Electronic Properties Due to Anisotropy in High-Temperature superconductors(高温超電導の異方性に起因する電子物性の研究)

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論　文　内　容　要　旨

Electronic Properties Due to Anisotropy in High-Temperature Superconductors

by Cristina BUZEA

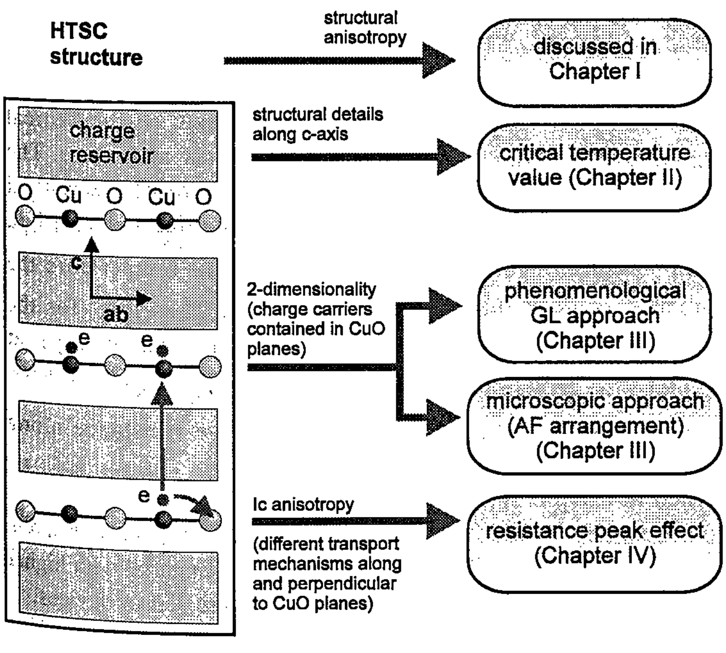
In this thesis are presented several electronic properties due to anisotropy in high temperature superconductors (HTSC). First, the structural of HTSC is discussed in comparison with the structure of low-temperature superconductors (LTSC), underlining the anisotropy of HTSC. High temperature superconductors have a layered structure composed of CuO planes and charge reservoir layers. It is shown that the details of the anisotropic layered structure may be related to the value of the critical temperature (Tc) of one compound, namely that its details along the c-axis determines the maximum attainable Tc. Also, one particular aspect of anisotropy in HTSC is the charge carrier confinement into the CuO planes, which is treated theoretical in this thesis from a phenomenological Ginzburg-Landau point of view and microscopic point of view based on antiferromagnetic arrangement of electronic spins. Another aspect of anisotropy in HTSC is the existence of different transport mechanisms along and perpendicular to CuO planes, which is shown to lead to the resistance peak effect. The schematics of the thesis are illustrated in Fig. 1.

The present thesis is systematised in 5 Chapters.

Chapter I reviews the structural difference between low-and high-temperature superconductors, underlining the crystallographic structure of the HTSC as a basis for their anisotropic properties.

In Chapter II are made empirical observations, referring to a possible connection between the anisotropic structure and critical temperature in HTSC. It is found on empirical basis that anisotropy, more exactly the structural details along c-axis may determine the Tc value. In the representation of mass of the ions contained in layers parallel to CuO planes versus the distance along c-axis we observed a certain mass scaling with distance. More exactly, collinearities between points represented by large mass ions and light mass ions. For example, in Fig. 2 is shown the ion mass versus distance along c-axis for Tl-1212. We observed that as a compounds has such more collinearities, its Tc is higher. On the basis of these correlations, we are able to predict which structures will have higher Tc.

