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Superconductivity Near Transition to Insulating State in MoC Ultrathin Films Studied by Subkelvin STM

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We study the homogeneously disordered MoC thin films with thicknesses of 10 and 5 nm and the superconducting transition temperatures near 6 and 4 K, significantly decreased as compared to the bulk $T_c = 8.32$ K due to a disorder. The scanning tunnelling spectroscopy reveals in the thicker sample a BCS superconducting energy gap Δ with a broadening parameter Γ equal to about 10 per cent of Δ. Remarkably, Γ increases with temperature. The thinner, more disordered sample shows a gapped superconducting density of states but without any coherence peaks at the gap edge, which could not be approximated by the BCS DOS. Moreover, the reduced DOS around the Fermi level persists above the resistive transition temperature reminding the pseudo-gap known from high-T_c cuprates.

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1. Introduction

The problem of the superconductor-insulator transition (SIT) has recently attracted a lot of attention. By Anderson theorem [1] the non magnetic scatterers do not affect superconducting pairing and superconducting transition temperature remains unchanged in moderately disordered superconducting materials. In a strong disorder the itinerant electrons become more localized and near the transition of the system to an insulating state the superconductivity is suppressed. A question has been raised if at the transition the Cooper pairs become localized, or first the superconductivity is suppressed and then the standard localisation of single electrons leads to insulating state. Recent tunnelling experiments on homogenously disordered superconducting films [2, 3] accumulated a support for the first hypothesis. It has been shown that in highly disordered films the coherence peaks in the superconducting density of states disappear close to SIT but superconducting gap can be found even above the resistive transition temperatures T_c, reminding the pseudo-gap in high-T_c cuprates. Our preliminary measurements on disordered MoC films show a similar tendency.

2. Measurements

MoC films were prepared by the reactive magnetron sputtering on single-crystal sapphire substrates. The Mo 99.95%, Kurt J. Lesker was used. Sputtering was realized in a mixture of Ar and acetylene gas. During the sputtering process the temperature of the substrates was set to 200 °C [4]. The sample with the thickness $t = 10$ nm reveals the sheet resistance $R_\square = 209\ \Omega$ at room temperature, increasing to 219 Ω at 10 K with the superconducting $T_c = 5.7$ K. The thinner film of thickness $t = 5$ nm reveals $R_\square = 360\ \Omega$ at room temperature, increasing to 382 Ω at 10 K with $T_c = 3.8$ K. A degree of disorder is characterized by the sheet resistance. Then, in our samples the lowering of thickness leads to higher disorder and consequently to lower T_c. Lee and Ketterson [4] have shown on MoC films, prepared in the same way, that the critical sheet resistance separating the superconducting and insulating phase is near 3 kΩ, i.e. significantly below the quantum resistance for pairs, $1/G_0 = h/4e^2 = 6.45$ kΩ. The thickness of the 5 nm film is close to its coherence length $\xi_0 = 4.3$ nm [4], which makes it a quasi two-dimensional superconductor, more susceptible to fluctuations. Moreover, enhanced disorder is manifested here by semiconducting trend in temperature dependence of the resistance.

The superconducting energy gap of the MoC thin films was determined by tunnelling spectroscopy. The experiment was performed by means of a homemade STM, inserted in a commercial Janis SSV ^{3}He cryomagnetic system, enabling measurements at subkelvin temperatures down to $T = 300$ mK and magnetic fields up to 8 Tesla. We used the atomically sharp gold tip prepared *in situ* [5].

3. Results and discussion

The evolution of the spectra with temperature on the 10 nm and 5 nm thick films is depicted in Fig. 1 and Fig. 2, respectively. Each spectrum has been normalized to the curve measured well above T_c, at $T = 10$ K.

