Planar hole-doping concentration and effective three-dimensional hole-doping concentration for single-layer high-$T_c$ superconductors

Tatsuya Honma$^{a,b}$ and Pei Herng Hor$^a$

$^a$Texas Center for Superconductivity and Dept. of Physics, University of Houston, Houston, TX. 77204-5002, USA.

$^b$Dept. of Physics, Asahikawa Medical College, Asahikawa, Hokkaido 078-8510, Japan.

Abstract

We propose that physical properties for the high temperature superconductors can be addressed by either a two-dimensional planar hole-doping concentration ($P_{pl}$) or an effective three-dimensional hole-doping concentration ($P_{3D}$). We find that superconducting transition temperature ($T_c$) exhibits a universal dome-shaped behavior in the $T_c$ vs. $P_{3D}$ plot with a universal optimal doping concentration at $P_{3D} \sim 1.6 \times 10^{21}$ cm$^{-3}$ for the single-layer high temperature superconductors.

Key-words; Room-temperature thermoelectric power ; hole-doping concentration ; Hall number ; superconducting transition temperature

1. Introduction

In high temperature superconductors (HTS) hole content per CuO$_2$ plane ($P_{pl}$) can be directly determined from the content of the cation dopant in the pure cation doped La$_{2-x}$Sr$_x$CuO$_4$ (SrD-La$_{214}$) and Y$_{1-z}$Ca$_z$Ba$_2$Cu$_3$O$_6$ (CaD-Y1236). Most recently, based on the thermoelectric power at room temperature ($S_{290}$) of the SrD-La$_{214}$ and CaD-Y1236, a universal $S_{290}(P_{pl})$-scale (hereafter $P_{pr}$-scale) [1] is constructed as new scale in contrast to $T_c(P_{pr})$-scale (hereafter $P_{Tc}$-scale) which was defined by a relation of $T_c/T_c^{\text{max}} = 1 - 82.6(P_{pr} - 0.16)^2$. While the $P_{pr}$ is intrinsically equal to $P_{pl}$ in SrD-La$_{214}$ [2], it is different in other systems. Using the $P_{pr}$-scale, the maximum in $T_c$ ($T_c^{\text{max}}$) was no longer universally pinned at $P_{pl} = 0.16$, it depended on the specific material system of HTS. However, many experimental data were interpreted using the $P_{pr}$-scale by taking $P_{Tc} = P_{pl}$ [3].

In-plane Hall number ($n_H = 1/eR_H$), where $R_H$ is in-plane Hall coefficient and $|e|$ is electron charge, has physical meaning of the mobile carrier concentration per volume and is a three-dimensional (3D) quantity. But, the $P_{pl}$ is intrinsically a two-dimensional (2D) quantity. Since both concentrations monitor doped carriers, the proper extension of $P_{pl}$ is expected to be comparable to $n_H$. When the planar carriers exist in the block layer with one CuO$_2$ plane, we can define an effective 3D hole-doping concentration ($P_{3D}$) in terms of $P_{pl}$ by a relation of $P_{3D} = P_{pl} \times (N_l/V_{u.c.})$. Here, $V_{u.c.}$ and $N_l$ are the unit cell volume and the number of CuO$_2$ plane per unit cell, respectively. Since $P_{3D}$ is defined on the universal 2D $P_{pr}$-scale, this definition has qualitatively taken into account the charge deconfinement effect of the holes in cuprates. Therefore $P_{3D}$ can be viewed as the “effective” 3D hole-doping concentration even when holes are completely confined in CuO$_2$ planes.

In this paper we make a clear distinction between $P_{pl}$ and $P_{3D}$. We show that the present $P_{3D}$ is comparable with $n_H$ and that the $T_c/T_c^{\text{max}}$ vs. $P_{3D}$ exhibits a universal dome-shaped curve with the universal optimal hole-doping concentration $P_{3D}^{\text{opt}} = 1.6 \times 10^{21}$ cm$^{-3}$ for single-layer HTS. We find that the $P_{Tc}$-scale is identical to the $P_{3D}$-scale. The detail is reported in Ref. 1 and 5.

