CHAPTER V

SUMMARY AND CONCLUSIONS
CHAPTER-V
SUMMARY AND CONCLUSION

In spite of advanced research, high temperature superconductivity (HTSC) and its interpretation is still one of the hottest scenarios in strongly correlated materials and continued to be an ever green theme. The reason is that there are number of open questions concerning the pairing mechanism, anisotropic properties, and theoretical interpretation of experimental findings which are indirectly influenced by the quality as well as quantities of the material. Initial experimental works on HTSC show large anisotropy not only in system parameters like penetration depth (\(\lambda\)), coherence length (\(\xi\)) but also in several physical properties like thermodynamic, transport and magnetic quantities. The magnetic field dependence of specific heat, entropy and magnetization show significantly different corresponding to the conventional type-II superconductors.

A satisfactory explanation could not be reached at that time for an answer of the existence of anisotropy. Several, attempts were initiated through introducing anisotropy into the existing theoretical models like Ginzburg-Landau theory (GL-theory), London theory of HTSCs. In doing so, effect of such anomaly in terms of anisotropic ratio (\(\gamma\)) was estimated and reported for different HTSCs. Number of experiments were also been carried out on HTSCs and showed the existence of anomaly of the field and temperature dependence of specific heat, entropy, magnetization etc and also estimated the value of anisotropic ratio, \(\gamma\). Taking above existing models of HTSC and modifying them, Kogan and co workers [33-Ch-II], Revaz and co workers [5-Ch-III], Ota and co workers [4-Ch-III] and others also estimated the value of anisotropic parameter (\(\gamma\)) for some HTSCs and compared with the existing experimental findings. Our present model, given in Chapter-II is based on Ginzburg-Landau theory in London limit, satisfactorily estimates the value of anisotropic parameter (\(\gamma\)) through both field and temperature dependence of change in specific heat (\(\Delta C\)) along with
field orientation. Usually, in the literature, the value of $\gamma$ is reported as the ratio of different characteristic system parameters like penetration depth ($\lambda_y$), value of effective mass tensor ($m_y$) and resistivity tensor components ($\rho_j$) as $\gamma = \lambda_c/\lambda_{ab}$, $\gamma = (m_c/m_{ab})^{1/2}$, $\gamma = \rho_c/\rho_{ab}$ respectively. Here, $i$ and $j$ corresponds to the different directions $a$, $b$, $c$ [4-Ch-III].

To estimate the value of $\gamma$ theoretically, one has to evaluate the values of $\lambda$ in different directions such as $\lambda_c$ or $\lambda_{ab}$ depending on the applied field direction along $ab$-plane or $c$-axis respectively through the expression of change in specific heat ($\Delta C$) as given in equation (30) of Chapter-II. It is observed that, the change in specific heat is inversely proportional to the square of the mean penetration depth ($\lambda_m$), which is expressed to be equal to either $\lambda_c$ or $\lambda_{ab}$ for applied field parallel or perpendicular to $ab$-plane. At a given strength of the applied field and orientation, change in specific heat is linear as a function of temperature. The slope of this variation gives the value of individual penetration depths i.e. for the field parallel to $c$-axis, $\lambda_{ab}$ and for perpendicular to $c$-axis, $\lambda_c$ respectively. After getting the two penetration depths and taking ratio, $\gamma$ value can be estimated.

It is interested to note that for small value of applied field, the separation of vortices is larger than the penetration depth ($\lambda$). In this situation, London model works well and mixed state is not disturbed. But if the strength of the field increased, the vortices swell so as to decrease the surface area and likely that nearby vortices overlap. Under this situation London theory fails to explain such anisotropy and needs some correction. In particular, with higher applied fields, the density of vortices increases, and begins to overlap with each other making nearest-neighbour distance less than the penetration depth. This high density case can be mostly treated by assuming the magnetic field at any point is a linear superposition of the fields from all the overlapping vortices and that relates the change in
penetration depth ($\lambda$) as well as $\gamma$ value. At high densities, field inside the material becomes very large and the variation of the field in the space between the cores becomes very small. Under this situation, the bare penetration depth ($\lambda_0$) acquires effective penetration depth ($\lambda_{\text{eff}}$) and are related as $\lambda_{\text{eff}} = \frac{\lambda^2}{1 - (B_a/B_{c2})}$. To explain the anisotropy in strong fields, the equations of change in specific heat, entropy are modified by replacing $\lambda_0$ to $\lambda_{\text{eff}}$ for explaining the anisotropy behaviour as well as to estimate the value of $\gamma$ for better fitting with experiment. Following our model and procedure cited above, we have explained the variation of change in specific heat with temperature, behaviour of change in entropy, and magnetization and estimated the value of $\gamma$ taking the experimental data that available for some HTSCs like Y-123, Dy-123, Nd-123, Bi-2212, Th-2223, NbS$_2$, SmFeAsO$_F$, NdFeAsO.

Revaz et al [5-Ch-III] studied experimentally for Dy-123 (DyBa$_2$Cu$_3$O$_{7-x}$), for the variation of $(\Delta C)$ with temperature in different applied field (1T to 16 T) and obtained anisotropic ratio for two different orientations of applied field. Our present model explains satisfactorily the existence of observed anisotropy in the change in specific heat as well as entropy with the variation of applied magnetic field for two different field orientations. Further, our model also estimates the value of $\gamma$ to be of 5.603 which is close to experimental result obtained as 5.3±0.5 by Revaz et al. [5-Ch-III]. As entropy is related to specific heat, the extrapolation of entropy from the specific heat found to give correct behaviour. The detail interpretation of this has been inculcated in the respective Chapter-III.

