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A superconducting superlattice of quantum stripes with a particular shape that gives the amplification of the critical temperature is called "superstripes". This superlattice is characterized by: a) the metallic stripe width L of the order of the de Broglie wavelength of electrons at the Fermi level, \( L \sim \lambda_F \), and b) the hopping of pairs between the stripes larger than the hopping of single electrons. "Superstripes" can be realized artificially to get new room temperature superconductors (RTS). This particular mesoscopic heterostructure at the atomic limit has been found as a self organized network of charges, in a short time and space scale, in doped cuprate perovskites near the micro-strain quantum critical point for "superstripes" formation.

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1. Introduction

The design of new materials by atomic manipulation at the atomic limit for the amplification of the superconducting critical temperature can lead to room temperature superconductors (RTS) following the invention of "superstripes" in Rome in 1993. This invention provides the physical parameters to design new superconducting heterostructures intended to amplify the critical temperature described in a patent and in following papers. The "superstripes" invention is based on the discovery that the superconductivity with high critical temperature is related to a particular heterogeneous structure that has been found in a cuprate perovskite Bi2212, where the "superstripes" appear as a self organized network of stripes of charges in small bubbles of few hundreds angstroms fluctuating with a time scale of \( 10^{-12} \) sec.

In the first part of this paper we describe how the critical temperature can be multiplied by an "amplification factor", by making artificial "superstripes", up to hundred times larger than that of the homogeneous material. In the second part we describe the natural superstripes in cuprate perovskites.

2. Design of superstripes to amplify the critical temperature

The invention gives the key parameters for material design to get \( T_c \) amplification. Fig. 1 shows the heterostructure of superconducting stripes: "superstripes". The heterostructure is formed by a superlattice of layers, (2) in Fig. 1. Each layer is made of a plurality of first stripes of a first superconducting material, (3) in Fig. 1, and a plurality of second stripes with different electronic structure, (4) in Fig. 1, intercalated to the first stripes, for their separation \( W \), up to realize a superlattice having period \( \lambda_p \).
The separation $W$ between the superconducting stripes measured in the $y$ direction is of the order of the superconducting Pippard coherence length $\xi_0$.

**Figure 1.** The heterogeneous structure made by a multi-layer of planes (2) where first metallic stripes (dashed stripes 3) of width $L$ are separated by second stripes (empty stripes 4) forming a periodic potential barrier of width $W$ for the charge carriers in the stripes (3) with period $\lambda_p$.

**Figure 2.** The density of states $N(E)$ of a superlattice of quantum stripes, "superstripes", as a function of the chemical potential $E$. The "shape resonance" is obtained by tuning the Fermi level, $E_F$, at a density of states peak $N(E_m)$ occurring near the threshold of the $m$ subband $E_m-E_{m-1}$ ($m=2$ in the figure). $N(E)$ is suppressed in the pseudogap regions between $E_m-E_{m+1}$.

The superconducting stripes, (3) in Fig. 1, are characterized in that the size $L$, measured in the $y$ direction, satisfies the "shape resonance" condition for the electrons at the Fermi level. The "shape resonance" occurs where the electrons at the Fermi level with wave-vector $k_F=2\pi/\lambda_F$ are trapped for a finite time in the stripes of width $L$ by resonant potential scattering. At the "shape resonance" the Fermi energy is tuned to the maximum of the electronic density of states $N(E)$ of a superlattice subband as shown in Fig. 2. The size $L$ of the superconducting stripes should satisfy the "shape resonance condition" (for small single particle hopping, $t_\perp \to 0$ between the stripes):
\[ k_F \approx \frac{m \pi}{L}; m > 2 \]  

where \( k_F \) is the wave-vector of the electrons at the Fermi level of the superconducting material. More in general the condition for the "shape resonance" can be written as

\[ E_F = E_m \]

that means that the Fermi energy is tuned near a maximum of the electronic density of the states \( N(E_m) \) as shown in Fig. 2. Moreover in the case that the values of \( L \) obtained by using the formula (1) are too small it is possible to use a second "shape resonance" condition:

\[ k_F - G \approx \frac{m \pi}{L}; m > 2 \]

Figure 3. The particular case where the Fermi level is tuned near the bottom of the \( m=2 \) subband, following formula (1), panel (a), and formula (3), panel (b). The Fermi level is tuned by changing the charge density of the stripe structure, to get the energy separation \( E_F - E_2 < \omega_0 \), where \( \omega_0 \) is the energy cutoff for the pairing interaction.

