

The Influence of Electron Transfer on T_c in Superconductors

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Abstract

Increase of T_c in $Al_{1-x}(SiO_2)_x$ cermets with increasing x is caused by electron transfer from the Al grains to the SiO_2 phase occupying surface states, expressed by $T_c/T_{c,max} = 1 - \gamma \cdot n^2$ (*), where n is the electron density in the Al phase and γ a characteristic parameter. Decrease of T_c in Pb-Cu-sandwiches is attributed to the electron transfer from the Cu film to the Pb film. γ and $T_{c,max}$ in equation (*) stands for the influence of the electron-phonon interaction and n^2 for the influence of the electron-electron Coulomb repulsion on T_c . The result that equation (*) holds for both hole-doped cuprate high-temperature superconductivity (HTSC) and $Al_{1-x}(SiO_2)_x$ cermets is an important indication that common mechanisms underlie HTSC and classical superconductors. The difference between the two is that in HTSC, electron transfer occurs between different electronic bands, but in $Al_{1-x}(SiO_2)_x$ cermets between different phases.

Keywords

High-Tc Superconductor, Electron Transfer, Electron Density, Hole Density, Cooper Pairs, Cermets, Granular Metals, Metal-Metal Sandwiches

1. Introduction

Since the discovery of high-temperature Superconductivity (HTSC) 38 years ago by Bednorz & Müller [1], the underlying mechanism has remained an unsolved mystery to this day. It has also been suggested that HTSC might be based on mechanisms other than electron-phonon interaction, and the question remains whether the BCS theory is also a useful description of HTSC.

A possible solution to this great puzzle was proposed in the recently published paper [2], where it was shown that the mechanism underlying HTSC can be

described very well by considering electron transfer between two different electronic bands, which for hole-doped cuprat HTSC lead to a strong reduction of the electron density n , which reduces the electron-electron Coulomb repulsion. A formula was derived, which describes the connection between T_c and the doping concentration x in hole-doped cuprat HTSC,

$$T_c(x)/T_{c,\max} = 1 - \left(\frac{1-x}{1-x_0} \right)^2, \quad (1)$$

which was derived using the formula

$$T_c/T_{c,\max} = 1 - \gamma \cdot n^2, \quad (2)$$

where γ is a characteristic parameter for a superconductor. x_0 is the concentration at which Superconductivity begins. $T_{c,\max}$ is the maximum of T_c for $x \rightarrow 1$.

Another important result in [2] was that in the concentration range $x_0 < x < 1$ superconductivity is realized by electron-Cooper pairs, but in $1 < x < 2 - x_0$ by so-called hole-Cooper pairs, where the formula

$$T_c/T_{c,\max} = 1 - \gamma \cdot p^2 \quad (3)$$

was found with p as the hole density, a virtually mirror image of Equation (2). This is the core of the hypothesis of electron-hole duality, put forwarded in [2], where Superconductivity is possible not only by electron-Cooper pairs, but also by hole-Cooper pairs consisting of two holes, where there is a complete analogy between electron-Cooper pairs and hole-Cooper pairs.

In this article, the following questions are asked:

1) why does T_c increase in $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermets (granular metals) with increasing x and

2) why does T_c decrease in Pb-Cu-sandwiches with increasing thickness of the Cu film on the Pb film, known as “proximity-effect”?

The answers on these two questions are of great importance in that they can support the approach that electron transfer is crucial for the emergence of Superconductivity and is a prerequisite for a further increase in T_c .

Cermets (also called granular metals) are generally prepared by thin film deposition of metals in oxygen or by co-evaporation or co-sputtering from two separate sources, metal and insulator, with the resulting layer containing metal grains in the range of 1 - 20 nm embedded in an amorphous insulator matrix. In practice, cermets are used as cermet film resistors for applications in microelectronics, as optical materials, as superconducting quantum interference devices (SQUIDS), and others. Cermets are interesting for scientific research because by varying the proportion of the metal component to the proportion of the insulator component, the composition can be easily varied and their physical properties can be easily measured.

