devices

Research and development on SQUID and Josephson devices using MgB_2 are being conducted in the Netherlands and the U.S. Particularly, Twente University of the Netherlands confirmed the action of SQUID using the weak linkage of nano-structure (70nm × 150nm × 150nm), which shows the possibility of high integration.

7.5 Conclusion

The discovery of the superconductivity of MgB_2, having a high critical temperature for a metallic superconductor, was very important also from the viewpoint of basic science. Because MgB_2 has a simple crystal structure, fabrication is easy and it has strong possibilities for practical applications. In the future, compounds consisting of light elements will be one of the fields to which priority should be given. Clarification of the mechanism of the superconductivity of MgB_2 will bring about ways to discover new materials that have still higher critical temperatures and enables to promote the search and application studies more strategically.

The study of MgB_2 was started by Japanese researchers and provides many possibilities for the future as described above. Therefore, we, Japanese researchers, should place more emphasis on comprehensive technical development ranging from the search for new materials to application technologies such as wire and thin film production.

Explanation of terms and reference

*1 In order to maintain a stable superconducting state when a magnetic field or current is applied, it is necessary to lower the cooling temperature than the critical temperature according to the magnitude of the current or magnetic field. Therefore, superconducting magnets must be used at a temperature lower than the critical temperature of the material being used.

*2 SQUID
Stands for superconducting quantum interference device. Very weak magnetic fields can be measured using this device.

*3 "Development of NMR/MRI Technologies", Forum of Superconductivity Science and Technology, March 2001.

*4 Preprint server
Normally, research papers undergo submission, review, acceptance, printing, and delivery; it was very rare for them to be opened to the public before acceptance. Recently, however, many papers are opened to the public on the Internet before they are reviewed and accepted. Researchers who want to get a head start in their research positively register their papers in computers that provide registering and publishing services called "preprint server". The papers can be retained on the servers during and after the publishing and offered for public inspection.

*5 SUPERCOM, Vol. 10, No. 2 (2001) in Japanese.

*6 Agere Systems
Former microelectronics division of Lucent Technologies, and now a separate subsidiary company.