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PROPERTIES OF VORTEX STATES IN HIGH TEMPERATURE SUPERCONDUCTORS

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ABSTRACT

This paper reviews vortex behavior and formation of vortex liquid due to vortex lattice melting in high temperature superconductors (HTSC). The microscopic theory of superconductivity and the basic concepts needed to understand the magnetic properties of type magnetic phase diagrams are presented. The transition from the vortex solid to the vortex liquid phase for HTSC is described I and type II superconductors are discussed briefly. Magnetic states of superconductors are described and. Effects of the point, columnar disorders and strong thermal fluctuations on the character of the transition between these two phases are studied. The effects on the vortex solid to liquid transition of high magnetic fields applied parallel to the superconducting layers are also studied.

Key Words: *Superconductivity, Vortex state, Vortex liquid, Abrikosov vortex.*

YÜKSEK SICAKLIK SÜPERİLETKENLERİNDE VORTEX BÖLGESİNİN ÖZELLİKLERİ

ÖZET

Bu çalışma, yüksek sıcaklık süperiletkenlerindeki vortex örgü erimesi sebebiyle vortex sıvının oluşumunu ve davranışını özetler. Süperiletkenliğin mikroskobik teorisi ve I. tip ve II. tip süperiletkenlerin manyetik özelliklerinin anlaşılması için gerekli temel kavramlar kısaca tartışıldı. Süperiletkenlerin manyetik durumları ifade edildi ve manyetik faz diyagramları gösterildi. Yüksek sıcaklık süperiletkenleri için vortex katıdan vortex sıvı faza geçiş ifade edilmektedir. Bu iki faz arasındaki geçişin özelliği olan vortexlerin vortex sütunlarındaki bozulma, güçlü termal dalgalanmalar ve nokta kusurlar araştırıldı. Aynı zamanda , süperiletken tabakalara paralel olarak uygulanan yüksek manyetik alanların vortex katı-sıvı geçişi üzerine etkileri tartışıldı.

Anahtar Kelimeler: *Süperiletkenlik, Vortex durum, Vortex sıvı, Abrikosov vortex.*

1. INTRODUCTION

Superconductivity is a phenomenon occurring in certain materials at low temperatures, characterized by the absence of electrical resistance and the exclusion of magnetic fields[1]. That is, superconductors have two important characteristics: they expel magnetic field and they conduct electrical current with zero resistance [2]. A superconductor acts as a perfect conductor and a perfect diamagnet.

Superconductivity was discovered by Heike Kammerlingh-Onnes in 1911. He was studying the behaviour of metals at the temperature of liquid helium and quite by accident noticed that the resistance of mercury dropped to zero below 4.2 K [3]. After a few years, in 1933 Walther Meissner and Robert Ochsenfeld observed that all magnetic flux is expelled from the interior of superconductor [4, 5, 6]. This major advance was the discovery of the Meissner effect which showed that a superconductor is a perfect diamagnet. Not very long afterwards (1935), the brothers H. and F. London proposed a phenomenological theory of the electromagnetic properties in which the diamagnetic aspects were assumed basic [7]. In 1950, V. L. Ginzburg and L. D. Landau proposed a new phenomenological theory to explain superconductivity that contained London theory [8]. Superconductivity was characterized by the three basic phenomena. These are infinite conductivity, perfect diamagnetism and existence of an energy gap. Any theory had first to explain these three features. In 1957 Bardeen, Cooper and Schrieffer produced theory of superconductivity. This theory is known as the BCS theory. They were predicted that energy gap changes with definition from zero to T_c [4,9]. The fundamental assumption of the BCS theory of superconductivity is that the carrier in superconductors is not a normal electron but a formation of two bound electrons called the Cooper pair, whose charge and mass is equal to twice that of the normal electron [10].

In subsequent years, superconductivity was intensively studied and various models were developed to explain the physical origin of the phenomenon [7]. High temperature superconductivity (HTSC) was discovered by G. Bednorz and A. Müller in 1986 [11]. Nowadays high temperature superconductivity is one of the most important research areas and also have many potential commercial uses. In order to explain the physical properties of superconductors and their behaviours we will mention some issues. And then, we consider that the classification type I and type II superconductors which exhibit very different magnetic properties. While a type-I superconductor totally expels an applied magnetic field, magnetic flux penetrates a type-II superconductor in the form of quantized vortices. So, in type II superconductors, known as mixed phase vortex state, ıts formation and behavior will be discussed.

1.1 Type I and Type II Superconductors

The phenomenology of superconductivity is based on Ginzburg-Landau (G-L) theory [12,13]. This theory which is related to Landau's theory of second-order structural phase transitions[13,14]. In this transition, there is no transfer of heat, but the heat capacity does change.
They introduced a complex pseudowave-function ψ as an order parameter within this phase transitions. In the superconducting phase which is the ordered phase $\psi \neq 0$ while for temperatures above T_c, $\psi = 0$ in the state of thermodynamic equilibrium [9]. This wave function ψ describes the superconducting electrons or superelectrons.