There are already answers to these two questions, 1) and 2): The increase of T_c in $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermets is interpreted to be associated with the enhancement of the

electron-phonon interaction, whereas the abrupt drop in T_c with further increase of x is determined by percolation effects resulting from grains becoming progressively more separated from one another ([3], there section IV, pp. 64), see **Figure 1**, where experimental data T_c vs $x/(1-x)$ for these $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermet films are shown.

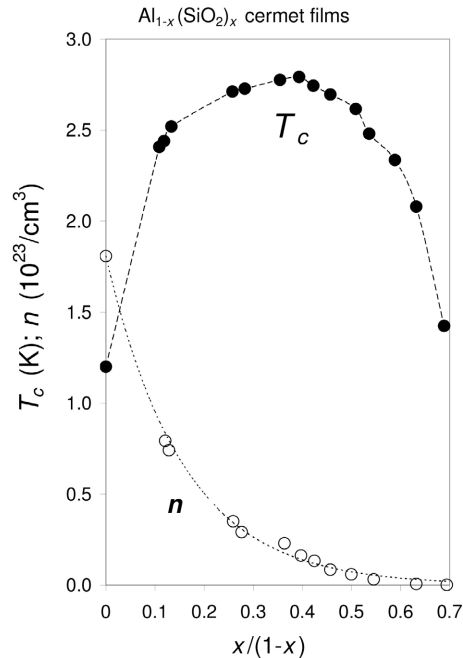


Figure 1. Experimental T_c data (full circles, taken from Abeles [3], there Figure 40) and the electron density n in the Al phase of $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermet films vs $x/(1-x)$. The open circles represent n calculated with Equations (6) and (7) for $L = 1.5$ nm. The dotted line represents n according to Equation (4) with $\beta = 6.4$ and $n_A = 1.81 \times 10^{23}/\text{cm}^3$. The T_c curve is a guide for the eyes.

The decrease of T_c in Pb-Cu-sandwiches with increasing thickness of the Cu film on the Pb film is interpreted within the framework of the Ginzburg-Landau-equations, where the coherence length plays an important role. It is concluded that the decrease of T_c is a consequence of the influence of the mean free path of the electrons in the Cu film (see [4], there section 6.1.2, pp.326, Figure 6.5 and Figure 6.6).

Unlike these two interpretations, we propose an alternative approach to answering questions 1) and 2): Based on the plausible assumption that, due to the increase in the electron-electron Coulomb repulsion between the electrons, large electron densities are rather unfavorable for achieving high T_c values, we assume that high T_c values are achieved when the electron density n is small. One mechanism that can lead to a significant decrease in n is the phenomenon of electron transfer, which offers the possibility that n can be reduced in this way. This consideration was crucial to understanding the high T_c values in the HTSC. In [2] the influence of the electron-phonon interaction was considered as fixed, as given by the structural framework in the superconductor, and such terms as coherence

length, order parameter, magnetic field influence, mean free path were intentionally left out. In other words, in the first approximation, we consider these terms constant and look to see whether there is a direct, unambiguous connection between n and T_c . With superconducting cermets, we have the unique opportunity to measure or determine n and T_c independently of each other.

In 2023 I published a book [5], which investigates the influence of the electron transfer on structure and electronic transport in solids. In this book, the equation

$$n = n_A \cdot \exp(-\beta\zeta), \quad (4)$$

which was already published in 1989 [6], plays a key role. It describes the electron transfer in amorphous alloys and nano-scaled composites (shortly nanocomposites), where $\zeta = v_B/v_A$ with v_A and v_B as the volume fractions of the phases A and B , respectively. n is the electron density in the phase A of the two-phase nanocomposite. The phase A is the one with the higher potential. β is a constant for a given nanocomposite, determined by the average potential difference between the two phases, ΔV . By the electron transfer, described by Equation (4), ΔV is balanced leading to a common electrochemical potential in the nanocomposite.

