The Study on Superconductivity & its Applications

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Abstract— Superconductivity is the property of material to conduct electricity by transporting the electrons from atom to atom with zero resistance. Which means that once material cool till its critical temperature and reach superconductive state, no heat, sound or any other form of energy will be released from superconductor interior. Unfortunately, almost all materials require a very low energy state (very cold temperature) in order to become superconductors. Currently, a lot of researches are being carried and superconductivity of the conductors is one of the most promising applied to the external world area of interest. Superconductors are used in various ways due to their properties - from completely zero resistance to quantum levitation. For now cooling superconductors require high amount of energy, which make them difficult to use for further applications due to inefficiency and high cost. This research paper will show influence of pressure effect on critical temperature of superconductor material. Most of material tended to reduce their critical temperature, however there are some exceptions. Let us take a proper look on this problem and compare critical temperature behavior in different materials.

Key words: Critical Temperature, Superconductivity, Meissner Effect, London Equation, Coherence Length, Vanadium Heat Capacity

I. INTRODUCTION

Dutch physicist and Nobel laureate Heike Kamerlingh Onnes was the one who discovered such phenomenon as Superconductivity in 1991.The limits of such phenomenon as “Superconductivity” have not yet been completely observed. Superconductivity is a property of some materials to have a strictly zero electrical resistance when they reach a temperature below a certain value T_c (critical temperature). Various compounds which include pure earth elements, alloys of different metal, ceramics, organic, high mass fermions, borocarbides, heavily doped (addition of impurity) semiconductors, iron and hydrogen based materials, which are then converted into a superconducting state, are known.

Material of superconductor defines critical values such as T_c (critical temperature), B_c (critical magnetic field) and J_c (critical current density) which grant it superconducting properties [1].

According to Nicholas Gerbis’s classification based on how superconductors react in a magnetic field there are mainly two types of Super Conductors. All pure materials, except Nb, relate to type-1category. Superconductors of type-1 show some conductivity at the room temperature. But if material of type-1 superconductor will get cooled below it’s critical temperature which is denoted by T_c, superconductor will exhibit zero resistivity. And also display perfect diamagnetism, which prevents magnetic fields from penetrating superconductor material.

Superconductors of type-2 are represented by compounds containing metals and alloys. These superconductors possess more complex diamagnetism.

II. THE MEISSNER EFFECT FROM THE LONDON EQUATION

Physicists consider superconductivity as one of the most significant, important and most widely used physical phenomenon. In 1933 other discovery in this field was made by German physicists Meissner and Ochsenfeldin and was named as the Meissner effect (Meissner – Ochsenfeld effect).

If material makes it’s transition for the normal transition state to the superconducting state it excludes the magnetic field which pass through the interior of it, this phenomenon is called the Meissner effect. The Meissner effect considerably so strong that it permits a magnet to levitate over a superconductive material.

London equation emphasizes the relation between the curl of the current density J to the magnetic field:

$$\vec{\nabla} \times \vec{J} = -\frac{1}{\mu_0 \lambda_L^2} \vec{B}$$

It can be deduced that the Meissner effect arises from London’s equation. The Maxwell's equation;

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$$

By using vector calculus identity

$$\vec{\nabla} \times \vec{\nabla} \times \vec{B} = -\nabla^2 \vec{B}$$

along with the curl of current density J of the Maxwell equation above

$$\vec{\nabla} \times \vec{\nabla} \times \vec{B} = \vec{\nabla} \times (\mu_0 \vec{J}) = -\frac{\vec{B}}{\lambda_L^2}$$

and by substitution

$$\nabla^2 B = \frac{B}{\lambda_L^2}$$

Since $\nabla^2 B = 0$ by Maxwell's equations, the value for B inside the superconductor must be equal to exact zero unless the penetration depth is up to infinity (i.e., not a superconductor).

