

THE THIRD CRITICAL FIELD (H_{c3}) OF SINGLE-CRYSTALLINE $K_{0.73}Fe_{1.68}Se_2$ BY GINZBURG-LANDAU APPROACH

Atirat Maksuwan¹, Arpapong Changjan^{1,*}, Phanuchai Pramuanl¹, Sumitta Meakniti², and Pongkaew Udomsamuthirun²

Received: December 20, 2021; Revised: May 08, 2022; Accepted: May 10, 2022

Abstract

In this paper, two-band Ginzburg-Landau (GL) equations for magnetic superconductors were solved analytically to determine the temperature dependence of surface critical magnetic field (H_{c3}). By variation method analytically from 1st GL equations and modified to the Changjan & Udomsamuthirun's temperature dependence model. We found that, our model could find a good agreement with the experimental data of single-crystalline $K_{0.73}Fe_{1.68}Se_2$ superconductors vicinity the critical temperature scenery and the ratio H_{c3}/H_{c2} (where H_{c2} is the upper critical field of single-crystalline $K_{0.73}Fe_{1.68}Se_2$) indicated powerful temperature dependence.

Keywords: Ginzburg-Landau theory, Magnetic Superconductors, Surface critical magnetic field (H_{c3})

Introduction

Superconductivity is a phenomenon that distinguished in certain materials where electrical resistance disappearance and the external magnetic fields are expelled from the material at low temperature (Ketterson and Song, 1998). Any material exhibiting these properties is a superconductor. The first superconductor was discovered in mercury in 1911 by Onnes (Buckel, 1991). Over a century since this discovery, superconductivity has become the underpinning technology for many of the world's most important science experiments and applied technology in many fields (Bray, 2009).

Superconducting magnets can produce greater magnetic fields, then it can applied to NMR (Nuclear Magnetic Resonance) and MRI (Magnetic Resonance Imaging). NMR spectrometers are used in biology, chemistry and pharmacy to study the structure, the interaction and the kinetics of complex molecules (Tampieri *et al.*, 2020) and MRI helping to give doctors an unprecedented view of structures deep within the human body (Aarnink and Overweg, 2012). The application of superconductors in addition to high-power electromagnetism also has a wide range of applications such as electronics and

¹ Department of Environmental Technology and Applied Science, Faculty of Science and Technology, Pathumwan Institute of Technology, Bangkok 10330, Thailand. Tel. 0-2104-9099; E-mail: otto_sinkronity@yahoo.com

² Prasarnmit Physics Research Unit, Department of Physics, Faculty of Science, Srinakharinwirot University, Sukumvit 23 Road, Bangkok 10110, Thailand

* Corresponding author

sensors (Bray, 2009). The Josephson effect (Tinkham, 1996) refers to the interesting ac and dc properties of current transfer between two superconductors which have a weak connection between them. This phenomena enabled devices such as SQUIDS (Superconducting QUantum Interference Devices) for the most accurate measurement of weak magnetic fields (Swithenby, 1980; Drung *et al.*, 2007) and voltage (Klushin *et al.*, 2002). Moreover, Superconductor was a core technology in accelerators (Georgescu, 2020) and thermonuclear fusion reactors (Zhai *et al.*, 2020). Although superconductor is currently widely applied in various fields, the understanding of the mechanism of superconductivity is unclear. Understanding the fundamental properties of superconductors is one of the keys to understanding the mechanism of superconductivity. The critical magnetic field is one of the fundamental properties of superconductors. For Type II superconductors, at lower critical field (H_{c1}) the applied field cannot penetrate into the superconductor. During lower critical field (H_{c1}) and upper critical field (H_{c2}), the external field begins to moderately pass through the superconductor. The sample is in a mixed condition with non-uniform flux penetration (mixed state) (Tinkham, 1996) and the superconductivity disappear above H_{c2} . Type II superconductor can be applied in many technologies because the H_{c2} can be quite high. Upon the applied field rather than H_{c2} , the superconducting state remains as thin layer on material's surface. This superconducting film could be completely destroyed when the applied external field over surface critical field (H_{c3}). The study on H_{c3} of superconductor was expected to be the guide line for preparation of thin film superconductors and further to develop the efficiency of superconductors (Meakniti *et al.*, 2014).