2. Experimental

The analyzed data are collected from the literatures [4,6-15] whenever the $P_{pl}$ can be reliably determined by $P_{pr}$-scale. For the calculation of $P_{3D}$, we used the typical value of the unit cell volume [5].
3. Results and discussion

Figure 1 shows the $n_H$ as a function of $P_{3D}$ for the single-layer SrD-La214, OD-Hg1201, OD-TI2201 and CD-Bi2201. The plotted $n_H$ come from the polycrystalline samples for SrD-La214 [12,13] and OD-TI2201 [4,14,16] and the single crystals for SrD-La214 [10-12] and CD-Bi2201 [7-8]. In the SrD-La214 and OD-TI2201, the $R_{HI}$ of the polycrystalline samples is experimentally confirmed to be almost equal to the in-plane $R_{HI}$ of the single crystals [12,17]. There are three linear $n_H(P_{3D})$ regimes (regime-I, II and III). In regime-I for $P_{3D} \leq 5.5 \times 10^{20}$ cm$^{-3}$, $n_H$ is identical to $P_{3D}$. At $P_{3D} = 5.5 \times 10^{20}$ cm$^{-3}$, the slope of linear $n_H(P_{3D})$ suddenly changes from 1 to ~3.2. In the regime-III for $P_{3D} \geq 1.6 \times 10^{21}$ cm$^{-3}$, the linear $n_H(P_{3D})$ changes slope to 25. The observed rapid increase in $R_{HI}$ may relate to the change in sign of $R_{HI}$ observed in the overdoped SrD-La214 [12]. We need to emphasize that this systematic behaviour for the single-layer HTS is not governed by the $P_{pl}$ but by the $P_{3D}$. In the inset of fig.1, we plot the same data set of $n_H$ as a function of $P_{pl}$. The $n_H$ for CD-Bi2201 and OD-TI2201 do not follow that of SrD-La214, and the three physically distinct regimes cannot be resolved.

Figure 2 shows $T_c$ as a function of $P_{3D}$ for SrD-La214 [6,15], OD-Hg1201 [9] and CD-Bi2201 [7,8]. The superconductivity appears at $\sim 5.5 \times 10^{20}$ cm$^{-3}$ where $T_c$ is corresponding to the boundary between the regime-I and II. The $T_{c,max}$ universally appears at $\sim 1.6 \times 10^{21}$ cm$^{-3}$ where $T_c$ is corresponding to the boundary between regime-II and III. The inset shows the $T_c/T_{c,max}$ vs. $P_{3D}$ of the same data set. The $T_c/T_{c,max}$ for SrD-La214, OD-Hg1201 and CD-Bi2201 follow the same dome-shaped curve. Now we can pin down the absolute 3D optimal hole-doping concentration in a relation of $T_c/T_{c,max} = 1 - 83.64(P_{3D} \times 10^{22} - 0.159)^2$. It is clear that the $P_{Tc}$-scale is not planar hole-doping concentration but physically identical to our defined $P_{3D}$. Therefore, we can understand why the $P_{Tc}$-scale worked in the earlier doping-dependence of $T_c$ studies [3]. However, we need to emphasize that the $P_{Tc}$-scale should be interpreted in the contexts of $P_{3D}$ as the proper carrier scale for 3D “bulk” cuprate properties.

In summary, we have shown that for HTS there are two types of hole-doping concentration depending on the dimensionality, that is, $P_{3D}$ and $P_{pl}$. Combining these two, we have a complete working scale to address various physical properties for all HTS. Indeed, we see that $n_H$ and the magnitude of $T_c$ are governed by $P_{3D}$, while pseudogap physics were described by $P_{pl}$ [1].

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