MgB_2 : A common Material with Uncommon Superconductivity

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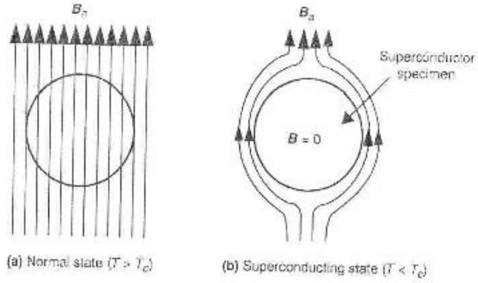
Abstract

The researches of superconductivity world wide have been processed for almost one decade and scientists still do not have a solid explanation to high Tc superconductivity while most physicists do believe they have a very good theory BCS theory to explain all the superconducting phenomena of conventional (low T_c) superconductors like elements and metal alloys. In Japan, a research team led by Akimitsu tested the commonest material in any materials or chemistry laboratories, MgB_2, and measured an unconventionally high T_c of 39 K [J. Nagamatsu et al, Nature 410 63-64, 2001] for this material with conventional structure of metal alloy which was firmly believed to obey the BCS theory which predicted the highest T_c of a conventional superconductor to be 30 K. This discovery shocks the superconductivity community, not just because it makes people re-think the mechanism of superconductivity, but also because this material still having the potential of boosting the T_c by doping (a common technique for varying the Tc of superconductors). Also MgB_2 is a very low cost material with a stable and high enough T_c, and it is ready to replace the expensive superconducting tapes of traditional niobium alloys for Magnetic Resonance Imaging (MRI) applications. This paper discusses the transport properties, structure, isotopic effect, applications and future research directions of MgB_2.

1 Introduction

Superconductors, materials that have no resistance to the flow of electricity were first observed in mercury by Dutch physicist Heike Kamerlingh Onnes of Leiden in 1911. While scientists still do not have a solid explanation to high Tc superconductivity most physicists believed they had a very good theory (BCS Theory) to explain superconducting phenomena of conventional (low T_c) superconductors like elements and metal alloys. But with the announcement of the discovery of superconductivity with $T_c \sim$ 39K in MgB_2 in January 2001 by a Japanese research team led by Professor J. Akimatsu [J Nagamatsu *et al, Nature* **410** 63-64, 2001] caused excitement in solid-state physics community, because it introduced a new, simple (three atoms per unit cell) binary intermetallic superconductor with a record high (by nearly a factor of 2) superconducting transition temperature for a non-cuprate and non-fullerene compound.

2 Meissner Effect



(a) Normal state ($T > T_c$) (b) Superconducting state ($T < T_c$)

Figure 1: *Meissner effect of a superconductor.*

By 1933 Walther Meissner and R. Ochsenfeld discovered that superconductors are more than a perfect conductor of electricity, they also have an interesting magnetic property of excluding a magnetic field. A superconductor will not allow a magnetic field to penetrate its interior. When the temperature is lowered to below the critical temperature, (T_c) the superconductor will ”push” the field out of itself. It does this by creating surface currents called supercurrents ($J - c$) in itself, which produces a magnetic field exactly countering the external field.The superconductor becomes perfectly diamagnetic, canceling all magnetic flux in its interior.Flux exclusion is referred to as the **Meissner Effect** . This will occur only if the magnetic field is relatively small. If the magnetic field becomes too great, it penetrates the surface of the metal and the metal loses its superconductivity.

3 BCS Theory

In the early days of superconductivity research most of the samples were metals or combinations of metals, and the mechanism for producing the super-current state was described by the BCS theory, named after John Bardeen, Leon Cooper, and Robert Schrieffer.

