Orissa Journal of Physics
ISSN 0974-8202

Vol. 26, No.2
August 2019
pp. 87-96

Study of magnetization in two band superconductor FeSe single crystal

G PUROHIT[1*], A PATTANAIK[2] and P NAYAK[1]

[1] School of Physics, Sambalpur University, JV, Burla, Odisha
[2] Department of Physics, IGIT Sarang, Odisha
** Corresponding author E-mail: geetanjolly@gmail.com*

Received: 11.06.2019 ; Revised : 12.7.2019 ; Accepted : 31.7.2019

Abstract. The magnetization anomaly of FeSe single crystal reported by Hafiez et al is examined through our Modified phenomenological Ginzberg–Landue (MPGL) theory applicable to two band superconducting systems. The present **MPGL** theory in the London limit calculates value of $\lambda_{ab}(0)$ as 445.696nm which is very close to the experimental value reported by Hafiez et al [**22**].

Keywords: Magnetization**,** two gap superconductor FeSe, MPGL theory, penetration depth.

PACS NO: 74.25.Bt, 74.20.De, 74.70 Vy

1. Introduction

FeSe has concerned substantial interest in recent times from other members of iron based superconductors (Fe-SC) because of its some unique features, The unique features are, (i) crystal structure of FeSe is regarded as representative of the entire family of Fe-SC (ii) its transition temperature T_c=8K [1] can be raised to 37K by the application of pressure [2-5] and to 50-100K by growing it as a monolayer on a $SrTiO_3$ substrate [6-9], (iii) high-quality single crystals with rather large dimensions can be grown [10-12] which are necessary for an accurate determination of bulk physical properties, (iv) it goes through a structural phase transition from a tetragonal to an orthorhombic phase at $T_s \approx 87$ K [13],which is not followed by a long-range magnetic order, (v) FeSe has simplest layered crystal structure and stoichiometry with critical temperature of about 8K for polycrystalline sample [14],(vi) Different experiments detected different superconducting gap structures while most experiments detected two superconducting gaps [2, 15–22] in FeSe single crystal,(vii)it is regarded as the most simplest Fe-based superconductors for studying the pairing mechanism [23].

The most mysterious property here is not even the pressure or strain induced T_c increase (the cuprates have already shown the tendency of increased T_c with reduction of the dimensionality), but a giant enhancement of the superconductivity at the Fe/$SrTiO_3$ interface, where $SrTiO_3$ (STO) has nothing in common with magnetic interaction [24].Although FeSe system possesses many attractive features, the investigation of its physical properties is still in infancy.

The isotope effect experiments in Fe-based superconductors show the iron isotope exponent (α_c) values between 0.35 up to 0.4. Thus, one could infer that electron pairing in superconductors of the FeSe family is facilitated by electron-phonon interaction. Furthermore, pure magnetic or spin-orbital interactions affect the interband coupling leading to decrease of thermodynamic T_c like in the case of MgB_2. Identifying the origin of the SC pairing mechanism is the key to understanding these interesting properties of FeSe [25]**.** The Fermi energy of FeSe is found to be extremely small and comparable to the superconducting energy gap (Δ), indicating that superconductivity in FeSe is realized in the crossover regime from Bardeen Cooper-Schrieffer (BCS) to Bose-Einstein-condensation (BEC) [20].

In HTSCs there exists a broad field domain where the reversible magnetization M is linear in logarithm of applied field (B_a).This behavior of of dependence of $M(\ln(B_a))$ implies the strong uniaxial anisotropy. This behavior implies a procedure of extracting the procedure for penetration depth from the linear part of the curve $M(\ln(B_a))$ vs.B_a [26]

Hafiez et al [22] investigated the FeSe to understand the properties of superconductors through lattice modification caused by doping sulphur (S) in the system. The authors investigated the superconducting properties $FeSe_{1-x}S_x$ (x=0, 0.04, 0.09, and 0.11). The study gives a conclusion that although the electronic specific heat of the SC state can be well described by using a two-band model, the change of specific heat induced by a magnetic field can be understood only in terms of multiband superconductivity.