Equation (4) allows to determine n and T_c independently of each other, T_c by direct measurement and n via Equation (4). And in the example of $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermets, there is sufficient experimental data available that allows a calculation of n vs x . And it turns out that there is indeed a clear connection between n and T_c , which is expressed in Equation (2).

On the basis of Equation (4) and its differential representation,

$$dn = -\beta \cdot n \cdot d\zeta, \quad (5)$$

a number of previously unsolved problems/questions that had played a major role in solid state physics in the second half of the 20th century could be answered, for example on the Giant Hall effect, the Mooij correlation, the metal-insulator transition, the proximity-effect, the positive Seebeck coefficient in simple metals and others. These two equations, (4) and (5), are also the starting point for answering the two questions posed above.

2. T_c in $\text{Al}_{1-x}(\text{SiO}_2)_x$ Cermets

The epsilon near zero (ENZ) core-shell metamaterial described by Smolyaninova *et al.* [7] is a way or method to triple the superconducting critical temperature T_c of bulk aluminum. Nano-sized Al grains are covered by a thin Al_2O_3 film. By this special arrangement, so the assumption by the authors, a considerable enhancement of attractive electron-electron interaction may be expected and the dielectric response function $\epsilon(q, \omega)$ may become small and negative forming Cooper pairs and Superconductivity.

The same effect, to triple T_c of bulk aluminum, is known for $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermets (Abeles [3], there Figure 40), reproduced in **Figure 1** as curve T_c vs $x/(1-x)$. (x not to be confused with the x in Equation (1).) T_c increases considerably with increasing SiO_2 content occurring a maximum at $x \approx 0.3$. The special structure in

$\text{Al}_{1-x}(\text{SiO}_2)_x$ cermets is a *granular* one characterized by spherical Al grains embedded in the amorphous SiO_2 phase. This structure is very similar to the one designed by Smolyaninova *et al.* [7] for their core-shell metamaterial.

In this section it will be shown that increase of T_c in $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermets is correlated with a progressive decrease of the electron density n in the Al grains as x increases due to an electron transfer from the Al grains to the SiO_2 phase occupying surface states. The question is whether there is a direct dependence between T_c and n as suggested by Equation (2).

In $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermets, Al and SiO_2 are the phases A and B , respectively. x is the volume percent of SiO_2 [3]. In the sense of Equations (4) and (5), $x = v_B$, $1-x = v_A$ and $\zeta = x/(1-x)$.

The decrease of n expressed by Equation (4) is also indirectly represented by the concentration dependence of the conductivity of the cermet, σ , as shown in **Figure 2**, where experimental data σ ($=1/\rho$) and σ_A vs $x/(1-x)$ for these $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermets are shown. σ_A is the conductivity of the phase A (Al) calculated by the approximation formula for two-phase alloys with $\sigma_B = 0$, [8] [9],

$$\sigma_A = \sigma \frac{2}{3(1-x)-1} \quad (6)$$

where x is the volume fraction of SiO_2 and $\sigma = 1/\rho$. The two straight lines shown in **Figure 2** are approximation lines for σ and σ_A vs $x/(1-x)$. β can be determined from the approximation line for σ_A using the Boltzmann transport equation (Kirejew [10], pp. 227)

$$\sigma_A = 2 \left(\frac{\pi}{3} \right)^{1/3} \frac{e^2}{h} L \cdot n^{2/3}, \quad (7)$$

where e , h and L are the elementary charge, Planck's constant, and the mean free path of the electrons in the Al grains, respectively.

Once β is known, one can determine n vs x , respective $x/(1-x)$, using Equation (4).

For $x=0$, σ is essentially larger than the intersection points of the two straight lines, σ and σ_A vs $x/(1-x)$ in **Figure 2**, because the mean free path of the electrons in the pure Al is essentially larger than in the cermets.