Pairs of electrons can behave very differently from single electrons, which are fermions and must obey the Paulie exclusion principle. The pairs of electrons act more like bosons,

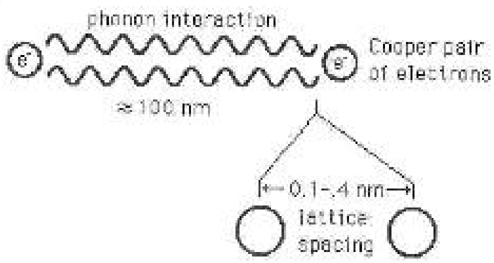


Figure 2: *cooper pairs*

which can condense into the same energy level. Here electrons pair up and eventually fall into a single quantum state in which the moving electron pairs are immune from electrical resistance (the hallmark of superconductivity) courtesy of a wavelike flexing of the crystal of atoms. An equivalent way of expressing this idea is to say that electrons pair up by exchanging phonons. The electrons are screened by the phonons and are separated by some distance. When one of the electrons that make up a Cooper pair and passes close to an ion in the crystal lattice, the attraction between the negative electron and the positive ion cause a vibration to pass from ion to ion until the other electron of the pair absorbs the vibration. The net effect is that the electron has emitted a phonon and the other electron has absorbed the phonon. The electron pairs have a slightly lower energy and leave an energy gap above them on the order of .001 eV. The BCS theory predicts a band gap of,

$E_g \sim \frac{7}{2}kT_c$

Which results in a maximum T_c=23.3 K.

As long as the superconductor is cooled to lower than T_c, the Cooper pairs stay intact, due to the electron phonon interaction. As the superconductor gains heat energy the vibrations in the lattice become more violent and break the pairs. As they break, superconductivity diminishes.

4 Structure of magnesium diboride

MgB2 possesses the simple hexagonal $A1B_2$-type structure, which are perhaps the most common structure types among the borides.

The above given is the crystal structure of MgB_2 of which the space group is *P6/mmm* (No 191) with Mg at $(0, 0, 0)$ and B at $(1/3, 2/3, 1/2)$ viewed along the c axis and perpendicular to an a axis. As shown, the boron atoms are arranged in layers, with layers of Mg interleaved between them. The structure of each boron layer is the same as that of a layer in the graphite structure: each boron atom is here equidistant from three other boron atoms. Therefore, MgB_2 is composed of two layers of boron and magnesium along the c axis in the hexagonal lattice. And the center of a hexagonal Boron ring lies both directly above and below each metal.

5 Resistivity as a function of temperature

The figure below shows the temperature dependence of the resistivity of MgB_2 under zero magnetic field. The onset and the endpoint transition temperatures are 39K and 38K,

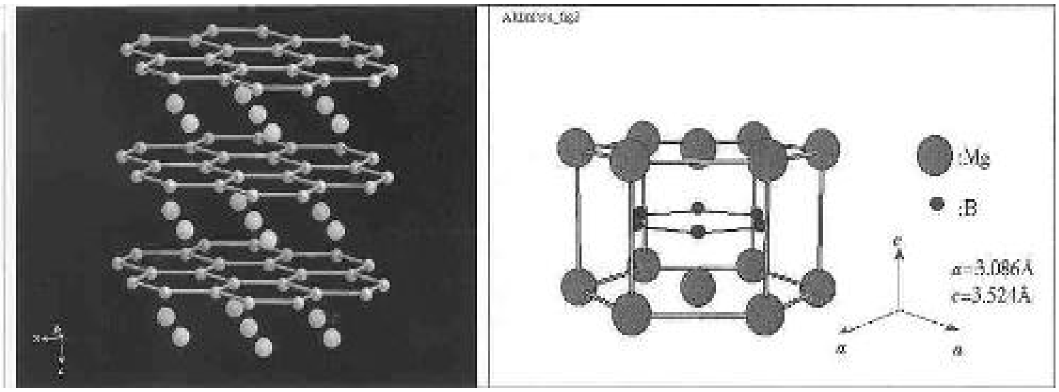


Figure 3: *The crystal structure of superconducting* MgB_2

respectively, indicating that the superconductivity is truly realized in this system