Taking the data for pure sample (x=0),in FeSe single crystal the values of $\Delta_1(T)/K_BT_c$ and $\Delta_1(0)/K_BT_c$, for larger gap are found to be 1.95 and 2.2 while $\Delta_2(T)/K_BT_c$, $\Delta_2(0)/K_BT_c$ for smaller gap are found to be 0.79 and 0.88 [22] .The values of larger energy gap (Δ_1(T), Δ_1(0)) and smaller energy gaps (Δ_2(T), Δ_2(0)) are comparable with those obtained from two band s-wave fit of specific heat data and Andreev reflection spectroscopy results [11,18].

Here, we have tried to explain magnetization anomaly of FeSe single crystal repoted by Hafiez et al.[22] and variation of in plane magnetic penetration depth λ_{ab} (T) with the temperature for FeSe single crystal. For this we have used the modified two band Gl theory. In addition we have tried to calculate λ_{ab} (0) for FeSe single crystal by using two gaps superconductivity as it is a two gap superconductor .The calculated result is very close to the experimental value reported by Hafiez et al [22]. The detailed procedure of calculations is given in next section.

2. Formalism

The theory developed by Kogan et al[**26**] and Mitra et al. [27] is proved to be successful to explain the magnetization anomaly of cuprate superconductors [28].They have explained the temperature dependent penetration depth λ(T) of cuprate superconductors. In addition the theory developed by Abrikosov et al [29] is used to explain the in plane penetration depth λ_{ab}(0) and λ_{ab}(T) in BCS clean limit and dirty limit for cuprate superconductors [28] due to single gap structure .For two gap superconductors like FeSe, it is not easy to explain anisotropic properties by using the above theory. So explain such anisotropic properties initial attempts were made through different approaches. Huang and Peng-Li Lv [30] have tried to explain upper critical field anisotropy though two band GL theory for KFe_2As_2. Here we have tried to explain the magnetization anomaly given by Hafiez et al [22] by modifying the single band λ(0) equation of Abrikosov et al [29] using our two band approximation [31] for another FeSe two band system due to the presence of two superconducting energy gaps .On comparison we find our calculated results show very close to that of experimental findings by [22]. The modification theory is given below

$$4\pi M = \frac{\phi_0}{8\pi\lambda_{\exp}^2}\ln(B_a)$$

The expression for magnetization found by Kogan et al. [26]

(Neglecting constant term) (1)

where M=magnetization,Φ_0=quantum of magnetic flux $=2.07\times10^{-7}$ Gcm^2,λ_{exp}=London penetration depth and B_a=applied magnetic field.

The temperature dependent in plane penetration depth [**26**] is given by

$$\lambda_{ab}(T) = \lambda_{\exp}\sqrt{f(\gamma)/2\gamma} \tag{2}$$

$$f(\gamma) = \gamma + (\gamma^2 - 1)^{-1/2}\ln\{(\gamma^2 - 1)^{1/2} + \gamma\} \tag{3}$$

From dirty limit one finds [29]

$$\lambda_{ab}(0) = \lambda_{ab}(T)\sqrt{\frac{\Delta(T)\tanh\left(\Delta(T)/2k_B T\right)}{\Delta(0)}} \tag{4}$$

Here Δ(T) is the temperature dependent energy and Δ(0) is energy gap at zero temperature.