III. The London Penetration Depth In Superconductors:-

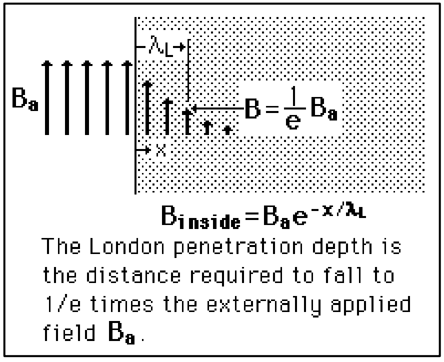

Fig. 1:

One of the best methods of approach to describe the superconducting state of a material is the London Equation. It is the relation between the current density J of the superconductor and the magnetic field B.

$$\vec{\nabla} \times \vec{J} = -\frac{1}{\mu_0 \lambda_L^2} \vec{B}$$

It helps to understand that the magnetic field inside the conductor decreases to zero exponentially. The decay nature is dependent on superconducting electron density n

$$\lambda_L = \sqrt{\frac{\varepsilon_0 mc^2}{ne^2}}$$

λ_L = London penetration depth
n = superconducting electron density

This equation gives the characteristic wavelength in supercondcutors.

III. THE LENGTH OF COHERENCE IN SUPERCONDUCTORS

The length of coherence is directly related to Fermi- Velocity of the material and the energy gap is associated with the condensation of the superconducting state, this is known that the electron density does not change very quickly there is a definite minimum length over which given changes can be effectively made. After this change a superconductor behaves as an ordinary conductor, and its superconducting state is destroyed. The state transition from the superconducting state to normal state will have a definite transition layer of finite thickness and that is directly co-related to coherence length.

$$\xi_0 = -\frac{2\hbar v_F}{\pi E_g}$$

v_F = Fermi velocity
E_g = Superconducting band gap

IV. MEASURED SUPERCONDUCTOR BANDGAP

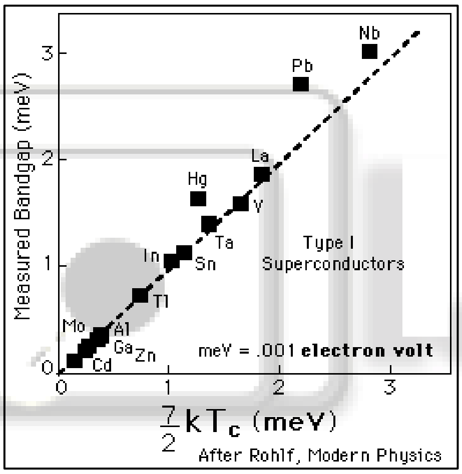

Fig. 2:

The measured energy band gap in Type 1 superconductors is the experimental evidence which supports BCS theory.

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

The energy band gap of a superconductor is directly related it’s coherence length.

VI. Vanadium Heat Capacity.

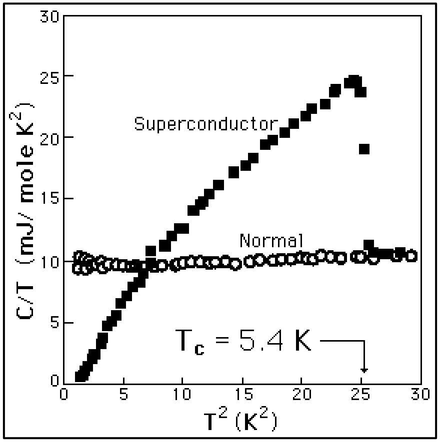

Fig. 3:

The heat conducting capacity of Vanadium is different that of the normal conducting state. The gradual decrease increase in heat capacity of the vanadium near the critical temperature suggest us the energy band gap for the superconducting materials.

V. EXPONENTIAL HEAT CAPACITY

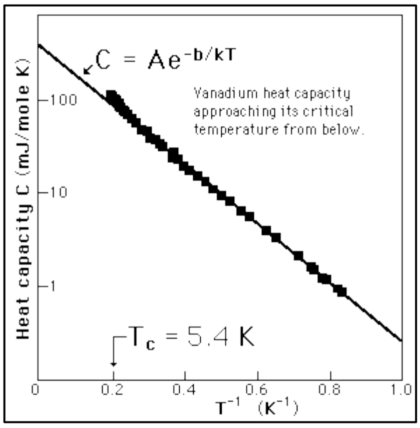

Fig. 4:

The heat conducting capacity of vanadium increases gradually increases towards the critical temperature T_c. "b" is the constant in the exponential heat capacity expression which is nearly half that of the energy band gap. If the slope of the line in the illustration is determined by scaling, it is about b=7.46k, corresponding to energy band gap of about 1.33 meV. The value predicted for vanadium from its critical temperature of 5.38 K by the BCS theory is nearly equal 1.6 meV.