The tunnelling spectrum - *differential conductance versus voltage* measured through a junction between a superconductor and a normal metal is generally proportional to the superconducting density of states (SDOS)

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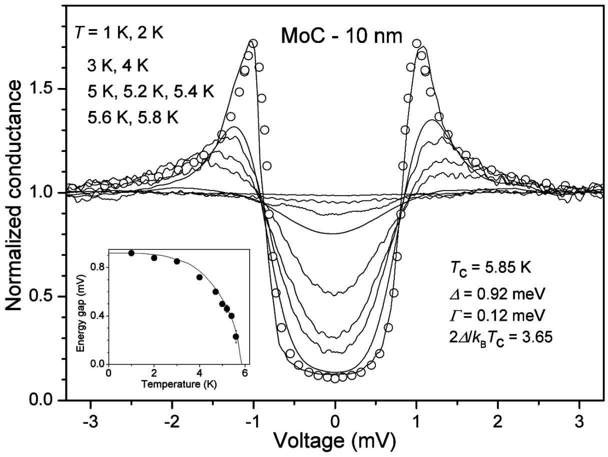

Fig. 1. Solid lines - tunnelling spectra on 10 nm MoC film at indicated temperatures. Open circles - BCS fit. Inset: symbols - inferred temperature dependence of the superconducting energy gap, line - BCS curve.

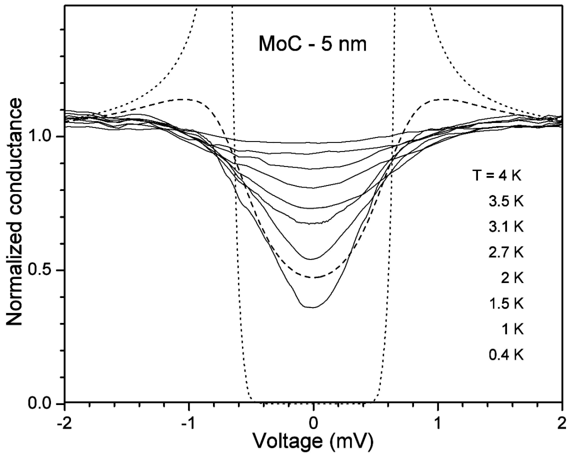

Fig. 2. Tunnelling spectra on 5 nm MoC film at indicated temperatures. Dotted curve - BCS SDOS at 1 K with $\Delta = 0.68$ meV and $\Gamma = 0$. Dashed line - the same SDOS with $\Gamma \sim 0.5\Delta$.

smeared by the derivative of the Fermi function. At very low temperatures the spectrum is practically equal to SDOS. SDOS of the BCS superconductor reads as $N(E) = Re\{E/(E^2 - \Delta^2)^{1/2}\}$, where E is the quasiparticle energy.

The spectrum on the 10 nm film cannot be well fitted by the BCS SDOS, unless the broadening parameter Γ is introduced via the substitution of complex number $E' = E - i\Gamma$ instead of E. Then, the fit results in the superconducting gap $\Delta = 0.92$ meV with $\Gamma = 0.12$ meV, which with the local T_c yields a coupling strength of $2\Delta/k_BT_c = 3.65$, close to the BCS value of 3.52. Such a spectrum has been found on many locations inspected by our STM. Also a finite tunnelling conductance at the zero bias on the order of 10% of the normal-state conductance (or conductance at high voltage) has been regularly found. This indicates a finite DOS at Fermi level due to unknown pair-breaking effect. Remarkably, Γ has been temperature dependent, increasing four times near T_c. This effect deserves further studies.

The spectrum in Fig. 2 taken on the more disordered film at 0.4 K shows a reduced tunnelling conductance around the zero bias in approximately the same voltage range as in Fig. 1, indicating a similar energy gap but, importantly, almost no coherence peaks at the gap edges are present. This reminds the evolution of spectra found in strongly disordered InO [2] and NbN [3]. Moreover, a reduced tunnelling conductance around the zero bias is found here also for temperatures above the resistive $T_c = 3.8$ K. The dotted and dashed curves in Fig. 2 document that neither a simple BCS DOS ($\Delta = 0.68$ meV and $\Gamma = 0$) nor its modified version, taking into account a broadening effect, can describe the measured spectra. The coherence peaks at the gap edge are linked to a long-range superconducting state. Contrary, the absence of the coherence peaks in the gapped DOS is an indication for localized Cooper pairs [6].

4. Conclusions

Via tunnelling spectroscopy on thin MoC films we showed that with increasing disorder the superconducting density of states loses the coherence peaks and the reduced DOS (pseudogap) survives also above the resistive T_c in the normal state. This indicates that localized Cooper pairs exist near the superconductor insulator transition.

Acknowledgments

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