where \( G \) is the vector of the reciprocal lattice of the superconducting material, \( k_F \) is the wave-vector of the electrons at the Fermi level and \( m \) is an integer number as it is shown in Fig. 3. The peaks of the density of states \( N(E) \) in figure 2 have a finite width determined by the dispersion of the superlattice subband in the direction perpendicular to the stripes i.e., due to a finite hopping \( t_\perp \) between the stripes. The maximum occurs at the crossover from a two dimensional (2D) the Fermi surface to a one-dimensional (1D) Fermi surface. In fact at the bottom of each subband the hopping of single electrons between the stripes \( t_\perp \) gives a 2D band with energy dispersion \( E = E_{\text{peak}} - E_{\text{bottom}} \). At higher energy \( N(E) \) decreases by increasing the energy, as for a 1D band, giving origin to the "pseudogap" generated by the superlattice of quantum stripes.
The superconducting gap shows a resonance centered at the maximum of the density of states and a width determined by the energy cutoff for the pairing interaction $\omega_0$. A characteristic feature of the Fermi surface of a superlattice of quantum stripes is that it is broken and different superconducting gaps are associated with different segments. In fact there is a different gap $^\sim \Delta_m$ for each subband "m". Considering the simple case shown in Fig. 2 and 3, where the chemical potential is tuned to the second "subband", two gaps appear in different portions of the Fermi surface.

![Figure 4](image-url)

**Figure 4.** The calculated critical temperature as a function of the coupling $\lambda$ for the pairing: $T_c^\infty$ for an infinite homogeneous material and $T_c^{\text{cn}}$ for a superlattice of quantum stripes by tuning the chemical potential to the $m$ shape resonance. The amplification of the critical temperature in the superstripes, from ref. 6, is shown.

Fig. 4 shows the amplification of the critical temperature that can be obtained by superstripes design. By tuning the chemical potential close to an artificial peak of the $N(E)$ for the superstripes, the superconducting critical temperature shows a resonant amplification that depends on the stripe width $L$ and the potential barrier between the stripes $^4\text{L.}$

Quantum phase fluctuations that usually suppress the superconducting "condensate" in low dimension are not effective in the superstripes. In fact the mesoscopic stripe width $L$ and the periodic potential barrier give sharp peaks in the density of states $N(E_m)$. By increasing artificially the local density of states $N(E_m)$ the hopping of electron pairs between the stripes $t^\perp \cdot N(E_m)$ can be made larger than the hopping of the single electrons between the stripes $t^\perp$.

\[
t^\perp \cdot N(E_m) > t^\perp
\]

If this condition is satisfied, the phase coherence of the superconducting phase is stabilized and quantum fluctuations, expected in low dimensional systems, do not suppress the critical temperature for the superconductivity.

The 1D charge ordering, or stripes formation, has been considered by the scientific community to be always detrimental for superconductivity. In fact $T_c$ is suppressed if
the chemical potential is tuned in the pseudo gap region. However $T_c$ is amplified by tuning the chemical potential at the shape resonance in the "superstripes. At the first and second conference on "Stripes and high $T_c$ superconductivity" only two papers were presented on "superstripes".

Seven years after the invention at the third conference held in Rome several papers on "superstripes" have been presented considering different scenarios for the formation of the periodic potential barrier, but confirming the mechanism of $T_c$ amplification in "superstripes". Some authors have shown the key role of two superconducting gaps for $T_c$ amplification resulting by two bands where the chemical potential is tuned to the bottom of the second band as shown in panel (b) of Fig. 3.

Direct experimental evidence for two dispersing bands in Bi2212, as predicted in Fig. 3, has been reported by several groups by using high resolution angle resolved photoemission. These experiments give a compelling experimental evidence for the presence of a superlattice of quantum stripes with wave-vector $Q(0.4\pi,0.4\pi)$ first observed in momentum scanning photoemission by Saini et al.

![Figure 5](image)

**Figure 5.** The phases of the 2D electron gas in cuprates at fixed doping by changing the micro-strain: (a) Metallic phase, quantum disorder, $\varepsilon\sim 0$; (b) Superstripes, metallic bubbles of stripes, $\varepsilon_{c} < \varepsilon < \varepsilon_{0}$; (c) Electron crystal of polaronic strings, $\varepsilon > \varepsilon_{0}$.