The local density of superconducting electrons was given n_s by [15].

$$n_s = |\psi(r)|^2 \qquad [1]$$

In this case,

$$\psi(r) = |\psi| \exp(i\varphi) \qquad [2]$$

Thus, we obtain that

$$\psi(r) = \sqrt{n_s(r)}e^{i\varphi} \qquad [3]$$

ψ wave function changes in a distance given by the coherence length ξ . This theory gives a quantitative description of superconductors near the transition point. Also this was the first theory to properly take into account the quantum nature of superconductivity [15]. By using G-L theory's solutions, two characteristic lengths were found that is very important for superconductors. The smaller one is "coherence length" which is the size of each Cooper pair. It can be defined as ξ and its value can vary between 1 and 1000 nm depending on the superconductor [16]. The larger one is "penetration depth", λ [17, 18]. The ratio of these two lengths is called G-L parameter κ which is material constant.

$$\kappa = \frac{\lambda}{\xi} \qquad [4]$$

In 1957, Soviet physicist A. A. Abrikosov investigated the effect of constant κ in the G-L theory. Depending on the value of the Ginzburg-Landau parameter, superconductors can be divided into two different types as type I and type II superconductors.

In case of $\kappa = \frac{\lambda}{\xi} \leq \frac{1}{\sqrt{2}}$, since $\lambda < \xi$, $\kappa < 1$, are known as type I superconductors. For this superconductors, λ and ξ values are, [10]. The value of κ could be defined from the surface energy between the normal and superconducting phases [18]. If $\kappa < \frac{1}{\sqrt{2}}$, the surface energy become positive. This kind of materials (type I superconductor) expels completely magnetic flux from the material. There are mainly type I superconductors such as lead (Pb), mercury (Hg), niobium (Nb) and tin (Sn) [19]. There is an upper limit to the magnetic flux that a superconductor can expel when a magnetic field is applied to a superconductor which is larger than the so-called critical field, H_c. Thus superconducting state is destroyed. Magnetic flux enters into superconducting sample and the sample becomes normal state [16]. Fig. 1(a) shows a schematic phase diagram for type I superconductor of magnetic field versus temperature. For magnetic fields below a certain critical field $H_c(T)$, the appearance of Meissner currents prevent penetration of the magnetic field into the sample [20].

The Meissner effect is present at low fields and temperatures. As H and T are increased above their critical values, the system undergoes a first-order transition into the normal state and superconductivity is destroyed [19]. In a first-order transition there is a transfer of heat between system and surroundings and the system undergoes an abrupt volume change. That is, in the an external magnetic field cannot penetrate into the bulk of the sample without destroying the superconducting condensate [21].

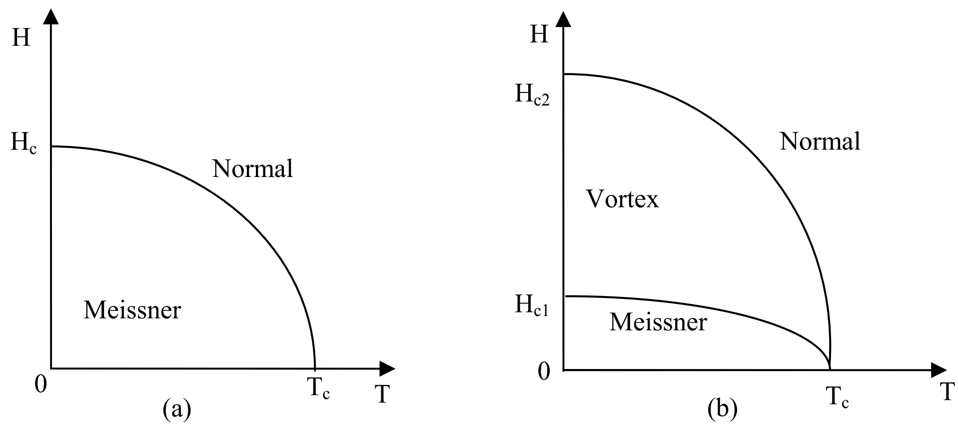

Figure1. Schematic H−T phase diagram for a) type I superconductor, b) type II superconductor [19,23].

In case of , $\kappa = \frac{\lambda}{\xi} > \frac{1}{\sqrt{2}}$ material presents a completely different magnetic behaviour. So Abrikosov called these type II superconductors to distinguish them from the type I. In case of, $\kappa > \frac{1}{\sqrt{2}}$ surface energy between normal and superconducting phases becomes negative [18]. These superconductors have two critical magnetic fields H_{c1} and

H_{c2}. H_{c1} is lower critical magnetic field and H_{c2} is upper critical magnetic field. In niobium, one of the few elemental type II superconductors, H_{C1} = 139 mT and H_{C2} = 268 mT at 4.2 K [16]. In compounds, the upper critical field can be much larger such as Nb_3Sn which has $H_{C2} \sim 25$ T at 4.2 K [16]. For several type II superconductors, H_{c2} values are given in Table I.

