Possibility of unconventional superconductivity of $SrTiO_{3-\delta}$

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Abstract

$SrTiO_{3-\delta}$ can show metallic behavior and superconductivity at $T < 500$mK. Due to its low carrier concentration ($\simeq 10^{20}$cm^{-1}) and huge dielectric polarisability ($\epsilon \simeq 300$) this compound is considered as a candidate for a polaronic superconducting pairing mechanism.

It is demonstrated that by variation of the annealing temperature in vacuum the transport properties of $SrTiO_{3-\delta}$ can be tuned continuously from semiconducting to metallic. We present measurements of the upper critical field $B_{c2}(T)$ which show near T_c a positive curvature. This unusual temperature dependence is consistent with a model of weakly interacting charged bosons which condense in the superconducting state (local pairing). However, measurements of current-voltage curves reveal only small critical currents of our samples. This observation is discussed in the framework of doping inhomogeneities.

Key words: bipolaronic superconductivity; $SrTiO_3$; B_{c2}(T)

1. Introduction

One of the first attempts to explain superconductivity was considering the condensation of a charged ideal Bose gas [1]. After the establishment of the BCS-theory this concept was considered as the basis of an unconventional mechanism of superconductivity [2], [3]. The basic idea is that polarons pair to bipolarons which then condense into a superfluid like state [4]. Although this theory seems not to apply to HT_c superconductors [5], there are other materials which are candidates for bipolaronic superconductivity; and $SrTiO_{3-\delta}$ is among these. The stoichiometric compound is an insulator, but doped it becomes conducting and even superconducting ($T_c < 0.5$K) [6]. The formation of polaronic charge carriers in doped $SrTiO_3$ is confirmed by several experimental observations (e. g. [7],[8]).
However, up to now there are no clear experimental indications of a pairing of the polarons and bipolaronic superconductivity in $SrTiO_3$.

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2. Experiment

The sample preparation started from commercially available $SrTiO_3(111)$ substrates of size $10 \times 10 \times 1$mm. For the definition of the contact pads two Mo stripes of width $400\mu m$ and distance of $200\mu m$ from each other were evaporated on two opposing sides of a substrate. Afterwards, the backsides of the substrates were polished down to a final sample thickness of $\simeq 300\mu m$. Then the samples were reduced in an MBE chamber (p$\simeq 10^{-8}$ mbar) for 1h at $T \simeq 1150$K. Finally, the substrates were cut into stripes of width $\simeq 700\mu m$. (see fig. 1)

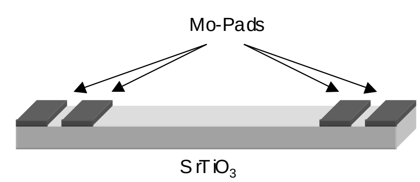

Fig. 1. Geometry of the $SrTiO_{3-\delta}$ samples with contact pads (schematic, not to scale).

Resistance measurements were performed in a standard 4-probes technique in a ^{3}He and a dilution cryostat. Depending on the reduction temperature it is possible to tune the resistivity of $SrTiO_{3-\delta}$ continuously from semiconducting to metallic. $R(T)$ curves are shown in fig. 2.

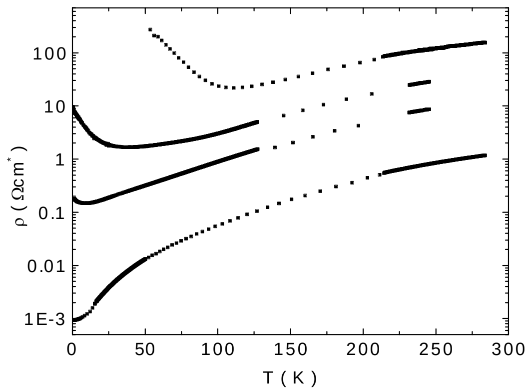

Fig. 2. Temperature dependent resistivity $R(T)$ of $SrTiO_{3-\delta}$ with increasing oxygen reduction. (* Specific resistivity calculated with the assumption of homogeneous doping in the sample.)

