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Superconducting fluctuations in molybdenum nitride thin films

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ABSTRACT

MoN thin films have been deposited using reactive sputtering. The change in resistance near superconducting transition temperature at various magnetic fields has been analyzed based on superconducting fluctuations in the system. The Aslamazov and Larkin scaling theory has been utilized to analyze the conductance change. The results indicate that most of the measurements show two dimensional (2D) nature and exhibit scaling behavior at lower magnetic fields (<7T), while a cross over to three dimensional (3D) nature has been clearly observed in measurements at higher fields (>7T). We have also analyzed our data based on the model in which there is no explicit dependence of Tc. These analyses also substantiate a crossover from a 2D nature to a 3D at larger fields. Analysis using lowest Landau level scaling theory for a 2D system exhibit scaling behavior and substantiate our observations. The broadening at low resistance part has been explained based on thermally activated flux flow model and show universal behavior. The dependence of U_o on magnetic field indicates both single and collective vortex behavior.

1. Introduction

Superconducting fluctuations in the normal phase of the superconductor are caused due to amplitude fluctuations of the order parameter [1]. In BCS type superconductors, these fluctuations happen over a small window of temperature just above the superconducting transition temperature (Tc). These fluctuations manifest as increased conductivity, specific heat and tunneling current with appearance of diamagnetism [1]. In strongly coupled bulk superconductors, these effects are observed only very close to the transition temperature while for disordered materials and very low thickness thin films which are superconducting these fluctuations can be observed in a larger temperature window [2]. The exact nature of these fluctuations can be obtained by analyzing the conductivity change in the temperature window above the transition temperature. Aslamazov and Larkin [3] have calculated the conductivity increase due to the short lived fluctuation induced cooper pairs, formed close to transition temperature. They derived a closed form relation between the excess conductivity due to fluctuations and the reduced temperature for bulk materials (3D), thin films (2D) and filaments (1D) from microscopic theory. In short, a scaling behavior is observed between these quantities. These results indicate that fluctuation effects are more favored in low coherence length systems and in lower dimensions. Superconducting fluctuations has been a topic of interest and have been studied on various materials including high temperature superconductors [4–8]. Disorder in conventional superconducting materials has been shown to reduce transition temperature, coherence length, etc [9]. It is expected that in disordered state the coulomb interactions have less screening and fluctuations are enhanced [10]. Disorder in TiN and NbN has been utilized to show existence of pseudo gap [11,12]. High upper critical field has been observed for disordered NbN [13]. Rare earth metal nitrides have higher strength, oxidation resistant and are superconducting at temperatures larger than their metal counterparts. Among the rare earth metal nitrides, Molybdenum nitride (MoN) has been predicted to be superconducting (Tc) at 29 K [14]. MoN deposited on AlN at ambient temperatures has shown a Tc of 8 K with upper critical field of 18T [15]. The large increase in upper critical field from 10T to 18T is mainly due to the increased slope dBc2(T)/dT at Tc which might have been caused due to disorder and nanocrystallinity of MoN thin films. In the present work, we have analyzed the excess conductivity due to superconducting fluctuations based on various formalisms to elucidate the dimensionality of these disordered and nanocrystalline MoN thin films.

2. Experimental

Molybdenum nitride thin films have been deposited on aluminum nitride buffered oxidized silicon substrates by reactive DC sputtering. A 30 nm aluminum nitride buffer layer is deposited by reactive RF sputtering on the oxidized silicon wafer. Molybdenum nitride of approximately 150 nm is deposited on AlN buffered substrate using a DC power of 400 Watts. During deposition 99.9995%

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Table 1
Tc (H) for different magnetic field measured and reported for sample A and C.

Sample\Magnetic field	0T	1T	2T	3T	4T	5T	6T	7T	8T	10T
Tc of sample A (K)	8.11	7.79	–	7.16		6.5	–	5.82	–	4.75
Tc of sample C (K)	7.82	–	7.19	–	6.49	–	5.76	–	5.02	4.25

pure Argon at a flow rate of 24 SCCM and 99.9995% pure nitrogen at a flow rate of 6 SCCM were employed using a mass flow controller. Sample A is deposited after stabilizing the pressure at 2.9×10^{-3} mbar and sample C is deposited at 3.2×10^{-3} mbar. The variation of resistance with temperature near the transition temperature has been measured for fields from 0T to 15T for one sample (termed sample A) and 0T to 14T in steps of 2T for another sample(termed sample C) to elucidate the upper critical field of the superconductor. The details of deposition conditions, measured superconducting properties for both samples with same nomenclature A and C has been reported earlier [15] along with elucidation of $B_{c2}(0)$ using Werthamer, Helfand and Hohenberg relation [16] for samples A and C.

3. Analysis and results

The GIXRD measurements on MoN samples which showed formation of cubic γ-Mo_2N is fitted to multi-Gaussian peak function [15]. The average grain size extracted by using Scherer formula from FWHM of first peak (111) is ~3.92 nm. The results of the critical field measurements H versus Tc(H) for both the samples A and C are given in Table 1. The upper critical field obtained from the above experiments for sample A is 18.1T and for sample C is 17.2T. The coherence length calculated using the upper critical field of 17.2T for sample C is 4.37 nm. Transport measurements for both the samples at 0T show negative temperature coefficient of resistance at higher temperatures and takes a down turn to superconducting transition after attaining a maximum value of resistance at a particular value of temperature T_p. This temperature T_p is magnetic field dependent and decreases as the magnetic field is increased. The negative temperature coefficient of resistance measured above T_p indicates disorder in these MoN thin films.