Table I. For several type II superconductors, critical temperature and upper field values [15, 24].

Type II superconductor	T_c (K)	H_{c2} (T)
Nb_3Al	18,7	32,4
Nb_3 Sn	18,0	24,5
Nb_3Ge	23	38
NbN	15,7	15,3
NbTi	9,3	15
$Nb_3(AlGe)$	21	44
V_3Si	16,9	23,5
V_3Ga	14,8	20,8
Pb Mo S	14,4	60

When applied field strength less than the lower critical field, $H < H_{c1}$, that superconductor will exhibit the usual Meissner effect. Thus, the magnetic field is completely expelled [1, 22, 25]. Between the critical fields H_{c1} and H_{c2} the system is described mixed or vortex state, where partial penetration of magnetic flux occurs. Magnetic flux may penetrate a type-II superconductor in the form of Abrikosov vortices (also called flux lines, flux tubes or fluxons), each carrying a quantum of magnetic flux [23]. Each of flux lines is surrounded by circular superconducting currents. Such object is called vortex. Each flux line represented by the cylinders in Fig. 2.

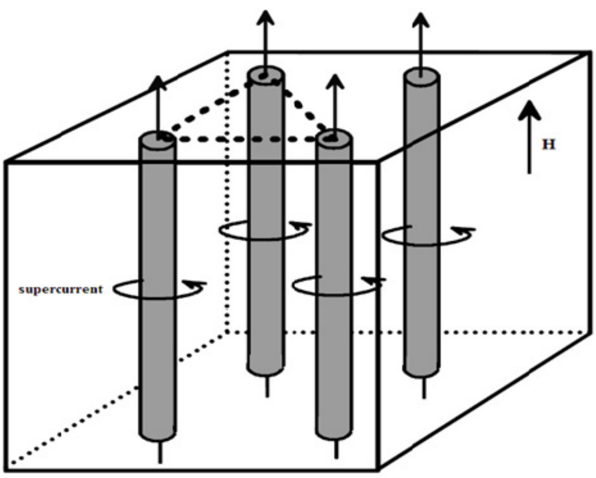

Figure 2. The flux quantum passes through the core of each vortice surrounded by supercurrents [1].

Each of these vortices carries a flux quantum of value [19]

$$\phi_0 = \frac{h}{2e} \qquad [5]$$

where h is Planck's constant and e is the elementary charge. Its numerical value in SI units is $\phi_0 = 2.07 \times 10^{-15}$ Wb [1,16]. Therefore the number of flux lines inside the sample is approximately proportional to the external field. The structure of an individual vortice depends on the coherence length and penetration depth. As shown in figure 3, the vortex structure consists of a central cylindrical core region whose radius is the coherence length where the density of Cooper pairs is greatly reduced, falling to zero at the centre. [16, 26].

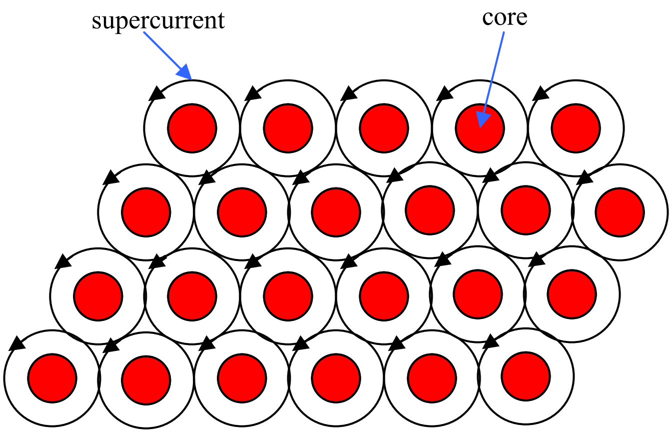

Figure 3. Schematic diagram of vortices that is surrounded by supercurrents [27].

The core of the vortex is in the normal state [18]. Each vortices is surrounded by supercurrents that produce magnetic field. Thus, in the middle of the normal core, the magnetic field has its highest value, and it decays exponentially with a characteristic length λ (Fig.4). The circulating supercurrents give rise to an interaction between the flux lines, extending out to a distance of order λ [28]. Fig. 4 illustrates λ the penetration depth, ξ the coherence length and the superelectron concentration in a vortice. In the vicinity of vortex axis, the order parameter grows linearly with distance [21].