FeSe is a two gap superconductor. It consists of two energy gaps ,one is larger ($\Delta_1(T)/K_BT_c$=1.95, $\Delta_1(0)/K_BT_c$=2.2) and smaller one is ($\Delta_2(T)/K_BT_c$=0.79, $\Delta_2(0)/K_BT_c$=0.88)**[22]**. So the above equation(4) is splitted into two equations for larger and smaller gaps assuming these energy gaps do exist along c-axis and ab directions.

$$\lambda_{ab1}(0) = \lambda_{ab}(T)\sqrt{\frac{\Delta_1(T)\tanh\left(\Delta_1(T)/2k_B T\right)}{\Delta_1(0)}} \tag{5}$$

$$\lambda_{ab2}(0) = \lambda_{ab}(T)\sqrt{\frac{\Delta_2(T)\tanh\left(\Delta_2(T)/2k_B T\right)}{\Delta_2(0)}} \tag{6}$$

3. Result and discussion

In one of the paper Abdel-Hafiez et al. (2015) [22] have reported the behavior of the specific heat and magnetization in a recently discovered FeSe single crystal having critical temperature approximately 8.5 K. In this paper the author have reported magnetization (M) versus field (B_a) curves at different temperatures and determined the absolute value of in plane penetration depth $\lambda_{ab}(0)$ as 446nm for FeSe single crystal. In addition they have also determined the value of anisotropic ratio as 2 for FeSe single crystal.

Here, we have tried to explain the magnetization anomaly in terms of λ_{ab}(T) and λ_{ab}(0) for FeSe single crystal following the magnetization properties of the FeSe crystal as a function of applied magnetic field and modified two band GL model developed by Purohit and Nayak (2016**)** [31]**.** The anisotropic properties of different quantities can be estimated in different way i.e. through mass anisotropy as $\gamma = \sqrt{m_c / m_{ab}}$,where m_c and m_{ab} are effective masses along c and ab directions respectively, one can also calculate the same value through upper critical field anisotropy as $B_{c2}^{\|c} / B_{c2}^{\|ab}$ .Similarly from resistivity analysis where the value of resistivity along c (ρ_c) is slightly differ from resistivity along ab directions (ρ_{ab}), so that γ can be expressed as ρ_c/ρ_{ab}. The ratio $\lambda_c(0)/\lambda_{ab}(0)$ also gives the value of γ where λ_c and λ_{ab} are evaluated through the square root of reciprocal of slope of the linear fit of specific heat curve for the field applied along c and perpendicular c directions. So that γ [32] is represented as

$$\gamma = \lambda_c(0)/\lambda_{ab}(0) = \sqrt{m_c / m_{ab}} = B_{c2}^{\|c} / B_{c2}^{\|ab} = \rho_c/\rho_{ab}$$

In this thesis, we have tried to explain the magnetization anomaly in terms of λ_{ab}(T) and λ_{ab}(0) for FeSe single crystal by using modified two band Gl theory developed by Kogan et al**.**[26] and Mitra et al.[27] taking the data from magnetization(M) vs. field (B_a) with different temperature(T) curve of the paper reported by Abdel-Hafiez et al. (2015) [22].The detailed procedure is given below.

The linear regression is obtained through the least square fit for a given temperature by the equation (1) .Thus the graphs are plotted between 4πM vs. ln (H) for temperatures 3,3.5 , 4 and 4.5 K for fields parallel to c- axis. The slope of each of the regression gives the values of $\phi_0 / 8\pi\lambda_{\exp}^2$ .So λ_{exp} values for the temperatures 3, 3.5, 4 and 4.5 K have been found from $\sqrt{\Phi_0 / 8\pi(slope)}$. The sample linear regressions curve along the c direction has been shown in the Figures 1**.** The variation of λ_{exp} with the temperature (T) has been displayed in Figure 2.

