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Electric Field Induced Superconductivity in an Overdoped Cuprate Superconductor

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Cuprate superconductors have a low carrier density and therefore their properties can be modified by an electric field. We describe an experiment where we observe field induced superconductivity on the surface of a cuprate material which is overdoped compared to optimal hole doping for maximum T_c. Ca-doped $SmBa_2Cu_3O_y$ films were grown by molecular beam epitaxy in an ozone beam. Ca doping causes an increase in hole concentration of the $SmBa_2Cu_3O_y$ and a decrease in T_c from 90K to 50K. $BaTiO_3$ is used as a dielectric across which an electric field is applied. We have observed an increase in T_c of about 1K when a positive voltage is applied.

Cuprate superconductors are of potential interest in applications not only because of their high transition temperatures, but also because their low electronic carrier density makes them susceptible to electric fields. This opens up the possibility of creating field effect devices [1,2]. In fact, although an electric field effect has been demonstrated in cuprate superconductors, the nature of such an effect has not been clearly verified. The usual assumption is a semiconductor-type model. Here one assumes an electric-field penetration depth where the carrier concentration is being modified [1,2]. However, the greatest field effect has been observed in the superconducting films with the worst transport properties, in terms of resistivity, T_c, and critical current. This leaves the possibility that the effect that has been observed is due to the inhomogeneous structure of the film and that the electric field affects only the weaker regions (weak links) of the superconductor, rather than the bulk of the film.

Here we present preliminary results of an experiment which is intended to study the field effect as a function of carrier doping of the superconductor. For a cuprate material which is overdoped with respect to optimum hole doping one would expect that the T_c will increase upon hole depletion. We observe such an effect on a thicker (50 nm) film and conclude that superconductivity is induced in a surface layer of the film.

The superconducting transition temperature in the cuprates is a function of the carrier concentration, n, in the CuO_2 sheet layers [3]. In order to change n in a given material, one can substitute cations of different valence or change the oxygen content in the lattice. For a maximum field effect, the material should be away from optimal doping, i.e. maximum T_c, $dT_c/dn = 0$, and closer to a maximum of the slope dT_c/dn.

In the "123" system it is possible to substitute Ca^{2+} for Y^{3+} (or a rare earth such as Sm). This has the effect of increasing the hole density in the sheet layers. Our Ca doped $SmBa_2Cu_3O_y$ films are made using a molecular beam epitaxy deposition system [4]. We find that the maximum substitution possible in our films is about 30-40% of Sm. In order to demonstrate that our films are indeed "overdoped", we have performed anneals in reduced pressures of oxygen, thereby taking oxygen out of the lattice. Figure 1 shows the results for three $Sm_{1-x}Ca_xBa_2Cu_3O_y$ films. We see that upon oxygen reduction the T_c increases, consistent with the overdoped assumption. For the most heavily doped sample the T_c increases by more than 20 K.

For the application of an electric field, the figure of merit is the εE_{BD} product which is proportional to the maximum induced charge aerial density on top of the superconductor. For our $BaTiO_3$ grown by MBE at 600°C, we obtain a dielectric constant ε of 520 ε_0 and a breakdown field E_{BD} of 0.5 MV/cm.

Our sample consists of a 50 nm layer of $Sm_{0.7}Ca_{0.3}Ba_2Cu_3O_y$ and a 100 nm layer of $BaTiO_3$ on top. The gate on top of the dielectric is Cu. Figure 2 shows the resistance versus temperature for no applied voltage and +1.5 V applied to the gate. The gate voltage is applied between the top Cu electrode and one of the voltage leads on the superconducting channel. The width of the measured channel is 65 μm and the current in the