### 3. Natural superstripes in cuprates

The complex inhomogeneous metallic phase of the doped antiferromagnetic CuO$_2$ plane in cuprate perovskites is due to charge segregation of metallic clusters pushed out by magnetic background as in doped magnetic semiconductors. A first type of *fluctuating short range* striped phases have been observed in some superconducting samples while not in others depending on the time scale of the experimental methods. These fluctuating metallic stripes show up in bubbles as shown in panel (b) of figure 5. A second type of *static long range* striped insulating phases due to charge ordering with 1D commensurate modulation have been found in doped manganites, nickelates and at 1/8 doping in La$_{2-x}$Nd$_x$CuO$_4$. These charge ordered phases are shown in panel (c) of figure 5.

Focusing the interest on superconducting materials that show the first type of striped phases it was found that they show a particular type of self organization "superstripes" within bubbles of 100-300 and on a short time scale of the order of
It was found that the detection of superconducting striped phases depends on the experimental measuring time, and the fluctuation time changes from sample to sample. Therefore in some samples, with fast superstripes fluctuations, the striped phases are difficult to be detected.

Figure 6. The new phase diagram of the metallic phase for all cuprate perovskites as a function of doping $\delta$, temperature $T$, and micro-strain $\epsilon$ acting on the CuO$_2$ plane. The phases (a), (b) and (c) in Fig. 5 appear in the ($\delta,\epsilon$) plane. The fluctuating bubbles of superconducting stripes, "superstripes", are formed near the quantum critical point (QCP) for superstripes formation. Critical charge, spin, and orbital fluctuations give the self-organized pattern of "superstripes" in a short time (~10$^{-12}$ sec) and length scale (100-300 Å) in the region of micro-strain and doping defined by the bold circle centered at the QCP.

Recently it has been shown that the elastic field plays a key role for the presence of "superstripes" in cuprates. It was known that the critical temperature of cuprate superconductors could be changed by applying a pressure, by atomic substitution via chemical pressure, and by the mismatch with the substrate in films, but the mechanism remained mysterious. Recently it has been shown that beyond temperature and doping a third variable is needed to define the phase diagram of cuprate perovskites: the micro-strain $\epsilon$ in the CuO$_2$ plane as shown in Fig. 6. There is a critical micro-strain for "superstripes" formation as shown in Fig. 6. Near this critical micro-strain the formation of fluctuating bubbles of "superstripes" has been found in doped cuprate perovskites. The superstripes are due to critical charge, spin and orbital fluctuations around this quantum critical point (QCP).

The new phase diagram for all cuprates, shown in Fig. 6, depends on the charge density (i.e., the doping), the temperature and the elastic field due to the micro-strain. In the plane ($\epsilon,\delta$), at $T=0K$, in Fig. 6 it is possible to identify the different phases (a),(b) and (c) shown in Fig. 5. The superstripes are formed beyond the critical micro-strain for formation of superstripes that determines the quantum critical point (QCP) shown in Fig. 6. Critical charge, spin, and orbital fluctuations give the self-organized bubbles of "superstripes" in the region of strain-doping defined by the gray circle centered at the QCP in Fig. 6.

Superstripes have been shown to be formed by self organization in a sample of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2122) close to the QCP. The heterogeneous phase of Bi2122 is made of i) a charge reservoir layer (Bi$_2$O$_{2+\delta}$) ii) a rocksalt block (Sr$_2$O$_2$Ca) and iii) the
two superconducting CuO$_2$ planes embedded within the rocksalt layers. The rocksalt layers induce a micro-strain on the CuO$_2$ plane larger than the critical strain for local lattice distortions (LLD). The dynamical buckling of the Cu-O plane forms a striped pattern with a wave-vector $Q=\langle 0.4\pi, 0.4\pi \rangle$ within a short coherence length of about 100-300 that gives the size of the fluctuating bubbles. Within the bubbles, the modulation of the second nearest neighbor hopping integral $t'$ gives a superlattice of quantum stripes with the formation of superlattice subbands observed by angular resolved photoemission. The Fermi level at optimum doping is at about 50-80 meV above the bottom of the highest subband and it has been shown that the chemical potential at optimum doping $\delta=0.16$ is tuned to the third, $m=3$, "shape resonance" as shown by the DOS in Fig. 7. The peaks and minima in the DOS due to the first and second subband (1 and 2) according with the formula (1) are indicated in Fig. 7. At negative doping it is possible to see the corresponding peaks due to the formula (3).

![Figure 7.](image)

In conclusion we have shown the $T_c$ amplification in a particular superlattice of quantum stripes, called "superstripes", and that fluctuating bubbles made by a superlattice of quantum stripes with period $\lambda_p=13$ show up in Bi2212 near a critical micro-strain. Here the Fermi level at optimum doping is tuned to a "shape resonance" that gives high $T_c$ superconductivity.

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