Motivated with the success of our results for Dy-123 system, an attempt has been made to apply this model to non oxide, non cuprate layered type-II superconductors with dichalcogenides, NbS$_2$. For this system, Kacmarcik et al [17-Ch-III] obtained the variation of ($\Delta C$) with temperature in different applied fields. Taking this temperature dependence of change in specific heat with different field orientations, we calculated anisotropic ratio, $\gamma$ by our model in terms of penetration depths and found to give correct behaviour as shown in experiment [17-Ch-III]. This has been elaborated in Chapter-III.

This part of work has been accepted for publication in Asian journal of Physics 22 (2012) **** (in press) [18] of Chapter-III and [6] of list of publication.

Besides cuprates, magnetic field dependent entropy of non cuprate superconducting systems has also been studied through our model. Welp et al. [10-Ch-III] has studied experimentally the variation of change in specific heat ($\Delta C$) and entropy ($\Delta S$) with temperature for two different field orientations for NdFeAsO$_{1-x}$F$_x$ single crystal. Further they have reported the calculated value of anisotropic ratio to be 4.09 to 4.34. Our model explains not only the anisotropic finding of ($\Delta C$) for NdFeAsO$_{1-x}$F$_x$ given by Welp et al [10-Ch-III] but also predict the $\gamma$ value to be 4.10 which is very close to the value 4.09 to 4.34 as reported experimentally.


To improve our model so as to explain the anisotropic behaviour in large magnetic field, vortex correction has been introduced. In doing so, the equation was modified and expressed in new form in terms of effective penetration depth ($\lambda_{\text{eff}}$) in place of bare penetration depth ($\lambda_0$) in equation
(30) of Chapter-II. Following the similar procedure as cited above we have tried to explain the anisotropic behaviour for NdBa$_2$Cu$_3$O$_7$ (Nd-123) and SmFeAsO$_{0.8}F_{0.15}$ where Welp et al. [128-Ch-I] experimentally observed the variation of specific heat with temperature. Taking the experimental results and fitting with our model we calculated the anisotropic ratio ($\gamma$) and found to give good results and have not compared as experiment data not available. This work will be communicated for publication.

Attributing all the above results it can be concluded that, mass anisotropy plays an important role in the properties of HTSCs. Further, this anisotropy makes superconducting properties quite different when measured in $ab$-plane or along $c$-axis.

As pointed out above, the magnetization also shows anisotropy as a function of applied field and temperature. Some experimental works have been carried out particularly in the systems YBa$_2$Cu$_3$O$_7$, Bi$_2$Sr$_2$CaCu$_2$O$_8$, HgBa$_2$CuO$_4$ and Tl$_2$Ba$_2$Ca$_2$Cu$_3$O$_{10}$. Thompson et al. [5-Ch-IV] have studied the behaviour of magnetization anisotropy for Hg-1201 and Tl-2223. In this connection it is to be pointed out that Nanda [10-Ch-IV] explained the magnetization anisotropy for Y-123 and Bi-2212 through London model both with and without vortex correction. In doing so, he compared the field dependence of magnetization for London model, Hao-Clem model and Vortex overlapping model. It has been shown that reversible magnetization with respect to applied field following his simple model in terms of overlapping of vortex cores is lying in between usual results of London model and Hao-Clem model for lower applied field. Encouraged by this result we have tried to explain the same thing in another two systems Hg-1201 and Tl-2223 and observed that the vortex overlapping theory gives better result compared to other two models [8-Ch-IV] similar to Y-123 and Bi-2212. Further, we have observed that in the above HTSC systems, temperature dependence of magnetization has some peculiar behaviour. In each case rigorous crossing point has been attributed near the transition temperature both for mean field and critical regions with different system parameters.


In an experiment, Roulin et al. [9-Ch-III] studied temperature dependant specific heat at different oxygen concentration for \( \text{YBa}_2\text{Cu}_3\text{O}_7-\delta \). In that paper they have reported that anisotropic ratio \( (\gamma) \) increases with the increase in oxygen concentration. This experiment showed that \( \gamma \) do influenced by the content of oxygen in the cuprate system. To explain this dependence we have tried to derive analytically the expression for \( \gamma \) as a function of concentration of oxygen. As in higher fields vertex do overlap, so to improve further, we have also included the vortex correction into it by replacing \( \lambda_{\text{eff}} \) in place of its bare value \( (\lambda_0) \) which is given in Eqn. (6) in chapter-III. After studying the behaviour of \( \gamma \) as a function of concentration, it is found that the derived relation shows that an increase in the value of anisotropic ratio \( \gamma \) with respect to oxygen content in cuprate HTSCs i.e. in \( \text{YBa}_2\text{Cu}_3\text{O}_7-\delta \). This analytic relation in terms of effective parameter is first and is not reported elsewhere earlier.


Correlating all the above results it can be concluded that our model in terms of modified phenomenological GL-theory in London limit along with vortex overlapping correction is well in form. It is giving suitable results for both field and temperature dependence along with different field orientations of specific heat, entropy, and magnetization of different layered type-II superconductors at higher applied fields.
Further, strongly anisotropic resistivity tensor can be explained in terms of phenomenological GL-theory in London limit with vortex correction of different superconducting systems. As resistivity tensor changes between $ab$-plane and $c$-axis along and also in between $a$- and $b$-axis, it is worthwhile to investigate anisotropy in resistivity by this simpler model for anisotropic type-II superconductors. This work will be explored and will be presented in future.

Depending of the availability of resource journal materials in the university library as well as Institute of Physics, BBSR, I have tried my best to incorporate them in this thesis at appropriate places. I may be excused, if any important references related to this work might have skipped as it is unintentional. Further, with utmost care, the thesis has been written and checked to make it error free. Still, there might be some typographical errors which may be ignored.