The c-axis tunneling properties of both pristine Bi2212 and its HgBr$_2$ intercalate have been measured in the temperature range 4.2 - 250 K. Lithographically patterned 7-10 unit-cell height mesa structures on the surfaces of these single crystals were investigated. Clear SIS-like tunneling curves for current applied in the c-axis direction have been observed. The dynamic conductance $dI/dV(V)$ shows both sharp peaks corresponding to a superconducting gap edge and a dip feature beyond the gap, followed by a wide maximum, which persists up to a room temperature. Shape of the temperature dependence of the c-axis resistance does not change after the intercalation suggesting that a coupling between CuO$_2$-bilayers has little effect on the pseudogap.

1. Introduction

The existence of a pseudogap in electronic excitation spectra is believed to be one of the very important features of high-$T_c$ (HTS) superconductors. This gap was reported to exist in underdoped samples, although some experiments indicate that the pseudogap is present in overdoped samples also.

The tunneling spectroscopy is particular sensitive to the density of states (DOS) at the Fermi level and therefore can be used to study any gap in the quasiparticle excitation spectrum. The most common experimental methods, STM and point-contact techniques are however essentially surface probes. The surfaces of most HTS compounds deteriorates with time unless special measures are undertaken. That is why there is a great variety of data quality reported in the literature.

It is now experimentally established that highly anisotropic layered HTS exhibit intrinsic tunneling effects. For example, in Bi2212 (Bi$_2$Sr$_2$CaCu$_2$O$_8$) the $\approx 3$ Å thick metallic copper oxide sheets (CuO-bilayers) are separated by $\approx$12 Å thick insulating layers. Out-of-plane (or c-axis) charge transport occurs via a sequential
tunneling of electrons or Cooper pairs between these sheets. The atomic perfection of the naturally occurring tunnel junctions in such materials provides a reliable basis for the tunneling spectroscopy inside the single crystal giving a high degree of homogeneity and reproducibility.

The phonon-mediated sub-gap structures of such intrinsic Josephson junctions (IJJ) has already been studied. The pseudogap spectroscopy with intrinsic tunnel junctions has also been attempted. Here, we repeat experiments of Refs. on HgBr$_2$-Bi$_2$212 samples. Insertion of inert HgBr$_2$-molecules in between adjacent BiO-layers results in a significant stretching of Bi$_2$212 crystals in the $c$-axis direction, see Fig. without affecting the superconducting critical temperature $T_c$ much. The intercalation leads to decrease in the $c$-axis critical current $I_c$ and increase in the normal state resistance $R_c$. The Joule heating, which was considered to be a problem in experiments on IJJ at high bias current can therefore be significantly suppressed. Moreover, the effect of the interlayer coupling on the pseudogap can be investigated.

Fig. 1. Schematic picture of HgBr$_2$-intercalation.

2. Experiment

Bi$_2$212 single crystals were synthesized by the traveling-zone method. The intercalation of HgBr$_2$ was performed by heating the vacuum sealed tube containing pristine single crystals and HgBr$_2$ during about one week. According to X-ray analysis, the lattice expansion after the intercalation was $\sim$ 12.6 Å.

To investigate the $c$-axis transport properties, several mesas with areas 10 – 600 $\mu$m$^2$ and heights 150 – 200 Å were fabricated on the freshly-cleaved surfaces of the single crystals using a standard photolithography and Ar-ion milling. The resulting mesas comprised $\sim$ 5 – 15 IJJ in series.
3. Results and discussion

Fig. 2 shows the temperature dependence of $R_c$ for both the pristine (a dash line) and intercalated samples (symbols and lines). The intercalation lead to a significant increase of the $c$-axis resistivity $\rho$. At $T \approx 175$ K it is about $\sim 10 \, \Omega \, cm$ for the former, and $\sim 2 \, k\Omega \, cm$ for the latter samples. The pristine samples were slightly overdoped after annealing in oxygen, which is seen both from the reduced value of $T_c \approx 75$ K, and from the temperature dependence of the resistance showing the linearly increasing with temperature part at high temperatures, see Fig. 2. It can be also
seen that the linear part of $R_c(T)$ disappeared after the intercalation in one sample, while conserved in another. After intercalation, $T_c$ somewhat further decreased, down to about 62-65 K. $T_c$ of Bi2212 seems to be less prone to HgBr$_2$-molecules as compared with other intercalates, despite larger stretching of the lattice.\[9,11\]