For $x=0$, $n = n_A = 1.81 \times 10^{23} \text{ cm}^{-3}$ (the electron density of the crystalline aluminium). In the concentration range $0 < x < 1/3$ $n(x)$ can be determined if L is independently of x . This is approximately realized for $0 < x < 1/3$ as suggested by the straight lines in **Figure 2**. It follows $\beta = 6.4$. The procedure as β has been determined, is demonstrated in **Figure 3**. From these calculations it follows $L \approx 1.5 \text{ nm}$ for $0 < x < 1/3$. This value for L agrees approximately with the sizes of the Al grains in the cermets for $0 < x < 1/3$. For $x > 1/3$, with increasing x , L decreases more and more because the sizes of the Al grains decreases as well. The smaller the grain size, the larger the total interface between the metal grains Al and the insulator phase SiO_2 . This is important in that with increasing x the amount of transferred electrons increases, according to Equation (4).

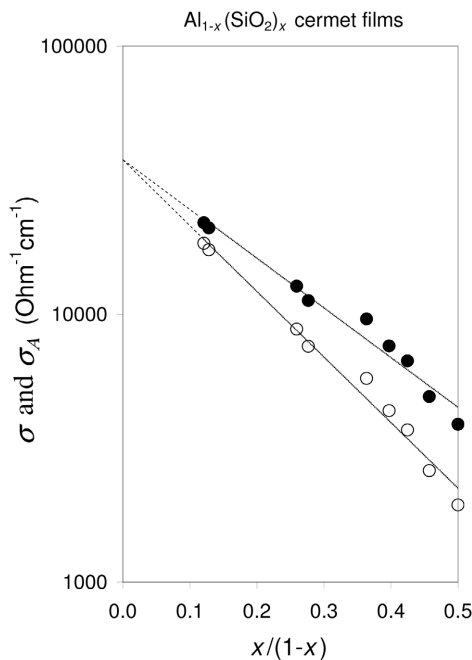


Figure 2. Conductivity data for $Al_{1-x}(SiO_2)_x$ cermet films vs $x/(1-x)$: Experimental data σ (open circles, taken from Abeles [3], there Figure 40) and σ_A (full circles), calculated with Equation (6).

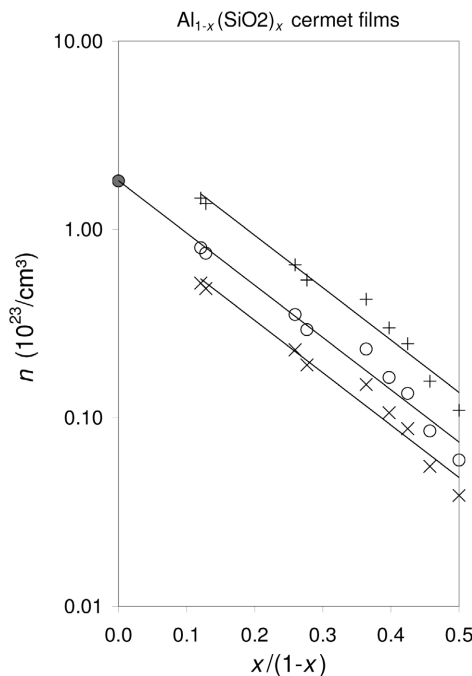


Figure 3. Determination of the parameters of the Equation (4) for $Al_{1-x}(SiO_2)_x$ cermet films applying Equations (6) and (7) using the experimental $\rho (=1/\sigma)$ data at $T = 4.2$ K taken from Abeles [3] (there Figure 40). The assumed values for L were $L = 1.0$ nm (+), $L = 1.5$ nm (o) and $L = 2.0$ nm (x). The full circle at $x = 0$ specifies the electron density of the crystalline aluminium, $n_A = 1.81 \times 10^{23}/cm^3$. The straight line for $L = 1.5$ passes exactly through the full circle at $x = 0$, which corresponds to $\beta = 6.4$ and $n_A = 1.81 \times 10^{23}/cm^3$.