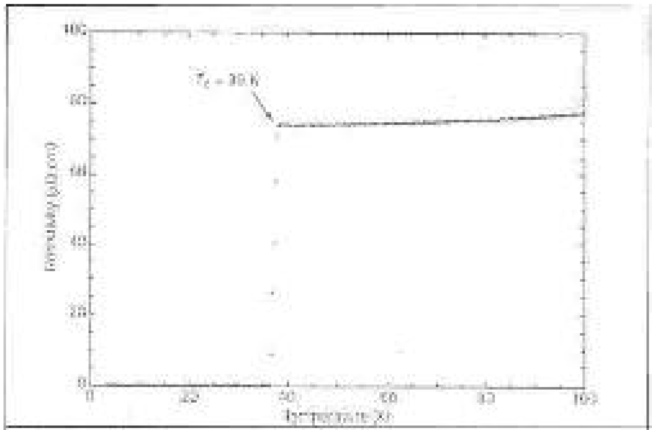


Figure 4: Tepreature dependance of the resistivity of MgB2 under zero magnetic field

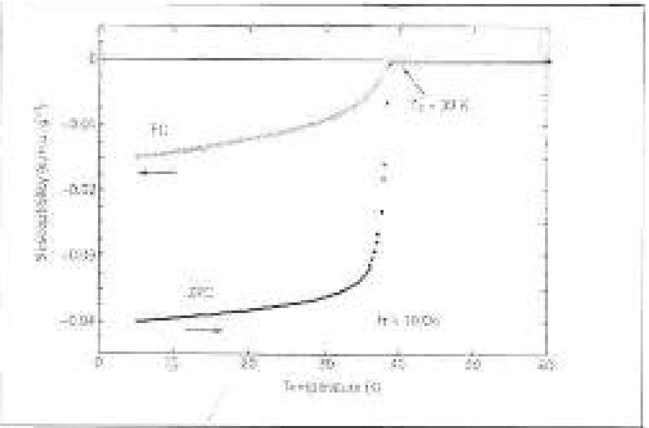


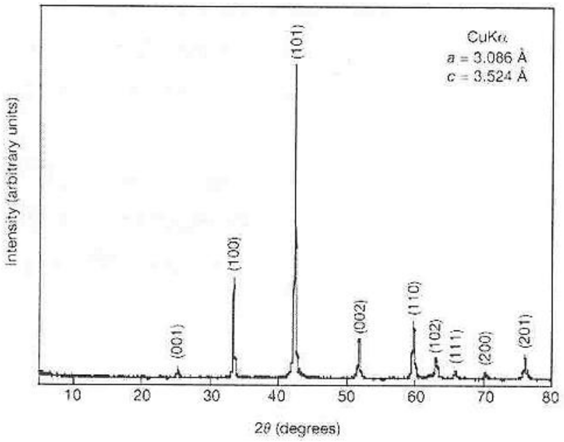
Figure 5: Magnetic Susceptibilty of MgB2 as a function of temperature. Data are shown for measurements under conditions of zero field cooling (ZFC) and field cooling (FC) at 10Oe.

6 Susceptibility as a function of temperature

The above figure shows the magnetic susceptibility of MgB_2 as a function of temperature, under conditions of zero field cooling (ZFC) and field cooling (FC) at 10 Oe. The existence of the superconducting phase was then confirmed unambiguously by measuring the Meissner effect on cooling in a magnetic field. The onset of a well-defined Meissner effect was observed at 39 K.

7 X-Ray Diffraction

Shows a typical X-ray diffraction pattern of MgB_2 taken at room temperature. All the intense peaks can be indexed assuming an hexagonal unit cell, with a = 3.086 Åand c = 3.524 Å. The X-ray measurements show that the sample is single-phased and electrical resistiv-



6:X-ray diffraction pattern of MgB_2 at room temperature.

ity and DC magnetization measurements confirm the onset of a sharp super conducting transition at 39.5 K.