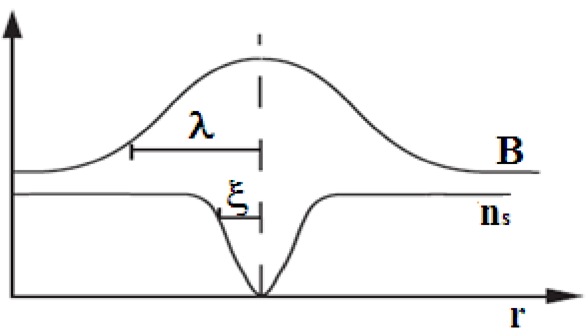

Figure 4. An illustration of a vortex line and the important lengths, λ the penetration depth and the coherence length ξ [6, 19, 21].

The flux lines in type II superconductors should in principle be able to move freely. However, inhomogeneties in the superconductor due to grain boundaries and lattice defects make that an energy barier must be overcome in order to move the vortices. Due to this so-called flux pinning, the magnetic flux in the superconductor will not change in a reversible manner as the externally applied field changes. The work needed to overcome this pinning force is connected with some losses in the superconductor [6]. For the purpose of applying type–II superconductors in external magnetic fields, an effective vortex pinning mechanism is essential, in order to minimize dissipative losses caused by the Lorentz–force induced movement of flux lines across the sample [29]. As an electric current is passed through the superconductor, the Lorentz force will act between electrons and the magnetic field carried by the flux lines [21]. At some critical current density, the Lorentz force overcomes the pinning force and the vortices start to move. This is called as flux flow. The motion of the vortices is normally more sporadic and much slower. Hence this situation has been named flux creep [6].

In a type-II superconductor, the applied external magnetic field maintains the vortices inside the superconductor. The long-range magnetic interaction is repulsive for straight parallel vortex lines and attractive for antiparallel lines. Without other forces, taking into account the mutual repulsion of the vortices, the vortices form a lattice, in order to keep each vortex in equilibrium and to maximize the average vortex spacing in order to arrange themselves into a state of low energy [1].

Because of this interaction the minimum energy configuration for a vortice system in an ideal isotropic superconductor consists of parallel vortex lines arranged in an hexagonal lattice in the plane perpendicular to the field direction. This hexagonal lattice is called Abrikosov vortex lattice. In this lattice, each vortex is surrounded by hexagonal array of other vortices. In this array, the nearest neigbour distance is

$$a_{\Delta} = \left(\frac{4}{3}\right)^{\frac{1}{4}} \left(\frac{\emptyset_0}{B}\right)^{\frac{1}{2}} = 1.075 \left(\frac{\emptyset_0}{B}\right)^{\frac{1}{2}} \qquad [6]$$

whereas for the four neighbors in a square array

$$a_{\blacksquare} = \left(\frac{\emptyset_0}{B}\right)^{\frac{1}{2}} \qquad [7]$$

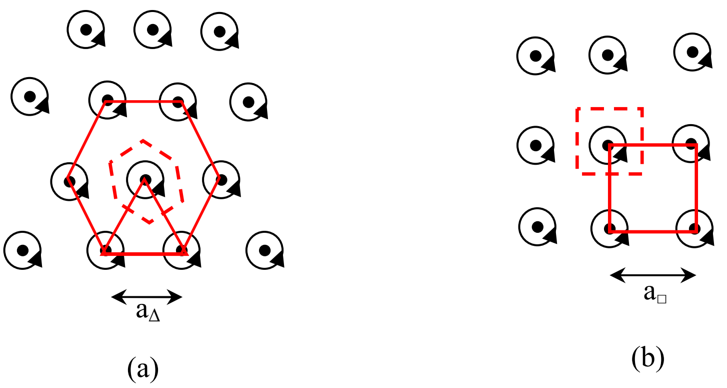

Figure 5. Schematic diagram of (a) square and (b) triangular vortex lattices [28].

As shown in Fig. 5, there are two natural forms. These are shown as the square and the triangular lattices[28]. All high temperature superconductors are type II superconductor which are special case of type II superconductors because of their high critical temperature. The discovery of HTSC renewed the interest in superconductors. These materials are type II superconductors in which external magnetic fields penetrate the material in the form of magnetic flux lines, vortices.

1.2 High Temperature Superconductors

HTSC are one of the most intensively studied areas of contemporary condensed matter physics. In 1986, Bednorz and Müller discovered a new type of ceramic materials that its higher Tc critical temperature value than the conventional superconductors, for the scientific world it was a big surprise [11]. These materials are called HTSC, which are extreme cases of type II superconductivity. Since its critical temperature is higher than traditional superconductors, these materials are called HTSC. After this discovery of HTSC, scientists started to search for new materials that have critical temperature higher than of 35K [6].