In **Figure 1**, the concentration dependences of n determined by Equations (6) and (7) is plotted vs $\zeta = x/(1-x)$, supplemented by the n curve calculated by Equation (4) with $\beta = 6.4$ and $n_A = 1.81 \times 10^{23} \text{ cm}^{-3}$. The calculated points for n lie very well on the analytical curve given by Equation (4). This confirms once again that Equation (4) correctly reflects the electron density distribution in this special system $\text{Al}_{1-x}(\text{SiO}_2)_x$. Therefore, Equation (4) can also be used for the assignment $x \leftrightarrow n$. The small deviations of the calculated points from the analytical curve are also reflected in the scatter of the points in **Figure 3** from the straight line for $L = 1.5 \text{ nm}$ and are an expression for the deviation of the mean free path L from the assumed mean value $L = 1.5 \text{ nm}$. The analytical formula, Equation (4), completely averages out these deviations from the mean value “ $L = 1.5 \text{ nm}$ ”. With Equation (4) we therefore have a possibility to specify n for the respective T_c measured values very precisely. The residual measurement errors of the concentration dependence T_c on $\zeta = x/(1-x)$, shown in **Figure 1** as well, are therefore limited only to those of the x values of the measured T_c values.

In **Figure 4** $T_c/T_{c,\text{max}}$ is drawn vs n , where $T_{c,\text{max}} = 2.79 \text{ K}$. The n values were calculated using Equation (4) for the respective x for which experimental T_c data are available in [3]. $T_c/T_{c,\text{max}}$ can be described very well by a parabolic dependence as given in equation (2) with $\gamma = 17.3 \times 10^{-48} \text{ cm}^6$ is a parameter, which is characteristic for $\text{Al}_{1-x}(\text{SiO}_2)_x$ superconductors.

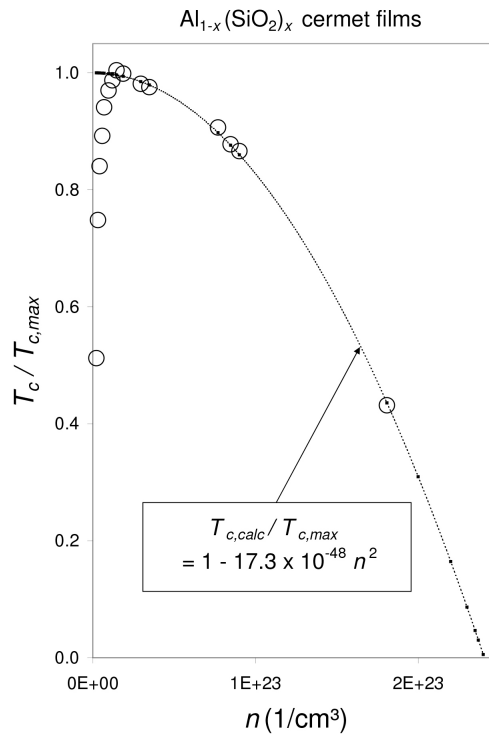


Figure 4. Experimental $T_c/T_{c,\text{max}}$ vs n for $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermet films. The n values were calculated using Equation (4) for the respective x for which T_c measurements were available in Figure 40 of [3]. The abrupt drop in the experimental $T_c/T_{c,\text{max}}$ data for very small n is caused by the granular structure as described in the text. (n in units of 10^{24} cm^{-3}).

Equation (2) is not only a random result for $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermets, but it has a more general meaning. It was used for derivation of Equation (1) which describes the concentration dependence of T_c on x for hole-doped Cuprat HTSC ([2]).

The experimental value $T_{c,\text{max}} = 2.79 \text{ K}$ is only an approximation of the true $T_{c,\text{max}}$. The true value for $T_{c,\text{max}}$ is surely a little larger than this experimental value, because for very small n , corresponding to $x > 0.3$, $T_c/T_{c,\text{max}}$ in **Figure 4** deviates considerably from the parabolic curve, Equation (2). For $x > 0.3$ T_c rapidly decreases again caused by the granular structure, where the direct contact between the superconducting Al grains are interrupted more and more with increasing SiO_2 content.