The first Fe-based superconductor was found in the oxypnictide $LaFeAs(O,F)$ at 26 K by Hosono group in 2008 (Kamihara *et al.*, 2008). To substitutions of the La by different rare earth (RE) elements (Sm, Ce, Nd, Pr and Gd) the critical temperature of Fe-based superconductor increases up to 55 K with Sm (Zhi-An *et al.*, 2008). Most of Fe-based superconductors are generally categorized into five systems by difference in chemical composition, and are called 11, 111, 122, 1111, and perovskite-type oxide systems (Shimoyama, 2014). To investigate the strain effect on the superconducting properties of thin films Fe-based show the critical temperature (T_c) can be tuned by strain (Lee *et al.*, 2010; Kawaguchi *et al.*, 2014) and higher T_c of superconducting film with respect to bulk materials (Bellingeri *et al.*, 2010). After the discovery of superconductivity in iron pnictides, it was noticed that the Fe-based superconductor possess an

extremely large upper critical field (Zhang *et al.*, 2011). As an example, the upper critical fields of the single crystalline $NdFeAsO_{0.82}F_{0.18}$ ($T_c = 49$ K) (Jia *et al.*, 2008) and $Ba_{0.55}K_{0.45}Fe_2As_2$ ($T_c = 30$ K) (Ni *et al.*, 2008) near T_c which were determined from the resistive measurements. Yin *et al.* (2009) presented an atomic resolution scanning tunneling spectroscopy study of superconducting $BaFe_{1.8}Co_{0.2}As_2$ single crystals in magnetic fields up to 9 T. $BaFe_{1.8}Co_{0.2}As_2$ is predicted to have an upper critical field of 43 T from the measured coherence length of 2.8 nm. Yuan *et al.* (2009) reported measurements of the electrical resistivity in single crystals of $(Ba,K)Fe_2As_2$ in a magnetic field up to 60 T. They found that the superconducting properties are in fact quite isotropic, being rather independent of the direction of the applied magnetic fields at low temperature. Fang *et al.* (2010) determined the resistive upper critical field of $Fe_{1.11}Te_{0.6}Se_{0.4}$ single crystals for fields applied both ab-plane and c-axis direction. It is found that the anisotropy of the upper critical field decreases with decreasing temperature and becoming rather isotropic at low temperature. Tsindlekht *et al.* (2011) reported the results of an experimental study of magnetic properties of a $K_{0.73}Fe_{1.68}Se_2$ single crystal when the external magnetic field is applied parallel to the ab-plane. The $H_{c3}(T)/H_{c2}(T) \approx 4.4$ at near T_c . Lin *et al.* (2014) fabricated $Sr_{0.6}K_{0.4}Fe_2As_2$ (Sr-122) tapes by hot pressing (HP) process and obtain critical current density (J_c) as 1.2×10^5 A/cm² at 4.2 K and 10 T. The very high H_{c2} , low anisotropy and large critical current values, which are only weakly reduced by magnetic fields at low temperatures, suggested considerable potential in large scale applications and due to the fact that this value is very high exceeds the capability of the common high field measurement system, so a theoretical model is needed for helping the experimenter to predict this quantity (Changjan and Udomsamuthirun, 2011a).

The Ginzburg-Landau (GL) theory is widely used to study the magnetic behavior of superconductor. However, the method of GL theory usually works only in the vicinity of the critical temperature (Ketterson and Song, 1998). Two-band GL theory were propose to studied the temperature dependence of lower (Askerzade *et al.*, 2002b), upper (Askerzade *et al.*, 2002a; Udomsamuthirun *et al.*, 2006) and thermodynamic critical field (Askerzade and Gencer, 2002) for non-magnetic superconductors. de Gennes and Saint-James (1963) explained the relationship between the surface critical magnetic field to the upper critical magnetic field as by solving the linearized GL equation for single-band isotropic superconductors. Askerzade (2003) determined the temperature dependence of H_{c3} for

a bulk MgB₂ analytically by two-band GL theory. It was showed that H_{c3} had the same temperature dependence with H_{c2} and the temperature dependence for H_{c3} gave positive curvature near T_c. Liu (2007) investigated the surface critical field (H_{c3}) of MgB₂ in the clean limit by the two-band GL theory. The ratio H_{c3}(T)/H_{c2}(T) exhibits strong temperature dependence. The Gibbs free energy of magnetic superconductors has been analyzed for magnetic superconductors (Hampshire, 1998; 2001). By included the spatial variation and the nonlinear magnetic response of the magnetic ions in-field, GL equations of magnetic superconductors had been found. Changjan and Udomsamuthirun (2013) studied the critical temperature of the two-band magnetic superconductor by Ginzburg-Landau (GL) approach in the absent of external magnetic field. The critical temperature ratio decreased as the interband-to-band ratio increased. The upper and lower critical fields of an anisotropic magnetic superconductor were explored by GL theory in single band (Changjan and Udomsamuthirun, 2011a) and two-band case (Changjan and Udomsamuthirun, 2011b). The surface critical magnetic field of magnetic superconductors was enquired by single-band GL approach (Changjan *et al.*, 2017) that included the Gibbs free energy of Hampshire (Hampshire, 1998; 2001). The temperature-dependent surface critical magnetic field was studied by four models; Chen's model (Chen *et al.*, 2011), Zhu's model (Zhu *et al.*, 2011), Shanenko's model (Shanenko *et al.*, 2011) and Changjan & Udomsamuthirun's model (Changjan and Udomsamuthirun, 2013).