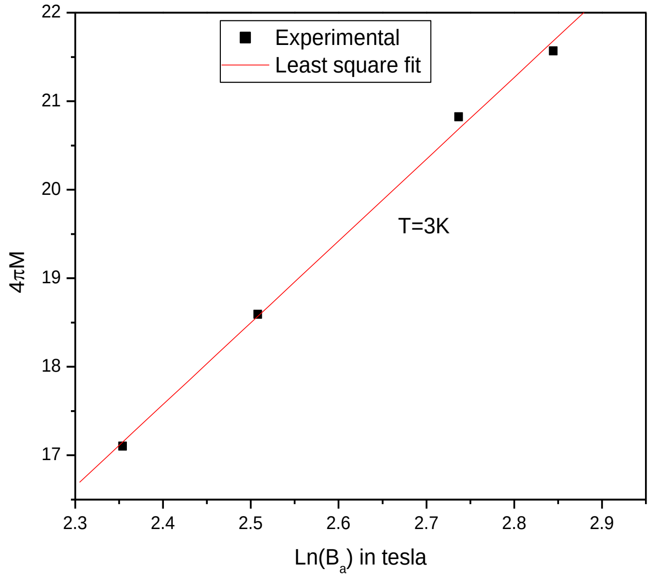

Fig.1. Sample curve of regression at applied field parallel to c-axis

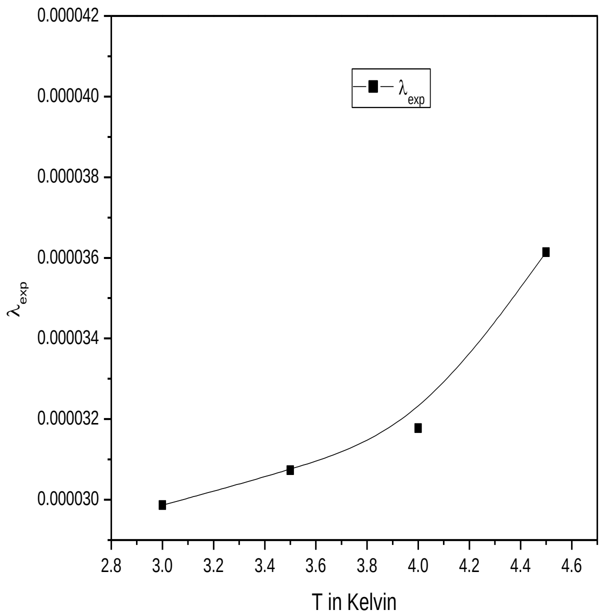

Fig. 2. The variation of λ_{exp} with the temperature (T)

Assuming anisotropic ratio γ=2 [22], using equations (2) and (3), we have calculate the values of λ_{ab}(T) for temperatures 3,3.5 ,4 and 4.5 K. The variation of λ_{ab}(T) with the temperature (T) has been displayed in Figure 3. From the figure it is clear that λ_{ab}(T) increases with the increase of temperature which is same as reported by Abdel-Hafiez et al. (2015) [22].

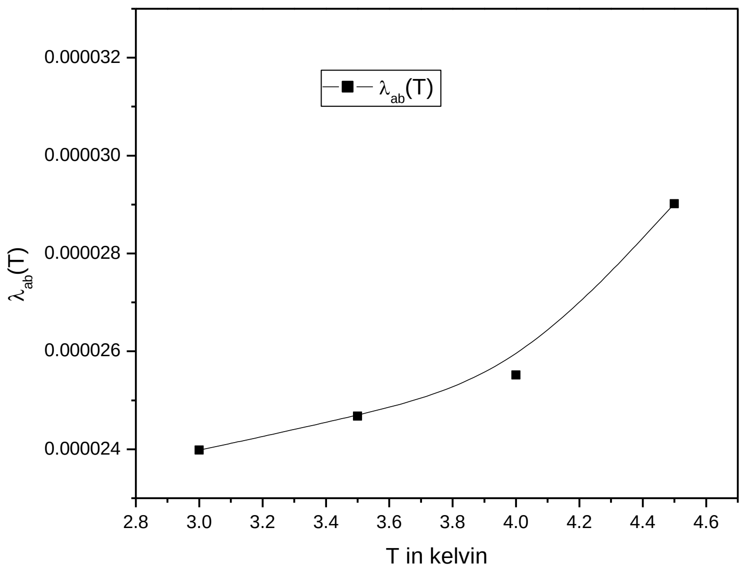

Fig.3. The variation of λ_{ab}(T) with the temperature (T)

