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

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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-dimentional 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} ~ 1.6 x 10^{21} cm^{-3} for the single-layer high temperature superconductors.

Key-wards; 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 $La_{2-x}Sr_xCuO_4$ (SrD-La214) and $Y_{1-x}Ca_xBa_2Cu_3O_6$ (CaD-Y1236). Most recently, based on the thermoelectric power at room temperature (S^{290}) of the SrD-La214 and CaD-Y1236, a universal $S^{290}(P_{pl})$-scale (hereafter P_{pl}-scale) [1] is constructed as new scale in contrast to $T_c(P_{Tc})$-scale (hereafter P_{Tc}-scale) which was defined by a relation of $T_c/T_c^{max} = 1 - 82.6(P_{Tc} - 0.16)^2$. While the P_{Tc} is intrinsically equal to P_{pl} in SrD-La214 [2], it is different in other systems. Using the P_{pl}-scale, the maximum in T_c (T_c^{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_{Tc}-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 $P_{3D} \equiv P_{pl} \times (N_l/V_{u.c.})$. 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_{pl}-scale, this definition has qualitatively taken into account the charge de-confinement 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^{max} *vs.* P_{3D} exhibits a universal dome-shaped curve with the universal optimal hole-doping concentration $P_{3D}^{opt.}$ = 1.6 x 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_{pl}-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-Tl2201 and CD-Bi2201. The plotted n_H come from the polycrystalline samples for SrD-La214 [12,13] and OD-Tl2201 [4,14,16] and the single crystals for SrD-La214 [10-12] and CD-Bi2201 [7-8]. In the SrD-La214 and OD-Tl2201, the R_H of the polycrystalline samples is experimentally confirmed to be almost equal to the in-plane R_H 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_H may relate to the change in sign of R_H 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-Tl2201 do not follow that of SrD-La214, and the three physically distinct regimes can not 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 ~5.5×10^{20} cm^{-3} where is corresponding to the boundary between the regime-I and -II. The T_c^{max} universally appears at ~1.6×10^{21} cm^{-3} where 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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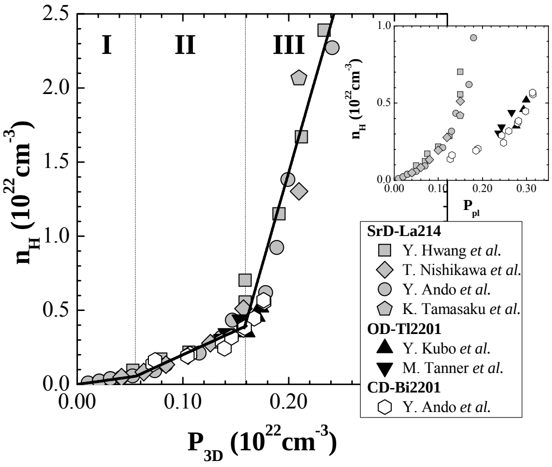

Figure 1 n_H *vs.* P_{3D} for the single-layer HTS. The inset shows n_H *vs.* P_{pl}.

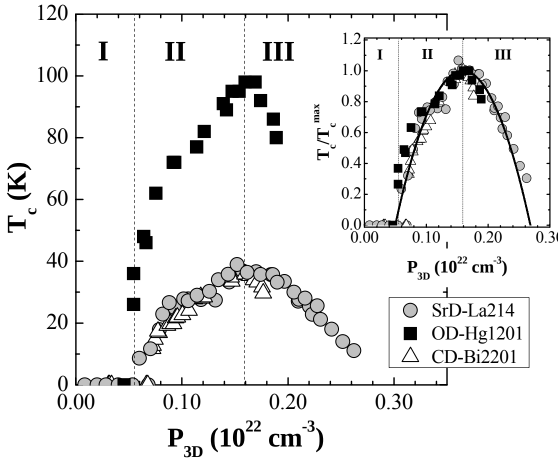

Figure 2 T_c vs. P_{3D} for the single-layer HTS. The inset shows T_c/T_c^{max} vs. P_{3D}.

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