In this research, we investigated the surface critical magnetic field of magnetic superconductors by two-band GL Theory and modified to the temperature dependence model of Changjan & Udomsamuthirun (Changjan and Udomsamuthirun, 2013). Finally, the ratio of temperature-dependent surface critical magnetic field over upper critical field (H_{c3}(T)/H_{c2}(T)) was investigated and applied to experimental data of K_{0.73}Fe_{1.68}Se₂ Superconductors (Tsindlekht *et al.*, 2011).

Materials and Methods

According to the two-band Ginzburg and Landau theory, there are two order parameters in the Ginzburg-Landau functional. The free energy of magnetic superconductors is of the form (Hampshire, 1998; 2001; Changjan and Udomsamuthirun, 2011b).

$$F_{sc}[\psi_1, \psi_2] = \int d^3r f_{sc} = \int d^3r (F_1 + F_2 + F_{12} + \int H_s dB) \quad (1)$$

With

$$F_{i(i=1,2)} = \frac{1}{2m_i} |(-i\hbar \nabla - 2e\vec{A})\psi_i|^2 + \alpha_i |\psi_i|^2 + \frac{1}{2} \beta_i |\psi_i|^4 \quad (2)$$

$$F_{12} = \varepsilon(\psi_1^* \psi_2 + c.c.) + \varepsilon_1 \left\{ (i\hbar \nabla - 2e\vec{A})\psi_1^* (-i\hbar \nabla - 2e\vec{A})\psi_2 + c.c. \right\} \quad (3)$$

Here, F_i and F_{12} are the free energy of the separate bands and the interaction term between bands respectively. m_i denotes the effective mass of carriers. ψ_i is the order parameter and $|\psi_i|^2$ is proportional to the density of carriers, the coefficient α_i depends on the temperature, while coefficient β_i is independent of temperature. $c.c.$ indicate the complex conjugate of previous term. The first term in Equation (2) accounts for the kinetic energy of the carriers and the last term in Equation (1) accounts for the energy stored in the local magnetic fields. $H_s = \frac{B}{\mu_0} - M_{ions}$, $M = M_{sc} + M_{ions}$ and $M_{ions} = \chi H_s$, where $\mu_0 M_{sc}$ is the field produced by the carriers and $\mu_0 M_{ions}$ is the field produced by the ions. When the magnetic superconductors place in magnetic field, there are the field produced by ions ($\mu_0 M_{ions}$), the applied field (μ_0) and the field produced by the carriers ($\mu_0 M_{sc}$) that can produce relationship between field as $B = \mu_0 H + \mu_0 M_{sc} + \mu_0 M_{ions}$ and $M_{ions} = \chi H_{c2}(T) + \chi'(H - M_{sc} - H_{c2})$ so that $B = \mu_0(\chi - \chi')H_{c2} + \mu_0(1 + \chi')(H + M_{sc})$ where the differential susceptibility (χ') is $\left(\frac{\partial M_{ions}}{\partial H}\right)_{T, H=H_{c2}}$ and susceptibility (χ) is $\left(\frac{M_{ions}}{H}\right)_{T, H=H_{c2}}$.

The properties of magnetic superconductors were depended on the interaction between the ions, superelectrons, and applied magnetic field. The magnetic respond can be a ferromagnetic contribution from the superconductivity that the superelectrons produce a field adding to the applied magnetic field. For small change in B-field, a series in B is introduced (Hampshire, 1998; 2001).

$$\gamma_0 + \gamma_1 B + \gamma_2 \frac{B^2}{2\mu_0} = \int (B - \mu_0 M_{ions}) \frac{dB}{\mu_0} - (B - \mu_0 M) M_{sc} - (B - \mu_0 M) M_{ions} \quad (4)$$

Here γ_0 , γ_1 , and γ_2 are coefficient parameters and $\gamma_1 = 1$ for non-magnetic superconductors. The coefficient parameter γ_1 depends on the gradient of field and $\gamma_1 = 0$ for the uniform applied field. Rewrite the free energy of two-band magnetic superconductors from Equation(1) as

$$F_{sc}[\psi_1, \psi_2] = \int d^3r f_{sc} = \int d^3r \left(F_1 + F_2 + F_{12} + \gamma_0 + \gamma_1 B + \gamma_2 \frac{B^2}{2\mu_0} \right) \quad (5)$$

We investigate the temperature dependence on the surface critical magnetic field of two-band magnetic superconductor by variation Equation (5) with respect to ψ_i^* ($i = 1, 2$) in order to an energy of the system is lowest by $\frac{\partial F_{sc}}{\partial \psi_i^*} = 0$. The 1st linearization GL equations including the magnetic ions can be found as:

$$\frac{1}{2m_1}(-i\hbar\nabla - 2e\vec{A})^2\psi_1 + \alpha_1\psi_1 + \varepsilon\psi_2 - \varepsilon_1(-i\hbar\nabla - 2e\vec{A})^2\psi_2 = 0, \quad (6)$$

$$\frac{1}{2m_2}(-i\hbar\nabla - 2e\vec{A})^2\psi_2 + \alpha_2\psi_2 + \varepsilon\psi_1 - \varepsilon_1(-i\hbar\nabla - 2e\vec{A})^2\psi_1 = 0. \quad (7)$$