8 Critical Current Density (J_c)

Since there is no loss in electrical energy when superconductors carry electrical current, relatively narrow wires made of superconducting materials can be used to carry huge currents. However, there is a certain maximum current that these materials can be made to carry, above which they stop being superconductors. If too much current is pushed through a superconductor, it will revert to the normal state even though it may be below its transition temperature. The value of Critical Current Density (J_c) is a function of temperature; i.e., the colder you keep the superconductor the more current it can carry.

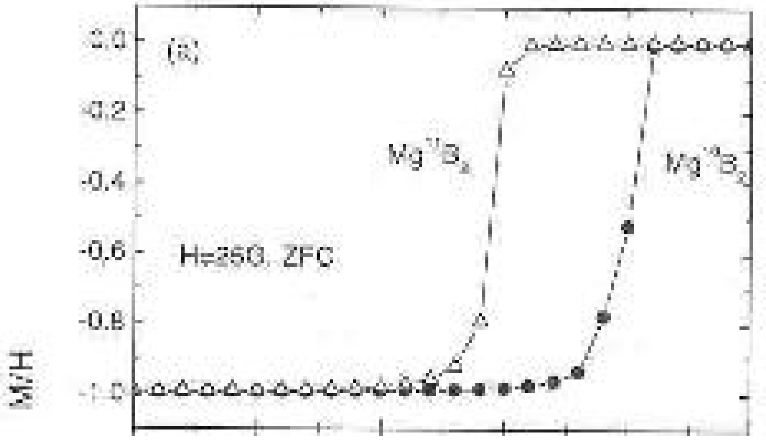
9 Boron Isotope Effect

One probe of the extent to which phonons mediate superconductivity is the isotope effect. Boron isotope effect is consistent with phonon-mediated coupling within the framework of the BCS model. In the classical form of BCS theory, the isotope coefficient α, defined by the relation,

$T_c \approx M^{-\alpha}$, where M is the mass of the element.

The powder x-ray diffraction pattern of the $Mg^{10}B_2$, powder is shown in Figure with the peaks indexed to the hexagonal unit cell of MgB_2 also the unit cell lattice parameters for $Mg^{10}B_2$ are a= 3.1432 0.0315 and c = 3.5193 0.0323 Å.

Figure above presents the temperature dependent magnetization of $Mg^{10}B_2$, and $Mg^{11}B_2$. There is a clear separation between the data of $Mg^{10}B_2$, and $Mg^{10}B_2$. The superconducting transition temperatures are 39.2 K for $Mg^{11}B_2$ And 40.2 K for $Mg^{10}B_2$ which implies a shift of 1K in T_c. The widths of the transitions are 0.4 K and 0.5 K for $Mg^{10}B_2$, and $Mg^{10}B_2$, respectively.



7:Magnetization divided by applied field as a function of Temperature.

10 Conclusion

The discovery of superconductivity with T_c 39 K in magnesium diboride (MgB_2) was announced in January 2001 . It caused excitement in the solid state physics community because it introduced a new, simple (three atoms per unit cell) binary inter-metallic superconductor with a record high (by nearly a factor of 2) superconducting transition temperature for a nonoxide and non-C based compound. The reported value of T_c seems to be above the limit suggested theoretically several decades ago for BCS, phonon-mediated superconductivity.The simple structure of MgB_2 belongs to conventional superconductors but T_c=39K ¿¿ T_c predicted by BCS theory which is believed to be correct for all conventional superconductors.

Because of the higher superconducting temperature and inexpensiveness when compared with Nb,in the future MgB_2 may become the preferred low-temperature superconductor for applications such as high field magnets used in magnetic resonance imaging (MRI) machines. Also MgB_2 might be used in making very fast computer components , where the oxygen-containing materials have proved hard to work with.

A significant boron isotope effect (Δ T_c=1.0 K, partial isotope exponent $\alpha_B \approx 0.26$) is observed in MgB_2 , which is consistent with a phonon-mediated BCS superconducting mechanism .

References

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