It is very likely that the increase of T_c realized by the special ENZ arrangement for Al embedded in thin Al_2O_3 shells designed by Smolyaninova *et al.* [7] is also caused by an electron transfer from Al to the Al_2O_3 shells.

3. T_c in Thin Film Sandwiches

There is also the opposite effect: Thin film staples consisting of a superconducting material and a normal metal have often a lower transition temperature T_c than the superconducting material alone.

Frydman [12] has found for Pb films deposited on 10 nm thick Ge layer as well as for Pb-Ag sandwiches that T_c decreases. In the case of the Pb on Ge sandwich T_c increases more and more as the Pb film thickness increases approaching T_c of pure Pb. And for Pb-Ag sandwiches Frydman found for a 25 nm thick Pb film a decrease of T_c as the Ag film thickness deposited on the Pb film increases. Similar results was found by Smith *et al.* [13] on Pb-Ag layer packages.

Considering the results from section 2, it is reasonable to assume that the reduction in T_c in the Pb containing film sandwiches is caused by an increase of the electron density in the Pb films due to electron transfer from Cu or Ag to the Pb film leading to an increase of the electron-electron repulsion.

The influence of the film thicknesses D_{Cu} and D_{Pb} on T_c in Pb-Cu-sandwiches has been studied experimentally by Hilsch [11]. His experimental data and the decay curves calculated by [11]

$$T_c = T_{c,Pb} - (T_{c,Pb} - \mathcal{G})(1 - \exp(-D_{Cu}/a)), \quad (8)$$

are reproduced in **Figure 5**. $T_{c,Pb}$ and T_c correspond to the superconducting critical temperature of the pure Pb film and the Pb-Cu-sandwich, respectively. \mathcal{G} is the asymptotic value of T_c for very large D_{Cu} (at D_{Pb} constant): $\mathcal{G} = 2.04, 3.53, 5.66, 6.60,$ and 7.08 K for $D_{Pb} = 10, 15, 30, 50,$ and 100 nm , respectively, following from **Figure 5**. For the decay constant $1/a$, the “effective thickness” $a = 10 \text{ nm}$ is used uniformly (Hilsch [11]).

T_c is generally smaller than in pure Pb. T_c increases with the growing D_{Pb} (at constant D_{Cu}) approaching T_c of the pure Pb when $D_{Pb} \gg D_{Cu}$.

Although Equation (4) refers to amorphous alloys and nanocomposites, let us check whether this formula gives also insights about the two-phase Pb-Cu sandwiches, **Figure 5**. With $\zeta = v_B/v_A = D_B/D_A$ it follows from Equation (4)

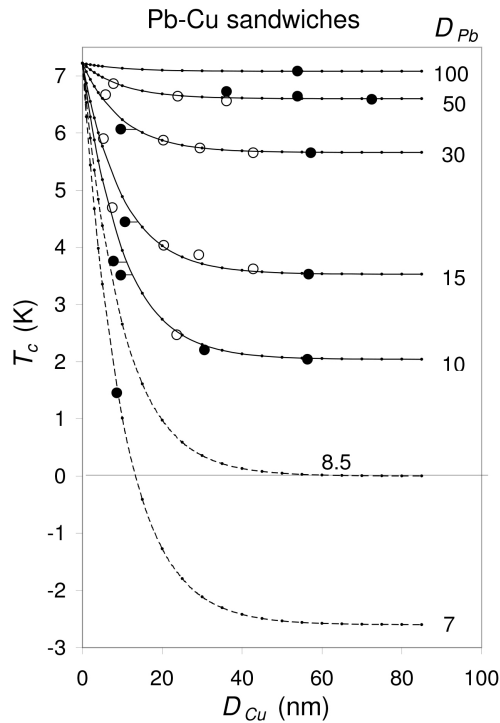


Figure 5. T_c of Pb-Cu sandwiches vs the Cu film thickness, D_{Cu} , reproduced using the original experimental data from Hilsch [11] (there Figure 6a). The numbers on the right are the Pb film thickness, D_{Pb} , as parameter. Layer sequence Quartz-Cu-Pb (full circles), Quartz-Pb-Cu (open circles). The curves are calculated by Equation (8), given by [11]. The “ $D_{Pb} = 8.5$ ” curve represents Equation (8) for $\vartheta = 0$.