Let $\psi_1(x) = e^{-\frac{\delta x^2}{2}}$, $\psi_1(x) = C\psi_2(x)$, $\alpha_1 = \alpha_2 = \alpha$, $m_1 = m_2 = m$ and set boundary conditions $\psi_1(\infty) = 0$, $\frac{d\psi_1(0)}{dx} = 0$ (Askerzade, 2003). Substitution in Equations (6) and (7) and combine two equation together, we get

$$-\hbar^2\left(\frac{1}{2m} - \varepsilon_1\right)\frac{d^2\psi_1}{dx^2} - 4e^2\left(\frac{1}{2m} - \varepsilon_1\right)\vec{A}^2\psi_1 + (\alpha + \varepsilon)\psi_1 = 0 \quad (8)$$

Determine the external magnetic field is on the z-direction then the vector potential can be represented by

$$\vec{A} = (0, B_o(x - x_o), 0) = (0, [\mu_0(\chi - \chi')H_{c2} + \mu_0(1 + \chi')(H + M_{sc})](x - x_o), 0) \text{ and } \frac{1}{\lambda} = \frac{\hbar}{2e}. \text{ So that}$$

$$-\frac{1}{\lambda B_o}\frac{d^2\psi_1}{dx^2} - \lambda B_o(x - x_o)^2\psi_1 = \frac{\lambda}{B_o} \cdot \frac{(\alpha + \varepsilon)}{4e^2\left(\frac{1}{2m} - \varepsilon_1\right)}\psi_1. \quad (9)$$

Let

$$\xi = (\lambda B_o)^{\frac{1}{2}}x, \quad \xi_o = (\lambda B_o)^{\frac{1}{2}}x_o, \quad \beta = \frac{\lambda}{B_o} \cdot \frac{(\alpha + \varepsilon)}{4e^2\left(\frac{1}{2m} - \varepsilon_1\right)}, \quad \xi^2 = (\lambda B_o)x^2,$$

therefore

$$-\frac{d^2\psi_1}{d\xi^2} - (\xi - \xi_o)^2\psi_1 = \beta\psi_1. \quad (10)$$

Determine surface critical magnetic field by setting $\psi_1 = e^{-\frac{1}{2}b\xi^2}$. By variation method, $\beta = \frac{\int_0^\infty \left[\left(\frac{d\psi}{d\xi}\right)^2 + (\xi - \xi_o)\psi^2\right]d\xi}{\int_0^\infty \psi^2 d\xi} = \frac{b}{2} + \frac{1}{2b} - \frac{2\xi_o}{\sqrt{\pi b}} + \xi_o^2$ and $\frac{\partial \beta}{\partial \xi} = 0$ then $\xi_o = \frac{1}{(\pi b)^{\frac{1}{2}}}$. The lowest eigen value

express as β'_{min} can evaluate by $\frac{\partial \beta}{\partial b} = 0$. Then, we get $\beta'_{min} = b = \left(1 - \frac{2}{\pi}\right)^{\frac{1}{2}}$. For applied magnetic field approach H_{C3} and then M_{sc} approach zero, we get $B_o = \mu_0(\chi - \chi')H_{c2} + \mu_0(1 + \chi')H_{c3}$. The surface critical magnetic field can be express by substitution β'_{min} and B_o into $\beta = \frac{\lambda}{B_o} \cdot \frac{(\alpha + \varepsilon)}{4e^2\left(\frac{1}{2m} - \varepsilon_1\right)}$, then the surface critical magnetic field of two-band magnetic superconductor as

$$H_{C3} = \frac{\frac{1}{\left(1 - \frac{2}{\pi}\right)^{\frac{1}{2}}} \left[\frac{\alpha + \varepsilon}{4e^2\left(\frac{1}{2m} - \varepsilon_1\right)} \right] H_{c2} - (\chi - \chi')H_{c2}}{(1 + \chi')}. \quad (11)$$

Our calculation can be reduced to isotropic one-band magnetic superconductor by setting $\varepsilon = \varepsilon_1 = 0$ and $\alpha = \frac{2e^2}{m}\alpha_o$ (Changjan *et al.*, 2017). To investigate the temperature-dependent surface critical magnetic field, we consider temperature dependent function from Changjan and Udomsamuthirun model (Changjan and Udomsamuthirun, 2013). The temperature-dependent surface critical magnetic field is given by

$$H_{C3} = \frac{\frac{1}{\left(1 - \frac{2}{\pi}\right)^{\frac{1}{2}}} \left[\frac{p\left(1 - \frac{T}{T_c}\right) + \frac{q}{2}\left(1 - \frac{T}{T_c}\right)^2 + \varepsilon}{4e^2\left(\frac{1}{2m} - \varepsilon_1\right)} \right] H_{c2} - (\chi - \chi')H_{c2}}{(1 + \chi')}. \quad (12)$$

Where p and q are arbitrary constant.