Chapter III contains a theoretical description of anisotropic superconductors, divided in a phenomenologic Ginzburg-Landau based approach and a microscopic description based on hydrodynamic calculations, leading to the appearance of Meissner effect. In the first part of this Chapter the system of charge carriers is studied in a Ginzburg-Landau approach by using the elliptic function formalism. We obtained exact solutions described by Jacobi elliptic functions. The derived superconducting parameters fit very well the experimental data. In the second part of Chapter III is a parallel approach for the same superconducting system, underlying the antiferromagnetic arrangement



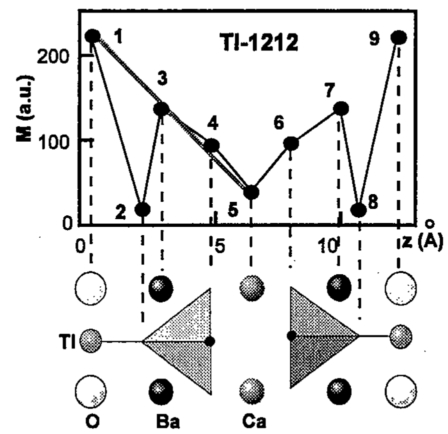


Fig. 2. M versus the distance along c-axis for Tl-1212

Fig. 1. Anisotropic structure consequences

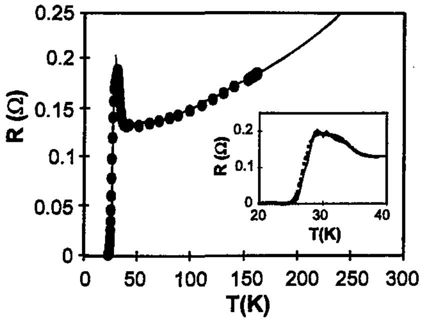


Fig. 3. R vs. T in a LSCO sample

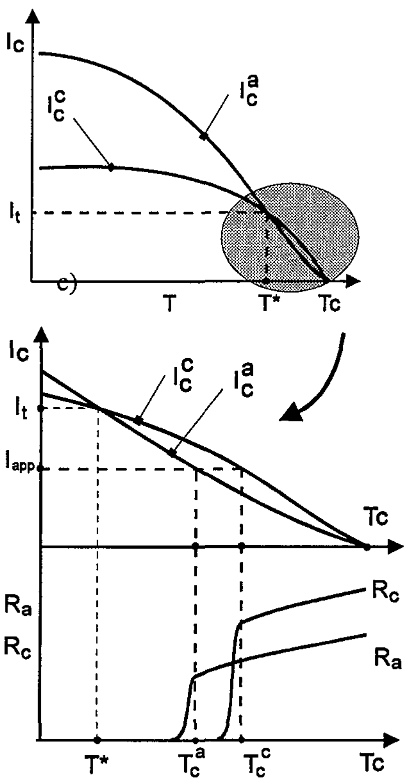


Fig. 4. Critical current along a- and c-axis, I_c^a, I_c^c, and resistances along a- and c-axis, R_a, R_c vs. T

of electronic spins and using the equivalence between the electron spin and a quantized vortex type object. The experimental data for the superconducting parameters are in good agreement with the theoretical observations made in this Chapter.

Chapter IV presents electronic properties due to anisotropy in HTSC, namely the resistance peak effect observed in LSCO thin films. First is presented the experimental procedure of thin film preparation by laser ablation, and a comprehensive study of film surface temperature variation during deposition as a function of the process parameters. Following, is the sample characterization together with the experimental procedure of film patterning. Finally, the resistance peak effect observed in measurements of LSCO patterned and unpatterned films, by using a four-point contact arrangement, are described. An example of the resistance peak in LSCO films is given in Fig. 3.

The theory proposed to explain the observed resistance peak effect is based on apparent critical temperature anisotropy along and perpendicular to the CuO planes. More exactly, the critical temperature along c-axis is higher than the one along the CuO planes or a-axis.

The apparent Tc anisotropy is due to different electrical transport mechanisms along and perpendicular to the CuO planes. In the CuO planes the current is described by a thermally activated flux model

$$I_c(ab-plane) = I_c(0)\left[1-\left(\frac{T}{T_c}\right)^2\right]^m \quad (1)$$

and along c-axis by the Ambegaokar-Baratoff relation for tunnel junctions

$$I_c(c-axis) = \frac{\pi K_B T_c}{2eR_n}\left[1-\left(\frac{T}{T_c}\right)^4\right]\tanh\left\{0.5\frac{T_c}{T}\left[1-\left(\frac{T}{T_c}\right)^4\right]\right\}. \quad (2)$$

In Fig. 4 top we plotted the critical current along a- and c-axis given by Eqs. (1) and (2). Usually, Ic along a-axis is much higher than Ic along c-axis, but one notices that near Tc the situation can be reversed for certain values of the parameters in the two equations.