There are two principle groups of high temperature superconducting materials. The former group is Yttrium-Barium-Copper-Oxide ($YBa_2Cu_2O_7$) shortly (YBCO). It has a critical temperature of 95K [19,31]. The latter common group is Bismuth-Strontium-Calcium-Copper-Oxide, which is abbreviated to BSCCO. It has two types of mixtures which are $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) and $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi-2223). They have a critical temperature of about 110K [6]. The highest T_c is 138 K in Tl doped sintered $HgBa_2Ca_2Cu_3O_8$. If high pressures are applied, this temperature can be increased to over 160 K [19,30]. Extensive research work has revealed that all HTSC have a number of common features, including strongly anisotropic properties, very low charge densities and extremely short coherence lengths and large penetration depths. For HTSC, $\lambda \approx 1500°A$ at zero temperature.

Due to the combination of high transition temperature, strong anisotropy, and short coherence length that occurs in HTSC, strong thermal fluctuations are present over a wide temperature interval in these materials [31-33]. These inherent properties lead to an unusually rapid flux creep, which causes energy dissipation [34].

2. VORTEX PHASE DIAGRAM

The traditional view of a superconductor in the mixed state was that a homogeneous solid vortex lattice phase exists in a field interval between the lower critical field H_{c1} and the upper critical field H_{c2}. Above H_{c2}, superconductivity disappears and above H_{c1}vortices start to penetrate into the superconductor [35]. Values of these critical fields depend on temperature that gives two first-order phase transition lines on the corresponding H-T phase diagram (Fig.6) [19].
In the absence of thermal fluctuations and of pinning induced disorder the vortex lattice is presented at certain fields below H_{c2}. However, in the presence of strong thermal fluctuations the vortex lines in the lattice vibrate with larger amplitudes as the temperature rises. At sufficiently high temperatures, vortex lattice begin to melt. There is a competition between the repulsive interaction among the vortices, which stabilizes them into a regular lattice, and the thermal energy. The melting transition occurs when the energy of thermal fluctuations becomes equal to the elastic energy barriers keeping vortices near their equilibrium positions in the lattice [22].

The flux line array in HTSC, such as BSCCO and YBCO is extremely susceptible to thermal and disorder-induced fluctuations due to the interplay of several parameters such as high transition temperature T_c, large magnetic penetration depth and short coherence length and a strong anisotropy of the material. This leads to the existence of a variety of fluctuation dominated phases of the flux-line array and very rich phase diagrams for the HTSC materials [43]. The phenomenological Lindemann criterion has proven successful determining in the locus of the melting transition for the first-order thermal melting transition. At sufficiently low disorder or low magnetic fields, the first order thermal melting transition can also be found in the presence of point disorder. In its conventional form for thermal fluctuations the Lindemann criterion is formulated as

$$\langle u^2 \rangle = c_L^2 a^2 \qquad [8]$$

where u is the displacement of vortex element, a is the vortex lattice constant. The Lindemann number c_L is introduced as a phenomenological parameter, is typically ~ 0.2 , in particular it is assumed to be independent of the magnetic field [17, 40, 41].

The HTSC have usually a very large region of mixed state [6]. In the mixed state of high T_c superconductors include different vortex phases, such as glass, liquid and lattice phases. These are complicated because of large thermal fluctuations due to the two dimensional layer structure and high temperature. The vortex pinning plays a great role in transport properties in real superconductors [36].

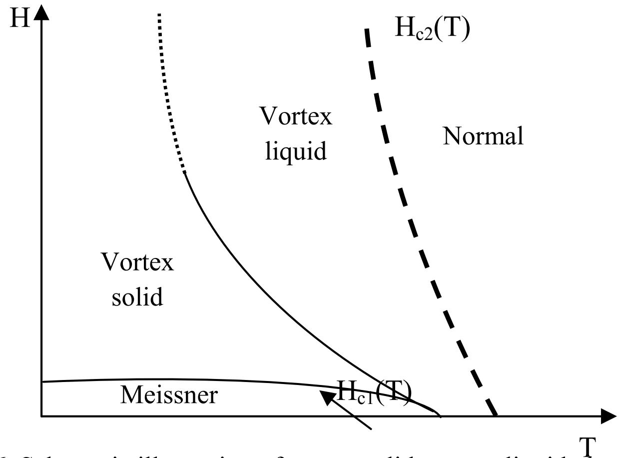

Figure 6. Schematic illustration of vortex solid- vortex liquid phase transition [19].

These phases are divided by several phase transition lines. That is, there are several phase boundaries in the H–T phase diagram. In the wide regions of the vortex phase diagrams, vortex liquid turn into Abrikosov vortex lattice because of the short coherence length, strong anisotropy and high critical temperature T_c [33, 37].

As shown in Fig. 6, large thermal fluctations of the vortex lattice cause vortex solid to vortex liquid transition [6, 38]. Also, the strong thermal fluctuations play an important role in HTSC. The presence of various forms of disorder
(such as point or columnar disorder) affects on this phase diagram (Fig.7) [39].