Results and Discussion

Two-band GL equations for non magnetic superconductor were solved analytically to determine the temperature dependence of H_{C3} on a bulk MgB₂ (Askerzade, 2003). The relationship between H_{C2} and H_{C3} is the same as in single-band GL theory. Temperature dependence of H_{C3} reveals positive curvature near T_c. The effect of diamagnetism, ferromagnetism, antiferromagnetism and paramagnetism on non temperature dependent H_{C3} of magnetic superconductor had been investigated by Meakniti *et al.* (2014). For diamagnetism and ferromagnetism superconductors, the higher and the lower values of critical magnetic field than convention value were found. Changjan *et al.* (2017) used the 1st GL equation to calculated

H_{c3} of magnetic superconductor by variation method analytically and modified to the temperature dependence properties (Chen *et al.*, 2011; Shanenko *et al.*, 2011; Zhu *et al.*, 2011; Changjan and Udomsamuthirun, 2013). The result of calculation could find a good agreement with the experimental data of $Pb_{82}Bi_{18}$ superconductors vicinity the critical temperature scenery. Tsindlekht *et al.* (2011) investigated the magnetic properties of a $K_{0.73}Fe_{1.68}Se_2$ single crystal when the external magnetic field is applied parallel to the ab -plane. The slope of the $H_{c3}(T)$ curve near T_c is ≈ -40 kOe/K. It appears that near T_c , the $H_{c3}(T)/H_{c2}(T)$ ratio is ≈ 4.4 , which is much larger than calculation that predicted for conventional SC material (de Gennes and Saint-James, 1963). In this work, we were interested in the effect of magnetism and interaction between energy band to temperature dependent surface critical magnetic field. We considered temperature dependent function from Changjan and Udomsamuthirun model (Changjan and Udomsamuthirun, 2013). Our calculation (Equation 13) can be reduced to Saints-James and de Gennes formula (de Gennes and Saint-James 1963) for temperature independent non-magnetic superconductor by setting $p = q = 0$, $\chi = \chi' = 0$, $\varepsilon = \varepsilon_1 = 0$, $\alpha = \frac{2e^2}{m}\alpha_o(T)$ and $\alpha_o(T) = 1$ (Changjan *et al.*, 2017). Figure 1 showed the comparison between our calculations with experimental data of $K_{0.73}Fe_{1.68}Se_2$ single crystal (Tsindlekht *et al.*, 2011), solid diamond for H_{c2} and solid square for H_{c3} . Dash line show the result of calculation for conventional superconductor (de Gennes and Saint-James, 1963). Solid line display the result of calculation from Equation (12), By setting $T_c = 30.8K$, $\chi = -1$, $\chi' = 0$, $p = 1$ and $q = 1$, we found that our calculation based on temperature dependent Changjan and Udomsamuthirun model (Changjan and Udomsamuthirun, 2013) corresponding to the experimental data of $K_{0.73}Fe_{1.68}Se_2$ superconductor at T_c scenery. The slope of the $H_{c3}(T)$ curve near T_c from our calculation is ≈ -45.57 kOe/K. The ratio $H_{c3}(T)/H_{c2}(T) \approx 4.4$ of $K_{0.73}Fe_{1.68}Se_2$ superconductor exhibit the unusual magnetic behavior of this superconductor, which is completely different from conventional superconductor. According to study the optical properties of the iron-chalcogenide superconductor $K_{0.8}Fe_{2-y}Se_2$ by Homes *et al.* (2012), this material have energy gaps about $2\Delta \approx 8.7$ meV at below T_c . This information confirms the presence of more than one energy band of this superconductor. As a result, the two-band model that we used in the calculations was more consistent with the experimental data than the single band model calculations.

Conclusions

In summary, the surface critical magnetic field ($H_{c3}(T)$) of magnetic superconductor was derived by temperature dependent two-band Ginzburg-Landau (GL) theory. Free energy of two-band magnetic superconductor (Hampshire, 1998; Askerzade, 2003; Changjan and Udomsamuthirun, 2011b) was minimizing to the 1st GL equation and calculated to $H_{c3}(T)$ by variation method. Our calculation could be reduced to temperature independent single band non-magnetic superconductor (de Gennes and Saint-James, 1963) by setting $p = q = 0$, $\chi = \chi' = 0$, $\varepsilon = \varepsilon_1 = 0$, $\alpha = \frac{2e^2}{m}\alpha_o(T)$ and $\alpha_o(T) = 1$ (Meakniti *et al.*, 2014). Our calculation based on temperature dependent of Changjan and Udomsamuthirun model (Changjan and Udomsamuthirun, 2013) has the slope of $H_{c3}(T)$ curve near T_c about -45.57 kOe/K and could be fit well with the experimental data of $K_{0.73}Fe_{1.68}Se_2$ superconductor at near T_c . Consequently, the two-band model that we used in this calculation was more correspondence with the experimental data than the single band model calculations that use for conventional superconductor.