In Fig. 4 middle is shown the enlarged dependence Ic(T) near Tc. If the applied current I_{app} is smaller than the threshold value of the current I_t for which the critical current along ab-plane is equal to the critical current along c-axis (at T*), then we will have the following picture. The resistance along c-axis will become zero when the value of the critical current along c-axis is higher than the value of the applied current, I_{app}, namely at a temperature smaller than the critical temperature of the material, T_c^{c-axis}. At this temperature the critical current along ab-plane is still smaller than the value of the applied current, I_{app}. Therefore, for the fixed value of the applied current I_{app}, apparently, along ab-plane the superconductivity is not achieved yet at temperatures between T_c and T_c^{c-axis}. Decreasing more the temperature below, at a value equal to $T_c^{ab-plane}$ the current along ab-plane will exceed the value of the applied current I_{app}, and finally, the resistance along ab-plane will become zero too.

Finally, the conclusions of this thesis are described in Chapter V.

The anisotropy research described in this thesis has potential applications and opens the possibility of future research. Based on the observed correlations between T_c and mass anisotropy it may be possible to prepare a material with higher T_c by material design. The resistance peak effect study may be useful in the fabrication of temperature-sensor devices.

審査結果の要旨

本研究では高温超電導体の異方性に起因する幾つかの電子物性を解明する重要な成果が得られた。異方的層状結晶構造と超電導転移温度は相関があり、c 軸方向の構造の規則性が転移温度の最高値を決めることが明らかにされた。また、異方性の特異な状況の一つとして超電導キャリアの CuO 面への局在を記述する 2 つの新たな理論を提案し、超電導の特徴を理解するために有用な結論を得た。本論文は、この研究成果をまとめたものであり、全文 5 章よりなる。

第 1 章では、高温超電導体の異方的性質の原因となる結晶構造を、低温超電導体と高温超電導体の構造的な相違を比較して記述している。

第 2 章では、高温超電導体の異方的構造と転移温度とのつながりを明確にするための経験則について述べている。経験的な立場から、異方性、より正確には c 軸方向の性質の構造的変化が材料の転移温度を決定することを見出し、最高の転移温度を示す新材料を提案している。

第 3 章は異方的超電導体の理論的記述を示したものであり、これはギンツブルグ-ランダウ（GL）理論と流体力学的な計算に基づく微視的理論に分けられ、マイスナー効果の発現を良く説明できることを明らかにしている。章の前半では超電導現象を楕円関数による GL 理論の定式化を行うことで、現象を記述する厳密解を得ている。この章の後半では、電子スピンと量子化渦糸との等価性を利用して、電子スピンの反強磁性配列に関する理論を提出し、超電導現象を解明している。これらの理論的計算が実験事実を良く説明することが分かり、理論の有用性が示された。

第 4 章では、異方性による電子的性質に起因した現象の一つ、つまり異方的超電導薄膜で観測される、転移温度付近での抵抗ピーク効果について述べられている。まず、レーザー蒸着による製膜の実験が述べられており、製膜時の薄膜表面温度の変化を調べることで薄膜作製に関する有益な成果が得られている。観測された抵抗ピーク効果は、臨界電流密度の異方性による見かけの超電導転移温度を考慮することで解釈され、実験結果と理論との整合性が非常に良いことが示されると共にその応用の可能性を論じている。

第 5 章は結論である。

以上要するに本論文は、第一に高温超電導体の異方性と臨界温度との相関を明確化することにより、高転移温度を持つ超電導体の材料設計に重要な指針を与えた。さらに抵抗ピーク効果の研究成果は高精度な温度センサーなどの超電導デバイス開発に寄与するもので、超電導エレクトロニクスの発展に寄与するところが少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。