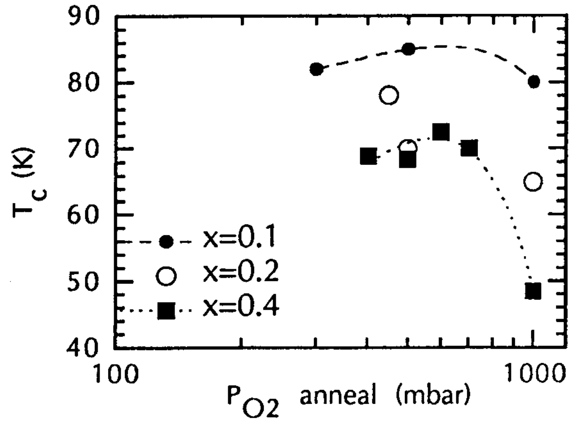

Figure 1. Transition temperature as a function of oxygen pressure during annealing. Anneals were done for 3 different $Sm_{1-x}Ca_xBa_2Cu_3O_y$ films at 450°C.

channel was 10 μA dc. The resistivity of the dielectric layer was above 10^{10} Ωcm at low temperature. The leakage current was continuously monitored and always kept below 10 nA. As an additional check each RT curve is taken twice with the opposite current directions in the channel, which would cancel out any leakage. The positive applied voltage corresponds to hole depletion of $\Delta N = 5 \cdot 10^{13}$ e/cm^2. The shift in the RT curve with applied voltage from Fig. 2 corresponds to an increase in zero resistance T_c of about 1 K. The two curves join at higher temperature, the width of the transition being about 20 K. No change in the RT curve was observed for negative bias on the gate. The shift in T_c with positive gate bias was not completely reversible with voltage and temperature cycling. When the shift was observed, it was always about the same magnitude and always in the same direction, i.e. higher T_c with hole depletion. After a few months of temperature cycling the sample T_c degraded and the shift was no longer observed.

We will attempt to explain the measurements within the semiconductor model. Simple carrier density considerations give a penetration depth of 8Å (isotropic model) or about 1-2 unit cells (assuming conducting sheets) for the "123" superconductor at optimal doping. Since our film is rather thick, i.e. more than 40 unit cells, we assume that the electric field is penetrating only the surface unit cell or two. Then, only the carrier density in that region is being modified. We assume a parabolic dependence of T_c on n [3]. Note that an induced lower transition

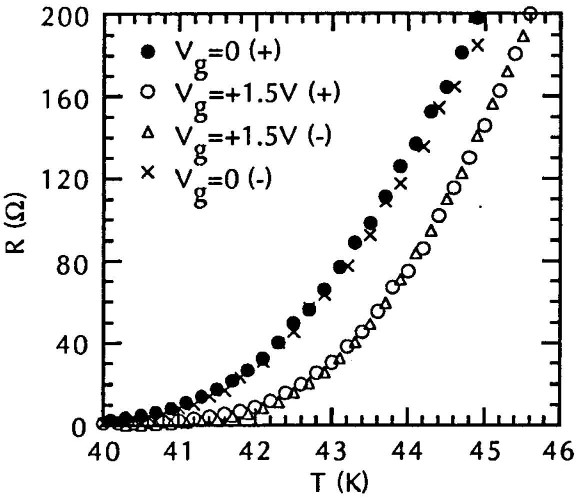

Figure 2. Superconducting transitions for a $Sm_{0.7}Ca_{0.3}Ba_2Cu_3O_y$ film, with and without an applied electric field. In each case two measurements are done with two different current directions in the channel.

temperature at the surface would never be measured since the bottom part would be superconducting in parallel, as observed in the measurements. Given our induced charge, the expected shift in T_c is 10 K (one unit cell penetration) or 6 K (two unit cell penetration), more than observed. On the other hand, given a ΔT_c of 1 K, the required penetration depth is 25 unit cells, much too large.

There are many possible explanations for the discrepancy of the observed effect and its simple predictions as well as for the poor reproducibility, none of which we can rule out at this time. Surface degradation is possible and likely. We know that our films are not atomically smooth. Interface charge traps could explain the problems with cycling the measurements. In addition, we cannot rule out that our film is not dominated by weak links. The transition is very broad and the critical current is rather low right below the zero resistance temperature, $J_c < 0.1$ MA/cm^2 at 30 K.

In conclusion, we have observed an increase in T_c by about 1 K in an overdoped cuprate superconductor upon hole depletion on the surface.

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