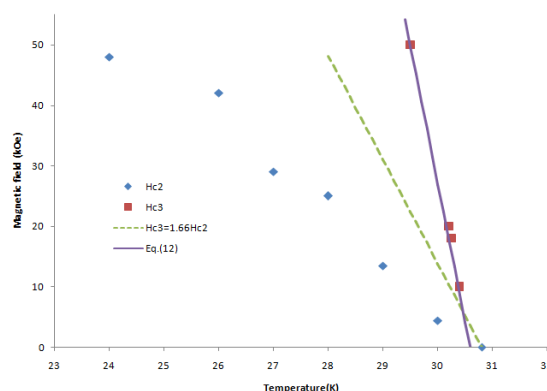


Figure 1. H-T phase diagram ($H_{c2}(T)$ and $H_{c3}(T)$) of $K_{0.73}Fe_{1.68}Se_2$ superconductor (Tsindlekht *et al.*, 2011) comparison with conventional superconductor (dash line) (de Gennes and Saint-James, 1963) and our calculation (solid line) (Equation 12)

Acknowledgments

The financial support of Thailand Science Research and Innovation (TSRI) under contract No. 2579223, Pathumwan Institute of Technology and Srinakharinwirot University are acknowledged.

References

- Aarnink, R. and Overweg, J. (2012). Magnetic Resonance Imaging, a success story for superconductivity. *Europhysics News*, 43(4):26-29. <https://doi.org/10.1051/epn/2012404>.
- Askerzade, I.N. (2003). Surface critical magnetic field $H_{c3}(T)$ of a bulk superconductor MgB_2 using two-band Ginzburg-Landau theory. *Pramana - Journal of Physics*, 61(3):611-616. <https://doi.org/10.1007/BF02705483>.
- Askerzade, I.N. and Gencer, A. (2002). Thermodynamic Magnetic Field and Specific Heat Jump of a Bulk Superconductor MgB_2 Using Two-Band Ginzburg-Landau Theory. *Journal of the Physical Society of Japan*, 71(7):1637-1639. <https://doi.org/10.1143/JPSJ.71.1637>.
- Askerzade, I.N., Gencer, A., and Güçlü, N. (2002a). On the Ginzburg-Landau analysis of the upper critical field H_{c2} in MgB_2 . *Superconductor Science and Technology*, 15(2):L13-L16. <https://doi.org/10.1088/0953-2048/15/2/102>.
- Askerzade, I.N., Güçlü, N., and Kiliç, A. (2002b). Two-band Ginzburg-Landau theory for the lower critical field H_{c1} in MgB_2 . *Superconductor Science and Technology*, 15(6):L17-L20. <https://doi.org/10.1088/0953-2048/15/6/101>.
- Bellingeri, E., Pallecchi, I., Buzio, R., Gerbi, A., Marrè, D., Cimberle, M. R., Tropeano, M., Putti, M., Palenzona, A., and Ferdeghini, C. (2010). $T_c = 21$ K in epitaxial $FeSe_{0.5}Te_{0.5}$ thin films with biaxial compressive strain. *Applied Physics Letters*, 96:102512. <https://doi.org/10.1063/1.3358148>.
- Bray, J.W. (2009). Superconductors in Applications; Some Practical Aspects. *IEEE Transactions on Applied Superconductivity*, 19(3):2533-2539. <https://doi.org/10.1109/TASC.2009.2019287>.
- Buckel, W. (1991). Superconductivity: fundamentals and application. VCH Publishers Inc., NY, 475p.
- Changjan, A. and Udamsamuthirun, P. (2011a). Critical magnetic field ratio of anisotropic magnetic superconductors. *Physica C: Superconductivity*, 471(1-2):23-25. <https://doi.org/10.1016/j.physc.2010.10.002>.
- Changjan, A. and Udamsamuthirun, P. (2011b). The critical magnetic field of anisotropic two-band magnetic superconductors. *Solid State Communications*, 151(14-15):988-992. <https://doi.org/10.1016/j.ssc.2011.04.032>.
- Changjan, A. and Udamsamuthirun, P. (2013). Critical temperature of magnetic superconductors by two-band Ginzburg-Landau approach. *Songklanakarin Journal of Science and Technology*, 35(5):611-614.
- Changjan, A., Meakniti, S., and Udamsamuthirun, P. (2017). The temperature-dependent surface critical magnetic field (H_{c3}) of magnetic superconductors: Applied to lead bismuth ($Pb_{82}Bi_{18}$) superconductors. *Journal of Physics and Chemistry of Solids* 107:32-35. <https://doi.org/10.1016/j.jpcs.2017.03.022>.
- Chen, L., Zuo, J., Lu, Y., and Huang, H. (2011). Two-band calculations on the upper critical field of superconductor $NbSe_2$. *Physica C: Superconductivity*, 471(23-24):1591-1594. <https://doi.org/10.1016/j.physc.2011.08.001>.
- De Gennes, P.G. and Saint-James, D. (1963). Elementary excitations in the vicinity of a normal metal-superconducting metal contact. *Physics Letters*, 4(2):151-152. [https://doi.org/10.1016/0031-9163\(63\)90148-3](https://doi.org/10.1016/0031-9163(63)90148-3).
- Drung, D., Abmann, C., Beyer, J., Kirste, A., Peters, M., Ruede, F., and Schurig, Th. (2007). Highly Sensitive and Easy-to-Use SQUID Sensors. *IEEE Transactions on Applied Superconductivity*, 17(2):699-704. <https://doi.org/10.1109/TASC.2007.897403>.