The upper critical field $H_{c2}(T)$ of superconducting $SrTiO_{3-\delta}$ was determined by measuring $R(T)$ curves in different magnetic fields in a dilution cryostat. Samples with high critical temperatures ($T_c > 200$mK) show sharp superconducting transitions ($\Delta T_c < 3$mK), whereas samples with reduced T_c have strongly broadened transitions with $\Delta\ T_c \simeq$50mK. However, ΔT_c is independent of the applied magnetic field and used measurement current. The obtained $B_{c2}(T)$ curves of two samples with different reduction level are shown in fig. 3.

The critical current density in zero field of the samples is only of the order of 1A/cm^2. This small value and the shape of the $V(I)$-curves are evidences that the doping of the samples is not homogeneous, which is consistent with the observations of ref. [10]. Although normal conductivity of $SrTiO_{3-\delta}$ is not limited to a surface layer, superconductivity is. However, the measurement current employed to determine the H_{c2} data had to be chosen carefully to avoid critical current effects.

3. Conclusions

It is obvious that the temperature dependence of B_{c2} differs strongly from the usual properties of BCS superconductors. Specifically, the magnitude of the upper critical field is relatively large, considering the values of T_c and $\frac{dH_{c2}}{dT}(T_c)$. Additionally, the curvature of $B_{c2}(T)$

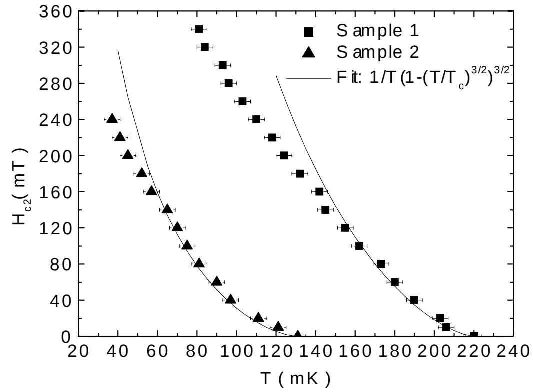

Fig. 3. Temperature dependence of the upper critical field of two $SrTiO_{3-\delta}$ samples with different reduction level. Magnetic field direction perpendicular to sample surface and current direction. The fits shown are according to Aleksandrov's theory of bipolaronic superconductivity [9].

is positive (less pronounced for samples with increased T_c). As a possible explanation for these observations we suggest the theory of bipolaronic superconductivity [11]. Calculations by A. Alexandrov, which are valid only close to T_c, predict the positive curvature as well as large upper critical fields. Fitted curves according to this theory are shown in fig. 3. However, a detailed discussion will also have to consider further possible explanations like an inhomogeneous superconducting state or conventional multigap superconductivity.

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References

[1] M. R. Schafroth, Phys. Rev. **100** (1955) 463.

[2] N. Mott, Nature **327** (1987) 185.

[3] D. Emin, Phys. Rev. Lett. **62** (1989) 1544.

[4] A. Alexandrov and J. Ranninger, Phys. Rev. B **23** (1981) 1796.

[5] B. K. Chakraverty, J. Ranninger, and D. Feinberg, Phys. Rev. Lett. **81** (1998) 433.

[6] J. F. Schooley et al., Phys. Rev. Lett. **14** (1965) 305.

[7] F. Gervais et al., Phys. Rev. B **47** 8187.

[8] D. M. Eagles, M. Georgiev and P. C. Petrova, Phys Rev. B **54** (1996) 22.

[9] A. S. Alexandrov, D. A. Samarchenko, and S. V. Traven, Sov. Phys. JETP **66** (1987), 567.

[10] K. Szot et al., Phys. Rev. Lett. **88** (2002) 075508.

[11] R. Micnas, J. Ranninger, and S. Robaszkiewicz, Rev. Mod. Phys. **62** (1990) 113.