The temperature dependence of resistance R_N measured at the maximum field (15T for sample A and 14T for sample C) above the Tp is taken as the reference curve. This variation of R_N with temperature is shown in Fig. 1 for both the samples A and C. The variation of R_N with T is fitted to a polynomial function of order 2 for sample A and order 1 for sample C for analysis. Deviation from this conductivity at any particular temperature is termed as $\Delta\sigma$ for that temperature and magnetic field. For the analysis of Azlamazov Larkin fluctuation model (AL) [10], initially T_c is taken as the temperature at which the resistance falls to 50% of normal state resistance just before the transition. To take into account the variation of R_N with temperature, we have plotted dependence of log $(\Delta\sigma/\sigma)$ versus log $((T-T_c)/T_c)$ in Fig. 1 to identify the dimensionality of the system. For 2D the slope is -1 and for 3D it is expected to be $-1/2$. As the slope depends on the parameter T_c which is not well defined for thin films in dirty limit, the slope is adjusted by changing T_c. To identify the optimum T_c, $\Delta\sigma/\sigma$ is fitted to a linear function with a constant term to $((T-T_c)/T_c)^{-\alpha}$, with $\alpha = 1$ for 2D and $\alpha = 1/2$ for 3D. After fitting, the constant term is set to zero and reevaluated to get $\Delta\sigma'$. Now T_c is adjusted by about 0.1 K to minimize the RMS difference between $\Delta\sigma'$ and $\Delta\sigma$. The maximum of adjusted T_c was about 0.18 K for the thin film C at 8T which is about 3.5% of T_c, while other changes are much less. With this revised T_c, log $(\Delta\sigma/\sigma)$ versus log $((T-T_c)/T_c)$ is plotted for all the measurements in a single graph. The scaling behavior is seen in this plot with an average slope of nearly 1 for most of the measurements indicating 2D character while for measurements at 10T

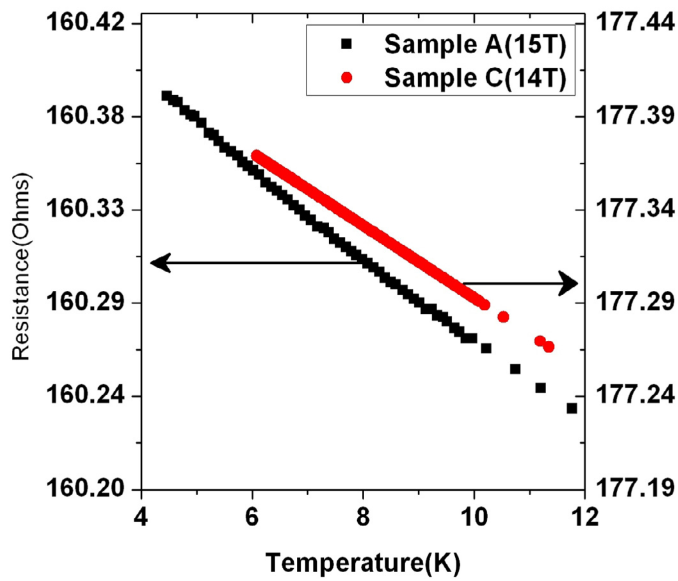

Fig. 1. Variation of R_N with temperature for MoN thin films above Tp for sample A and C.

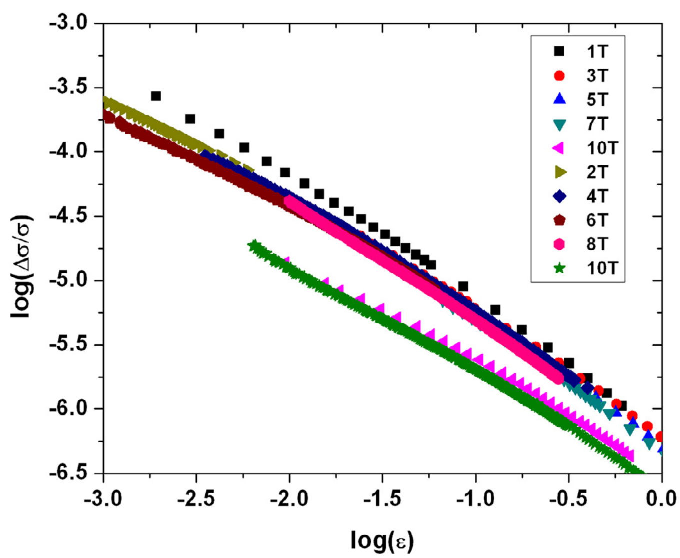

Fig. 2. Scaling behavior seen in sample A and C for the relation between excess conductivity ratio $(\Delta\sigma/\sigma)$ and reduced temperature (ε).

for both the samples show different slope and does not merge with the other graphs. It is to be noted that though there exist scaling between $\Delta\sigma/\sigma$ and $((T-T_c)/T_c)$, it is not constant over the entire range of temperature. This plot reveals that most of the measurements show 2D behavior and fall under single curve (scaling behavior), while the measurement at 10T for both the samples give different behavior though not fully showing 3D behavior (Fig. 2).

The failure in analysis to fit to a particular behavior of 2D/3D could be due to the definition of T_c, which has been defined for clean materials and in the absence of fluctuations. To overcome this problem, Testeradi et al. [17] have analyzed the temperature