- Fang, M., Yang, J., Balakirev, F.F., Kohama, Y., Singleton, J., Qian, B., Mao, Z.Q., Wang, H., and Yuan, H.Q. (2010). Weak anisotropy of the superconducting upper critical field in $Fe_{1.11}Te_{0.6}Se_{0.4}$ single crystals. *Physical Review B*, 81:020509(R). <https://doi.org/10.1103/PhysRevB.81.020509>.
- Georgescu, I. (2020). Superconducting accelerator technologies. *Nature Reviews Physics*, 2:128. <https://doi.org/10.1038/s42254-020-0155-y>.
- Hampshire, D.P. (1998). Ferromagnetic and antiferromagnetic superconductivity. *Physica C: Superconductivity*, 304(1-2):1-11. [https://doi.org/10.1016/S0921-4534\(98\)00293-7](https://doi.org/10.1016/S0921-4534(98)00293-7).
- Hampshire, D.P. (2001). The non-hexagonal flux-line lattice in superconductors. *Journal of Physics: Condensed Matter*, 13:6095-6113. <https://doi.org/10.1088/0953-8984/13/27/304>.
- Homes, C.C., Xu, Z.J., Wen, J.S., and Gu, G.D. (2012). Optical conductivity of superconducting $K0.8Fe2-ySe2$ single crystals: Evidence for a Josephson-coupled phase. *Physical Review B*, 85:180510(R).
- Jia, Y., Cheng, P., Fang, L., Luo, H., Yang, H., Ren, C., Shan, L., Gu, C., and Wen, H.H. (2008). Critical fields and anisotropy of $NdFeAsO_{0.82}F_{0.18}$ single crystals. *Applied Physics Letters*, 93:032503. <https://doi.org/10.1063/1.2963361>.
- Kamihara, Y., Watanabe, T., Hirano, M., and Hosono, H. (2008). Iron-based layered superconductor $La[O_{1-x}F_x]FeAs$ ($x = 0.05-0.12$) with $T_c = 26$ K. *Journal of the American Chemical Society*, 130(11):3296-3297. <https://doi.org/10.1021/ja800073m>.
- Kawaguchi, T., Sakagami, A., Mori, Y., Tabuchi, M., Ujihara, T., Takeda, Y., and Ikuta, H. (2014). The strain effect on the superconducting properties of $BaFe_2(As, P)_2$ thin films grown by molecular beam epitaxy. *Superconductor Science and Technology*, 27:065005. <https://doi.org/10.1088/0953-2048/27/6/065005>.
- Ketterson, J.B. and Song, S.N. (1998). Superconductivity. Cambridge University Press, Cambridge, 512p.
- Klushin, A.M., Behr, R., Numssen, K., Siegel, M., and Niemeyer, J. (2002). Accurate measurements of quantum voltage steps on arrays of bicrystal Josephson junctions. *Applied Physics Letters*, 80(11):1972-1974. <https://doi.org/10.1063/1.1458072>.
- Lee, S., Jiang, J., Zhang, Y., Bark, C.W., Weiss, J.D., Tarantini, C., Nelson, C.T., Jang, H.W., Folkman, C.M., Baek, S.H., Polyanskii, A., Abrahimov, D., Yamamoto, A., Park, J.W., Pan, X.Q., Hellstrom, E.E., Larbalestier, D.C., and Eom, C.B. (2010). Template engineering of Co-doped $BaFe_2As_2$ single-crystal thin films. *Nature Materials*, 9:397-402. <https://doi.org/10.1038/nmat2721>.
- Lin, H., Yao, C., Zhang, X., Dong, C., Zhang, H., Wang, D., Zhang, Q., Ma, Y., Awaji, S., Watanabe, K., Tian, H., and Li, J. (2014). Hot pressing to enhance the transport J_c of $Sr_{0.6}K_{0.4}Fe_2As_2$ superconducting tapes. *Scientific Reports*, 4:6944. <https://doi.org/10.1038/srep06944>.
- Liu, M. (2007). Surface critical field of MgB_2 : the two-band Ginzburg-Landau theory. *Superconductor Science and Technology*, 20:157-161. <https://doi.org/10.1088/0953-2048/20/3/008>.
- Meakniti, S., Changjan, A., and Udamsamuthirun, P. (2014). The Study on Surface Critical Magnetic Field of a Layered Magnetic Superconductors. *Advanced Materials Research*, 979:224-227. <https://doi.org/10.4028/www.scientific.net/AMR.979.224>.
- Ni, N., Bud'ko, S.L., Kreyssig, A., Nandi, S., Rustan, G.E., Goldman, A.I., Gupta, S., Corbett, J.D., Kracher, A., and Canfield, P.C. (2008). Anisotropic thermodynamic and transport properties of single-crystalline $Ba_{1-x}K_xFe_2As_2$ ($x = 0$ and 0.45). *Physical Review B*, 78:014507. <https://doi.org/10.1103/PhysRevB.78.014507>.
- Shanenko, A.A., Milošević, M.V., Peeters, F.M., and Vagov, A.V. (2011). Extended Ginzburg-Landau Formalism for Two-Band Superconductors. *Physical Review Letters*, 106:047005. <https://doi.org/10.1103/PhysRevLett.106.047005>.