$$n = n_A \cdot \exp\left(-\beta \frac{D_{Pb}}{D_{Cu}}\right). \tag{9}$$

Figure 6 shows T_c vs D_{Pb}/D_{Cu} for data groups of Pb-Cu sandwiches, where D_{Pb} is constant: $D_{Pb} = 10, 15, 30, 50,$ and 100 nm. Each of the data groups can be described relatively well by approximating straight lines with a slope that becomes flatter as D_{Pb} increases. β is no longer a constant.

The picture in picture in **Figure 6** shows the intersection points of these straight lines with the verticale straight line at $D_{Pb}/D_{Cu} = 1$, that is, $T_c/T_{c,Pb}$ vs D_{Pb} for Pb-Cu sandwiches, where D_{Pb} is replaced by D , because of $D_{Pb} = D_{Cu}$.

The decrease of T_c is the larger the smaller D ($D_{Pb} = D_{Cu}$), because n in the Pb film increases more and more as D decreases. On the other side, even for relative large values of D there is still an influence on T_c . This means that the influence of electron transfer also works over large distances, although in an increasingly weakened form the longer the distances are. The electron-electron interaction still works over very large distances.

Although Equation (5) holds for nanocomposites, it is surely reasonable to say that the electron transfer between the Pb and Cu layers (phases) in the layer stacks, expressed by dn , is also determined by the proportionality $-dn \propto n$ and $\beta \propto \Delta V$. The difference is, that β is constant for the nanocomposite, however

it is not for the layer stacks. Nevertheless, the electronic properties of both types, nanocomposites and layer stacks, are essentially influenced by the potential difference between the two phases, ΔV , which the system tries to balance by electron transfer in order to realize a common electrochemical potential.

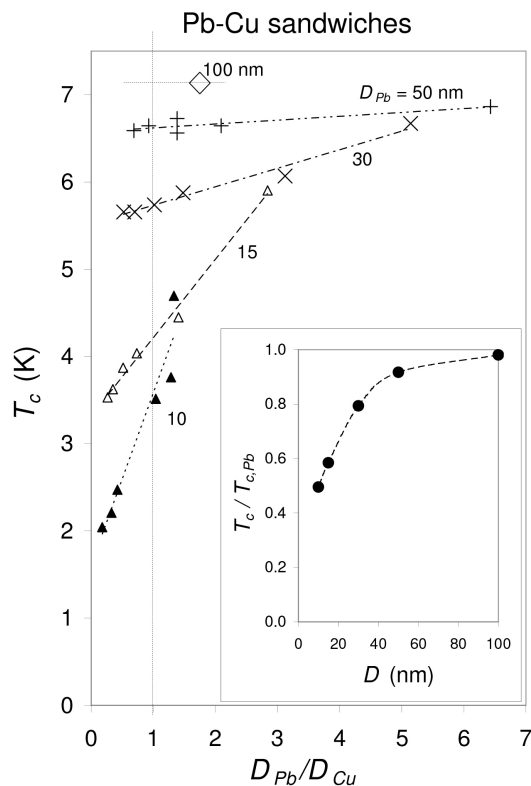


Figure 6. T_c of Pb-Cu sandwiches vs D_{pb}/D_{cu} for data groups with a constant D_{pb} : 10 (full triangles), 15 (open triangles), 30 (x), 50 (+), and 100 nm (rhombus), taken from **Figure 5**. The data groups can be described relatively well by approximating straight lines. The picture in picture shows the respective intersection points of the straight lines with the vertical line at $D_{pb}/D_{cu} = 1$, drawn as $T_c/T_{c,Pb}$ vs D , where $D \equiv D_{pb} = D_{cu}$. The dashed curve is a guide for the eyes.