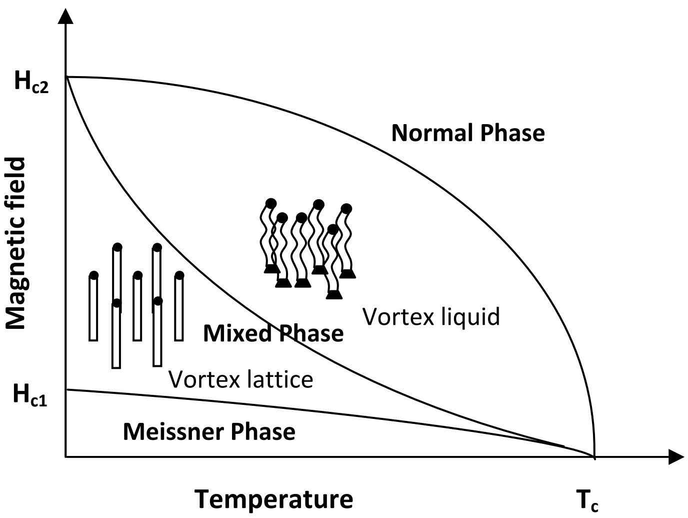

Figure 7: Schematic magnetic phase diagram of HTSC [38].

Point disorder has been induced by electron irradiation with electrons whereas columnar disorder has been induced by heavy ion irradiation. A significant difference has been observed between the effects of columnar and point disorder on the location of the melting line. Weak columnar defects stabilize the solid phase with respect to the vortex liquid phase and shift the transition to higher fields, whereas point like disorder destabilizes the vortex lattice and shifts the melting transition to lower fields [42].

2.1 Vortex Motion

When an external current density **j** is applied to the vortex system, the flux lines start to move under the action of the Lorentz force $F_L = j \times \frac{B}{c}$. For a single vortex $f_L = \left(\frac{\varnothing_0}{c}\right) j \times n$, where n denotes the unit vector along the vortex.

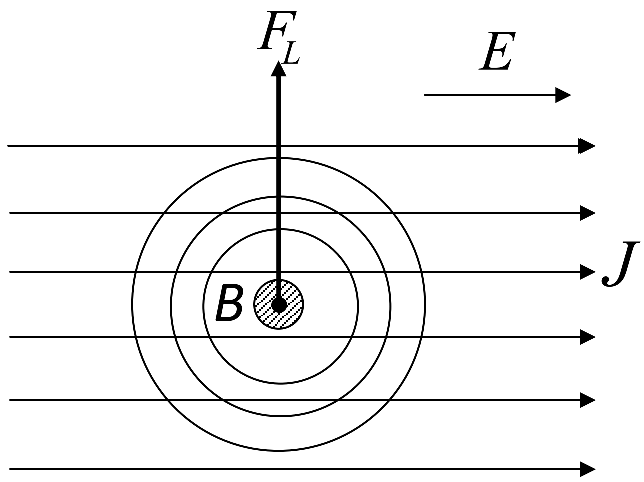

Figure 8. Vectorel expression of Lorentz force [12].

Within a perfectly homogenous system the driving Lorentz force is counteracted only by the friction force $F_\eta = -\eta v$,where v is the steady-state velocity of the vortex system. The dissipation is due to the appearance of a finite electiric field E as a consequence of the flux motion, $E = B \times \frac{v}{c}$. Since both **j** and **E** run parallel, the power is dissipated in the system and superconducting property of dissipation-free current flow is lost[12]. This force is perpendicular to both the current and the magnetic field. This case is illustrated in Fig. 8. In any type II superconductor, the Lorentz force on the vortex lattice is opposed by interactions between the vortices and pinning centres [45]. If this driving force is larger than the pinning force of the sample, the flux lines would begin to move. Flux motion can be prevented if the material contains imperfections that strongly and abruptly alter its superconducting properties over spatially small regions [44]. Vortex pinning occurs because the condensation energy (lost in the normal vortex core) can be regained by positioning the vortex on a defect [46]. The various defects in the material prevent the vortices from moving freely since the vortices are pinned down and do not move at all until a greater force acts upon on them to free the vortices from pinning. Defects which lead to sudden changes in the superconducting state such as grain boundaries and point defects can pin the vortices [47].

3. CONCLUSION AND DISCUSSION

Type-I superconductors completely expel an applied magnetic field. In type II superconductors below H_{c1} critical field, magnetic field totally is expelled. From H_{c1} critical field value to H_{c2} upper critical value, magnetic field penetrates superconductor partially which the form of quantized vortices. The HTSC are strongly type II, their phenomenology is dominated by the presence of vortices over most of the phase diagram. Their H-T phase diagram comprises a Meissner phase characterized by complete flux expulsion at low magnetic fields $H < H_{c1}$. In the intermediate region between H_{c1} and H_{c2} there is a mixed state at which the magnetic field penetrates into the superconductor in the form of quantized flux lines, or vortices. Vortices form a triangular vortex lattice, are called Abrikosov vortex lattice. With increasing field the density of vortices increases until the vortex cores overlap when the upper critical field is reached. Above this field superconductors recover the normal metal state.