- Shimoyama, J. (2014). Potentials of iron-based superconductors for practical future materials. *Superconductor Science and Technology*, 27:044002. <https://doi.org/10.1088/0953-2048/27/4/044002>.
- Swithenby, S.J. (1980). SQUIDS and their applications in the measurement of weak magnetic fields. *Journal of Physics E: Scientific Instruments*, 13(8):801-813. <https://doi.org/10.1088/0022-3735/13/8/001>.
- Tampieri, A., Szabó, M., Medina, F., and Gulyás, H. (2020). A brief introduction to the basics of NMR spectroscopy and selected examples of its applications to materials characterization. *Physical Sciences Reviews*, 6(1): 20190086. <https://doi.org/10.1515/psr-2019-0086>.
- Tinkham, M. (1996). *Introduction to Superconductivity*. McGraw-Hill, Inc, NY, 454p. <https://doi.org/10.1063/1.2807811>.
- Tsindlekht, M.I., Felner, I., Zhang, M., Wang, A.F., and Chen, X.H. (2011). Superconducting critical fields of single-crystalline $K_{0.73}Fe_{1.68}Se_2$. *Physical Review B*, 84:052503. <https://doi.org/10.1103/PhysRevB.84.052503>.
- Udomsamuthirun, P., Changjan, A., Kumvongsa, C., and Yoksan, S. (2006). H_{c2} of anisotropy two-band superconductors by Ginzburg-Landau approach. *Physica C: Superconductivity and its Applications*, 434(1):62-66. <https://doi.org/10.1016/j.physc.2005.12.001>.
- Yin, Y., Zech, M., Williams, T.L., Wang, X.F., Wu, G., Chen, X.H., and Hoffman, J.E. (2009). Scanning Tunneling Spectroscopy and Vortex Imaging in the Iron Pnictide Superconductor $BaFe_{1.8}Co_{0.2}As_2$. *Physical Review Letters*, 102:097002. <https://doi.org/10.1103/PhysRevLett.102.097002>.
- Yuan, H., Singleton, J., Balakirev, F.F., Baily, S.A., Chen, G.F., Luo, J.L., and Wang, N.L. (2009). Nearly isotropic superconductivity in $(Ba,K)Fe_2As_2$. *Nature*, 457:565-568. <https://doi.org/10.1038/nature07676>.
- Zhai, Y., Tan, Z., Liu, X., Shen, B., Coombs, T.A., and Wang, F. (2020). Research Progress of Contactless Magnetization Technology: HTS Flux Pumps. *IEEE Transactions on Applied Superconductivity*, 30(4):1-5. <https://doi.org/10.1109/TASC.2020.2983412>.
- Zhang, J.L., Jiao, L., Chen, Y., and Yuan, H. (2011). Universal behavior of the upper critical field in iron-based superconductors. *Frontiers of Physics*, 6(4):463-473. <https://doi.org/10.1007/s11467-011-0235-7>.
- Zhi-An, R., Wei, L., Jie, Y., Wei, Y., Xiao-Li, S., Zheng-Cai, L., Guang-Can, C., Xiao-Li, D., Li-Ling, S., Fang, Z., and Zhong-Xian, Z. (2008). Superconductivity at 55 K in Iron-Based F-Doped Layered Quaternary Compound $Sm[O_{1-x}F_x]FeAs$. *Chinese Physics Letters*, 25(6):2215-2216. <https://doi.org/10.1088/0256-307X/25/6/080>.
- Zhu, X., Yang, H., Fang, L., Mu, G., and Wen, H.H. (2008). Upper critical field, Hall effect and magnetoresistance in the iron-based layered superconductor $LaFeAsO_{0.9}F_{0.1-\delta}$. *Superconductor Science and Technology*, 21(10):105001. <https://doi.org/10.1088/0953-2048/21/10/105001>.