For dirty limit .by using equation (5),the values of $\lambda_{ab1}(0)$s are calculated for temperatures 3,3.5 , 4 and 4.5K for larger gap. The average values of penetration depth $\lambda_{ab1}(0)$ is found to be 239.514nm for larger gap. For dirty limit by using equation (6) ,the values of $\lambda_{ab2}(0)$s are calculated for temperatures 3,3.5, 4 and 4.5K for smaller gap .The average value of $\lambda_{ab2}(0)$ is found to be 206.181nm for smaller gap. The total value of penetration depth $\lambda_{ab}(0)(= \lambda_{ab1}(0)+\lambda_{ab2}(0))$= 445.696nm which is close to the value reported by Hafiez et al [22]

4. Conclusion

MPGL theory in the London limit has been successfully applied to the single crystal FeSe system.

References

[1] R Khasanov, K Conder, E Pomjakushina, A Amato, C Baines, Z Bukowski, J Karpinski, S Katrych, H.-H. Klauss, H Luetkens and A Shengelaya, N D Zhigadlo, *Phys. Rev*. **B 78**,220510(R) (2008)

[2] F C Hsu, J Y Luo, K W Yeh, T K Chen, T W Huang, P M Wu, Y C Lee, Y L Huang, Y Y Chu, D C Yan and M K Wu, *Proc. Natl. Acad. Sci. U S A.* **105,** 14262 (2008)

[3] Y Mizuguchi,F Tomioka, S Tsuda, T Yamaguchi,Y Takano, *Appl. Phys. Lett*. **93,** 152505 (2008)

[4] S Medvedev, T M. McQueen, I Trojan, T Palasyuk, M I Eremets, R J Cava, S Naghavi, F Casper, V Ksenofontov, G Wortmann and C Felser, *Nature Mater*. **8**, 630 (2009)

[5] S Margadonna, Y Takabayashi, Y Ohishi, Y Mizuguchi, Y Takano, T Kagayama, T Nakagawa, M Takata, and K Prassides, *Phys. Rev. B* **80**, 064506 (2009)

[6] T Imai, K Ahilan, F L Ning, T M McQueen and R J Cava, *Phys. Rev. Lett*. **102,** 177005 (2009)

[7] W Q.-Yan , L Zhi , ZW Hao , Z Z.-Cheng , ZJ Song , Li Wei , D Hao , OY.-Bo , D Peng , C Kai , Wen Jing, S C.Li , H Ke , J J Feng, J S.-Hua , WY-Yu , W L-Li , C Xi , M X.Cun , X Q-Kun, *Chin. Phys. Lett*. **29**, 037402 (2012)

[8] J.-F Ge, Z L.Liu, C Liu, C L Gao, D Qian, Q K Xue,Y Liu, J F Jia, *Nature Mater*. **14**, 285 (2015)

[9] Q Fan, WH Zhang, X Liu, YJ Yan, MQ Re, R Peng, HC Xu, BP Xie, JP Hu, T Zhang and DL Feng, *Nature Phys*. **11**, 946 (2015)

[10] Y Zhang, J J. Lee, R G. Moore, W Li, M Yi, M Hashimoto, D H Lu, T P Devereaux, D-H Lee and Z-X Shen, *Phys. Rev. Lett*. **117,** 117001 (2016)

[11] A E Böhmer, F Hardy, F Eilers, D Ernst, P Adelmann, P Schweiss, T Wolf, and C Meingast, *Phys. Rev*. **B 87**,180505(R) (2013)

[12] D Chareev, E Osadchii, T Kuzmicheva, J-Y Lin, S Kuzmichev, O Volkova and A Vasiliev, *Cryst. Eng.Comm*. **15,** 1989 (2013)

[13] R Hu, H Lei, M Abeykoon, E S Bozin, S J L Billinge and J B Warren, Theo Siegrist and C Petrovic, *Phys. Rev*. **B83**, 224502 (2011)