Recently, it has been shown that the onset of the upturn in $R_c(T)$ correlates with appearance of the non-linearities in the $c$-axis tunneling characteristics with decreasing temperature.\[7\] These non-linearities bear witness of pseudogap features in the $c$-axis transport. From our experiments we see that the intercalation does not influence the characteristic temperature $T^*$ in a straightforward way. Despite significant increase, the $c$-axis resistivity can preserve the form of the temperature dependence. This implies that the out-of-plane resistance and pseudogap features are determined mainly by properties of individual CuO-bilayers in Bi-2212. The coupling between different bilayers seems has a little effect on pseudogap, as long as oxygen content is preserved.\[12\]

The main frame of Fig. 3 shows a typical $I-V$-characteristic of a mesa with 10 IJJ. The inset shows an enlarged central part of the $I-V$-characteristic. The majority of junctions have $I_c \sim 0.1$ mA, which is more than an order of magnitude smaller than $I_c$ of the pristine-crystal mesas with the same area $A$ ($\sim 200 \mu$m).\[13\] The normal state tunneling parts of the $I-V$-characteristics are clearly seen at $\sim 1$ mA. The dynamic conductance $dI/dV$ vs. the average voltage per one IJJ in the mesa was deduced by numerical differentiation of the $I-V$ curve corresponding to all 10 IJJ being in the quasiparticle state, Fig. 4. $dI/dV$ of 0.01 S at $\sim 100$ mV in our experiments would correspond to $10^{-10}$ S for typical STM-contact areas (say, $15 \times 15$ Å$^2$), emphasizing a high quality of the tunneling barriers in IJJ.

Fig. 4. $dI/dV(V)$ at different temperatures for (HgBr$_2$)Bi2212- sample.

Sharp peaks seen in Fig. 4 likely correspond to the superconducting energy
gap $V_g$ of CuO$_2$ layers. The dips at $\sim 1.5V_g$ were attributed to strong-coupling effects. A gently sloping dip at the zero voltage at $T > T_c$ likely represents the pseudogap in the DOS. It has the almost temperature independent energy scale of $\sim 100$ mV per each IJJ, which is somewhat larger than in experiments of Suzuki et al. It is gradually smearing with temperature, although being seen in $I-V$’s at temperatures up to about 250 K for some samples.

![Fig. 5. The normalized energy gap parameter $\Delta$ vs. temperature for the pristine (circles and triangles), and (HgBr$_2$)Bi2212- (squares) samples. All lines are guides for the eye. There were two distinct gap features for the pristine sample, $\Delta_1$ and $\Delta_2$. The empty symbols correspond to the disappearance of the c-axis critical current.](image)

The temperature dependence of the normalized energy gap parameter $\Delta$ is shown in Fig. 5. The BCS-like temperature dependence is shown for comparison. For the pristine sample there were two distinct features in $dI/dV(V)$-curves, which may reflect either the in-plane anisotropy of the superconducting energy gap parameter, or proximity effects in the complex multilayer system of Bi2212.

The superconducting energy gap cannot be traced close to $T_c$, the corresponding feature of the $dI/dV(V)$-curves vanishes earlier, although the superconducting critical current can be seen clearly from measured $I-V$-characteristics in the whole temperature range up to $T_c$, see closed and open symbols in Fig. 5.

4. Conclusions

In conclusion, we observed both superconducting and pseudogap features of low-transparency intrinsic tunneling in Bi-2212 single crystals intercalated with HgBr$_2$. The dramatic decrease of the coupling between CuO$_2$-bilayers in the c-axis direction after the intercalation does not influence much the shape of $R_c(T)$-curves. The characteristic temperature when the pseudogap features set in in the current-voltage
Pseudo-gap features of intrinsic tunneling in (HgBr$_2$)-Bi$_2$212 single crystals

characteristics with decreasing of temperature stays also nearly unchanged. All this implies that it is properties of an individual CuO$_2$-bilayer (plus surrounding charge reservoirs) which determine both $R_c(T)$ and the pseudogap in the single particle spectrum of Bi2212.

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