As an electric current is passed through the superconductor, the Lorentz force will act between electrons and the magnetic field carried by vortices. If the vortices move in response to this force, work is done and so energy is dissipated and the sample behaves as though it had a finite electrical resistance even though it is superconducting.

Thermal fluctuations play an important role in HTSC. These fluctuations lead to melting of the Abrikosov vortex lattice. While at low temperatures, this lattice is vortex solid state, at high temperatures turns into vortex liquid to melt. The character of the transition between these two phases depends on the type and amount of disorder present in the system. In high-temperature superconductors a large region of the magnetic phase diagram is occupied by a vortex phase. This phase has a rich diversity due to several competing energy scales such as vortex elastic energy, pinning energy and the thermal energy.

REFERENCES

[1] F. Yang, "Heterogeneous vortex dynamics in high temperature superconductors", Doctoral Thesis, Ecole Polytechnique, Palaiseau, France, 13-19 (2009).

[2] B. Chen, W. P. Halperin, P. Guptasarma, D. G. Hinks, V. F. Mitrovic, A. P. Reyes, P. L. Kuns, "Two-dimensional vortices in superconductors", Nature physics, 3, 239-240 (2007).

[3] H. K.Onnes, "Investigations into the properties of substances at low temperatures, which have led, amongst other things, to the preparation of liquid helium", Nobel Lecture, 333-335 (1913).

[4] J.R. Schrieffer, "Macroscopic quantum phenomena from pairing in superconductors", Nobel Lecture, (1972).

[5] J. E. Hirsch, "Explanation of the Meissner effect and prediction of a spin Meissner effect in low and high Tc superconductors", Physica C, (2009).

[6] M. Sjöström, "Hysteresis modeling of high temperature superconductors", Doctoral Thesis, Swiss Federal Institute of Technology Lausanne, Stockholm, 25-32 (2001).

[7] J. Bardeen, L. N. Cooper, J. R. Schrieffer, "Theory of superconductivity", Phys. Rev., 108,1175-1180 (1957).

[8] N. Avraham , "Study of the thermodynamic nature of the disorder-driven vortex matter phase transition", Weizmann Institute of Science, 1-8 (2000).

[9] M. Cyrot, "Ginzburg-Landau theory for superconductors", Rep. Prog. Phys. ,36, 103 (1973).

[10] Z. Y. Wang, "On the mechanism of superconductivity", Physica C, 299, 256–258(1998).

[11] J. G. Bednorz, K. A. Müller "Perovskite-type oxides-The new approach to high-T_c superconductivity", Rev. Mod. Phy.,60, 585-595 (1998).

[12] G. Blatter, M.V. Feigelman, V.B. Geshkenbein, A.I. Larkin, V.M. Vinokur, "Vortices in high temperature superconductors", Reviews of Mod. Phy., 66 (4), 1130-1140 (1994).

[13] V. L. Ginzburg, "Nobel Lecture: On superconductivity and superfluidity (what I have and have not managed to do) as well as on the "physical minimum" at the beginning of the XXI century", Rev. Mod. Phy.,76, 981-990 (2004).

[14] V. L. Ginzburg, "On superconductivity and superfluidity", P. N. Lebedev Physics Institute, Russian Academy of Sciences, Nobel Lecture, (2003).

[15] G. Burns, "High Temperature Superconductivity An Introduction", Newyork, 9-27 (1992).

[16] J.C. Loudon, P.A. Midgley, "Imaging flux vortices in type II superconductors with a commercial transmission electron microscope", Department of Materials Sci. and Met., 1-6.

[17] J. R. Clem, "Anisotropy and two-dimensional behaviour in the high-temperature superconductors", Supercond. Sci. Technol, 909–914 (1998).

[18] A. A. Abrikosov, "Type II superconductors and the vortex lattice", Materials Science Division., 59-65 (2003).

[19] B. E. Arronte, "Resistivity and the vortex solid-to-liquid transition in high-temperature superconductors", Doctoral Thesis, Stockholm, Royal Institute of Technology, Sweden, 1-23 (2006). O $_{7\text{-}6}$

[20] J. F. Puig, "Defects and the vortex liquid state in superconducting textured YBa_2Cu_3", Doctoral Thesis, Department de materials magnetic superconductors, Bellaterra, 1-15 (2003).

[21] L. F. Cohen, H. J. Jensen, "Open questions in the magnetic behaviour of high-temperature superconductors", Rep. Prog. Phys., 60, 1581–1672 (1997).