[14] T M McQueen, A J Williams, P W Stephens, J Tao, Y Zhu, V Ksenofontov, F Casper, C Felser and R J Cava, *Phys. Rev. Lett*. **103**, 057002 (2009)

[15] J K Dong, T Y Guan, S Y Zhou, X Qiu, L Ding, C Zhang, U Patel, Z L Xiao and S Y Li1, *Phys. Rev*. **B 80**, 024518 (2009)

[16] R Khasanov, M Bendele, A Amato, K Conder, H Keller, H-H. Klauss, H Luetkens and E Pomjakushina, *Phys. Rev. Lett*. **104**, 087004(2010)

[17] YG Ponomarev, SA Kuzmichev, MG Mikheev, MV Sudakova, SN Tchesnokov, TE Shanygina, OS Volkova and AN Vasiliev, *Th.wolf, J. Exp. Theor. Phys*. **113**, 459 (2011)

[18] J-Y. Lin, Y S Hsieh, D A Chareev, A N Vasiliev, Y Parsons, H D Yang, *Phys. Rev*. **B 84**,220507(R) (2011)

[19] M Abdel-Hafiez, J Ge, A N Vasiliev, D A Chareev, J Van de Vondel, V V Moshchalkov and AV Silhanek, *Phys. Rev*. **B 88**, 174512 (2013)

[20] S Kasahara, T Watashige, T Hanaguri, Y Kohsaka, T Yamashita, Y Shimoyama, Y Mizukami, R Endo, H. Ikeda, K Aoyama, T Terashima, S Uji, T Wolf, H von Löhneysen, T Shibauchi, Y Matsuda, *Proc. Natl. Acad.Sci*. **111,** 16309 (2014)

[21] P Bourgeois-Hope, S Chi, D A Bonn, R Liang, W N Hardy, T Wolf, C Meingast, N Doiron-Leyraud and Louis Taillefer, *Phys. Rev*. **Lett. 117**, 097003 (2016)

[22] M Abdel-Hafiez, Y-Y Zhang, Z-Y Cao, C-G Duan, G Karapetrov,VM Pudalov, V A Vlasenko, DA Chareev, OS Volkova, AN Vasiliev and X-J Chen, *Phys. Rev*. **B 91**, 165109 (2015)

[23] R Thomale, C Platt, W Hanke, J Hu and B A Bernevig, *Phys. Rev. Lett*. **107**, 117001 (2011)

[24] J J Lee, FT Schmitt, R G. Moore1, S Johnston, Y-T.Cui, W Li, M Yi, Z K Liu, M Hashimoto, Y Zhang, DH. Lu, T P Devereaux, D-H Lee and Z-X Shen, *Nature* (*London*) **515**, 245 (2014)

[25] R H. Liu, T Wu, G Wu, H Chen, X F Wang, Y L Xie, J J Ying, Y J Yan, Q J Li, B C Shi, W S Chu, ZY Wu and X H Chen, *Nature* (*London*) **459**, 64 (2009)

[26] VG Kogan, MM Fang and S Mitra, *Phys. Rev*. **B38**, 11958 (1988)

[27] S Mitra, J H Cho, W C Lee, D C Johnston and V G Kogan, *Phys. Rev.* B **40**, 2674 (1989)

[28] A Schilling, F Hulliger and H R Ott, *Z. Phys.* B **82**, 9(1991)

[29] A A Abrikosov, LP Gor'kov and IY Dzyaloshinskii, *Physics* (Pergamon, Oxford, 1965)

[30] H Huang and P-L Lv, *J. Supercond Nov Magn* **26**, 3037 (2013)

[31] G Purohit and P Nayak, *J Supercond and Nov*. *Magn*. **29,** 1279 (2016)

[32] M Zehetmayer, *Supercond. Sci. Technol*. **26**, 043001 (2013)