In a Pb-Cu sandwich the electron density in the Pb layer perpendicular to the substrate is location dependent, i.e., there is a gradient in n , vertical to the sandwich. One can assume that T_c is determined by the lowest value of n in the Pb layer, which occurs directly at the interface to the substrate, n_{if} , provided that there is no electron transfer between the metal film and the substrate. The four data points in **Figure 5** connected with the analytic curves by a short horizontal line (for $D_{pb} = 10, 15$ and 30 nm) suggest, however, that there is also an additional influence by electron transfer from the metal layer to the substrate reducing the potential additionally. If we neglect this influence of the substrate, one can say that n_{if} approaches the electron density of the pure Pb more and more, the larger D is.

There is an important difference between the Pb-Cu-sandwiches and the

$\text{Al}_{1-x}(\text{SiO}_2)_x$ cermets. While in the $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermets $T_{c,\text{max}}$ can be determined experimentally, because with increasing x , n decreases, going towards the maximum of the T_c vs n curve, for Pb $T_{c,\text{max}}$ cannot be determined using Pb-Cu sandwiches, because with increasing D_{Cu} , n increases going towards smaller values of T_c .

In the book [4] another sight to the physics of Pb-Cu-sandwiches has been described: the difference between the two curves 1 and 2 in [4] (there Abb. 6.5 on p. 328), T_c vs D_{Pb} , is interpreted to be caused by different mean free paths of the electrons in the Cu layer. Unfortunately, the different values for D_{Cu} in the curves 1 and 2 are not cited. However, as we have seen in the **Figure 5** and **Figure 6**, D_{Cu} plays a decisive role regarding the reduction of T_c .

4. Conclusions

The result that Equation (2) holds for both, hole-doped cuprat HTSC [2] and $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermets is an important indication that a common mechanisms underlie HTSC and classical superconductors. The difference between the two is that in HTSC electron transfer occurs between two different electronic bands, but in $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermets between different phases. For both types of superconductors electron transfer is evident. The results to the Pb-Cu-sandwiches are an additional indication that electron transfer plays a prominent role in superconductors. This finding can be of great use in the search for new superconductors with even higher values of T_c . Electron transfer is the key to achieving high values for T_c .

Equation (2) reflects both influences that determine T_c , that of the electron-phonon interaction and that of the electron-electron Coulomb repulsion. To put it bluntly, one could also say that Equation (2) represents an analytical separation of these two influencing factors that determine T_c : γ and $T_{c,\text{max}}$ in Equation (2) stand for the influence of the electron-phonon interaction and n^2 for the influence of the electron-electron Coulomb repulsion on T_c . Considering both formulas, Equations (2) and (3), the influence of the electron-phonon interaction can be formally separated from the influence of the electron-electron interaction or hole-hole interaction, where the former is represented by γ and $T_{c,\text{max}}$, the latter by n^2 or p^2 , respectively.

In a figurative sense, γ and $T_{c,\text{max}}$ can be understood as the parameters that define the limits within which Superconductivity is possible, comparable to a container or “pot” that has to be filled by the electrons or holes, represented by the term n^2 or p^2 , respectively. The more the “pot” is filled with electrons or holes, the less space remains for Superconductivity. The comparison of the $T_{c,\text{max}}$ values for HTSC with $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermets shows that the “pot” for the former is much larger than the “pot” for the latter, which is why the theoretically possible or achievable maximum values for T_c are much larger for HTSC than for $\text{Al}_{1-x}(\text{SiO}_2)_x$ cermets. A challenge for theoretical physics here might be to find out why much larger $T_{c,\text{max}}$ are possible if the lowering of n or p takes place by electron transfer between electronic bands rather than between different phases.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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