[22] S., Karakaya, "The properties of vortex states in high temperature superconductors", Master Of Science Thesis, Eskişehir Osmangazi Üniversitesi Fen Bilimleri Enstitüsü, Eskişehir, 29-55 (2006).

[23] B. T. Maruszewski, A. Drzewiecki, R. Starosta, "Anomalous features of the thermomagnetoelastic field in a vortex array in a superconductor: propagation of love's waves", Journal of Thermal Stresses, 30, 1049–1065 (2007).

[24] R. A. Serway, "Fen ve Mühendislik İçin Fizik", 3, Palme Yayıncılık, 1290 (1996).

[25] C. Kıttel, "Introduction to Solid State Physics", 7nd edition, John Wiley&sons, Newyork, 338 (1996).

[26] A. M. Campbell, J. E. Evetts, "Flux vortices and transport currents in type II superconductors", Advances in Physics, 50, 1249-1449 (2001).

[27] Internet: http://hyperphysics.phy-astr.gsu.edu/hbase/solids/scbc.html#c4
[28] M. Tinkham, "Introduction To Superconductivity", 2nd ed., Singapore, 1-16 (1996).

[29] U. C. Tauber, "Localized Flux Lines and the Bose Glass",Cond. Mat.,1-5 (1996).

[30] M. B. Maple, "High Temperature Superconductivity", Pure and Applied Physical Sciences, California 92093, USA.

[31] D. Giller, "Disorder-induced vortex phase transition in high- temperature superconductors", Ph. D. Thesis, Bar-Ilan University, Israel, 2-5, (2002).

[32] J. Hu, A. H. MacDonald, "Universal phase diagram for vortex states of layered superconductors in strong T., magnetic fields", Physical Review B, 56, 2788-2790 (1997).

[33] Nishizaki, N. Kobayashi, "Vortex-matter phase diagram in $YBa_2Cu_3O_y$", Supercond. Sci. Technol., 13, 1-11 (2000).

[34] S. X. Dou, P.N. Mıkheenko, X. L. Wang , H. K. Liu, "High Temperature Superconductors", Institute of Materials Technology and Manufacturing, 363-368, Australia.

[35] V. Vinokur, B. Khaykovich, E. Zeldov, M. Konczykowski, R.A. Doyle, P.H. Kes, "Lindemann criterion and vortex-matter phase transitions in high-temperature superconductors", Physica C, 295, 209–217 (1998).

[36] R. Kato, Y. Enomoto, "Simulation of narrow-band noise induced by vortex dynamics in type-II superconducting films with periodic pinning arrays", Physica C, 1-3 (2005).

[37] S. L. Liu, G. J. Wu, H. J. Tan, X. B. Xu, H. M. Shao, " The transition from vortex liquid to vortex slush in $YB_2Cu_3O_y$ superconductors", Supercond. Sci. Technol., 19**,** 508–511 (2006).

[38] J. J. Chang, J. Mesot, "Microscopic neutron investigation of the Abrikosov state of high-temperature

[39] superconductors", Journal of Physics, 71 (4), 679-685 (2008).

[40] B. Davoudi, M. Kohandel, "Numerical study of the vortex phase diagram using the bose model in STLS approximation", Cond-Mat., 9908080(1), (2005).

[41] T. Nattermann, S., Scheidl, "Vortex-glass phases in type-II superconductors", Con.Mat. Supr., 1-3, 4-16, (2008).

[42] J. Kierfeld, V. Vinokur, "Lindemann criterion and vortex lattice phase transitions in type-II superconductors", Physıcal review, B 69, 1-5 (2004).

[43] Y. Y. Goldschmidt, "Phase transitions of the flux-line lattice in high-temperature superconductors with weak columnar and point disorder", Physical review B, 56, 2800-2803, (1997).

[44] J. Dietel, H. Kleinert, "Phase diagram of vortices in high-tc superconductors from lattice defect model with pinning", Con.Mat. Supr., 1-3 (2008).

[45] W. C. Chan, C. H. Chiang, Y. J. Hsu, "Direct Lorentz force measurement for $YBa_2Cu_3O_{7-\delta}$ superconductor", Cryogenics, 1-2, (2010).

[46] M. G. Blamire, R. B. Dinner, S. C. Wimbush, J. L. MacManus-Driscoll, "Critical current enhancement by Lorentz force reduction in superconductor–ferromagnet nanocomposites", Supercond. Sci. Technol., 22, 1-3 (2009).

[47] Kusevıc, E. Babı´c, "Vortex pinning and critical currents in nanostructured novel superconductors", Fizika A, 14, 75–88 (2004).

[48] S. Aktas, "The effects of point-like pinning in a vortex lattice", J. Phys. Condens. Matter, 8, 6747–6758, (1996).