VI. PRESSURE EFFECT ON SUPERCONDUCTORS

Pressure effect on super conductors is well established due to its property to decrease critical temperature of superconductors. Such negative pressure coefficient explained by electron-phonon couples leading to certain interaction between electrons. However some materials have more complex behavior of critical temperature e.g. Tl and Re, which is caused due to the changes in Fermi surface characteristic.

Scientists are aiming to make superconductive state possible to reach in room temperature. In 1969 Allen and Cohen proposed simplest metal - Li as element with high critical temperature. But only recent made researches showed superconductivity exists in Li at pressure of 20 Gpa and temperature to 20 K. Which gave hope to find the superconductor (such as metallic hydrogen) with extremely high critical temperature [13].

VII. APPLICATIONS

At the present time scientific work more and more influenced by applications. Currently the most wide spread applications on Superconductivity are generators, motors, phase transitions, one dimensional organic conductors etc. Finding their usage in the medical diagnostic, transport technologies, communications, science and industrial fields [8].

There are lots of requirements on superconductor material. Main problems of using superconductors in our daily life appearing in front of researches are high costs, refrigeration, and reliability. Effective way to make production much cheaper is to find new superconductive materials with higher critical temperature. However such approach entails high risk. Prospective customers, e.g. electric utilities require long-termed research and further development. Usually it takes around 20-25 years to move new material from laboratory to actual commercial arena. Also worth to be mentioned that products based on superconductors are much more environmentally benign then their analogues.

REFERENCES

[1] Ibrahim Adam Ibrahim Hammad, Mubarak Dirar, Nadia Omar Alatta, Rasha Abd Alhai Taha, Kh. M. Haroun, Rawia A. Elgani. Pressure Effect on Superconducting Critical Temperature According to String Model. International Journal of Fluid Mechanics & Thermal Sciences. Vol. 3, No. 6, 2017, pp. 70-74. doi: 10.11648/j.ijfmts.20170306.12
[2] Shrivastava, Shailaj. (2017). Search for Higher Critical Temperature (TC) IN Superconducting Materials. International journal of engineering and scientific research. 5.
[3] B. Lorenz and C. W. Chu High Pressure Effects On Superconductivity
[4] John Bardeen, Comments On Superconducting Science And Technology
[5] Superconductivity concepts Reference Rohlf, Ch 15
[6] Superconductivity concepts References Kittel Ch 12
[7] Ekaterina Kurbatova. Comparative Analysis of the Specific Characteristics of the Magnetic Bearings with HTS Elements Transactions on Applied Superconductivity IEEE Transactions on Applied Superconductivity, VOL. 28, NO. 4, JUNE 2018 5207704
[8] 2009 CCAS: Coalition for the Commercial Application of Superconductors, Present and future applications.
[9] Berk, N. and Schrieffer, J. (1966) in Superconductivity. Phys. Rev. Lett, 17, 433.
[10] Bray, J.W. J Supercond Nov Magn (2008) 21: 335. https://doi.org/10.1007/s10948-008-0345-9
[11] David Larbalestier, Panel Chair Richard D. Blaugher Robert E. Schwall Robert S. Sokolowski Masaki Suenaga Jeffrey O. Willis. Power Applications Of Superconductivity In Japan And Germany
[12] L. D. Jennings and C. A. Swenson, Phys. Rev. 112, 31 (1958).
[13] B. Lorenz and C. W. Chu. High Pressure Effects On Superconductivity
[14] Bardeen, J., Cooper, L.N., Schrieffer, J.R.: Phys. Rev. 108, 1175 (1957)
[15] J. S. Schilling and S. Klotz, in: physical Properties of High Temperature Superconductors III, edited by D. M. Ginsberg (World Scientific, Singapore, 1992), p. 59.
[16] Christian Barth, (2013) High Temperature Superconductor Cable Concepts for Fusion Magnets, KIT scientific publishing, ISSN: 1869-1765.
[17] Mourachkine. (2004) Room-temperature superconductivity, cambridge international science publishing, UK.
[18] Wesche. (2015) Physical properties of high-temperature superconductors, John Wiley & Sons, United Kingdom.
[19] Michel Cyrot and Davor Pavuna. (1992) Introduction to superconductivity and high-Tc materials, world scientific, Singapore.