Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 13 (2): 330-332, 2013
ISSN 1812-5654 / DOI: 10.3923/jas.2013.330.332

Pseudogap Effects in Disordered Niobium Nitride Superconducting Thin Films

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Abstract: The pseudogap region in the disordered Niobium Nitride (NbN) superconductors has been a subject of contemporary interest and its existence for higher disorder films have been established. Niobium Nitride (NbN) thin films have been deposited by reactive direct current magnetron sputtering at 0.266 Pa total pressure in a mixture of argon and nitrogen. The Glancing Incidence X-ray Diffraction (GIXRD) analysis indicates the formation of NbN cubic fcc B1 structure. All the films were found to be superconducting with a maximum superconducting transition temperature (T_c) of 12 K. At higher temperatures, all the films exhibited a negative temperature coefficient of resistance indicating the presence of disorder in the films. The downturn of resistance due to the appearance of superconducting state is observable in the resistance versus temperature plot at a temperature above T_c defined as T*. It has been observed the downturn in resistance versus temperature plot of NbN thin film happens at a temperature around 20 K (T*) for a sample which is superconducting at 11.5 K (T_c).

Key words: Niobium nitride, thin-films, reactive sputtering, superconductors, pseudogap

INTRODUCTION

Superconductivity has been a fascinating subject for over hundred years since the discovery of the first superconductor by Kammerlingh Onnes in 1911. Even after the discovery of High Temperature Superconductors (HTSC), interest in Low Temperature Superconductors (LTSC) has not waned. The prime reason for this interest is the wide spectrum of applications of these LTSC superconductors and the rich physics, which governs the observation of new phenomena. Niobium nitride (NbN) is such a material that has a significant application potential and is being investigated both from the point of view of basic physics as well as applications (Chand *et al*., 2012; Abdo *et al*., 2006; Villegier *et al*., 2009). Though deposition of thin films of NbN by reactive DC/RF sputtering has been well-understood (Wang *et al*., 1996), the properties of these NbN thin films have not been fully unraveled. Superconducting state is characterized by the existence of a gap in the electronic density of states and this energy gap is expected to vanish at T_c. With the discovery of HTSC materials, it has been noted that this gap structure extends above T_c, not as a full gap but as a depression in electronic density of states; this phenomenon is termed as pseudogap (Ding *et al*., 1996). This pseudogap region in the disordered superconductors has been a subject of contemporary interest and has been investigated by many experimental techniques including measurement of electrical resistivity (Passos *et al*., 2006). Pseudogap state in conventional superconductors like NbN has been shown to exist at temperatures T* higher than T_c, when the disorder in thin films is strong while T* merges with T_c in thin films which are only weakly disordered according to the phase diagram (Chand *et al*., 2012). In these highly disordered NbN thin films, the maximum T* does not exceed the maximum T_c exhibited by low disorder NbN films. The pseudo gap temperature T* has been identified in Hg-Re system using resistivity measurements (Passos *et al*., 2006), where the derivatives of resistance with temperature serve to establish a criterion for identifying the T*. In this study, the existence of T* which is larger than the maximum T_c observed in NbN system has been identified using measurements of electrical resistivity.

DEPOSITION OF THIN FILMS

The NbN thin films were deposited by reactive sputtering in a load locked deposition chamber with a base pressure reaching 8×10^{-8} mbar. The sputtering is carried out using a 100 mm diameter niobium target of 99.999% purity. The target to substrate distance is around 0.2 m. The sputtering is carried out in a mixture of argon and nitrogen with a steady argon flow of 33 SCCM and a Nitrogen flow of 7 SCCM at a total pressure of 0.266 Pa. The NbN thin films were deposited on 19×25 mm rectangular glass substrates and oxidized Silicon wafers of size 20×10 mm. The substrates were sputter cleaned in

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the load lock chamber using Argon plasma at a RF power of 80 W for 10 min before transferring the substrates to the Deposition chamber (DPC) using a magnetic manipulator. The substrates were positioned in 80 mm square steel holder capable of holding multiple substrates and rotated about a central axis to ensure uniformity in the thickness of the deposited film. The substrate holder is cooled by flowing water to avoid undesirable rise in temperature. The rate of deposition as well as the total thickness of NbN thin films was measured by the ***in-situ*** Quartz crystal monitor. NbN thin films with a nominal thickness of 140 nm were deposited on these substrates at a deposition rate approximately 0.2 nm $\sec^{-1}$. The thickness of the deposited NbN films is measured subsequently using a DEKTAK 3030 A surface profiler. The thin films have been patterned into standard four-probe geometry for electrical resistivity measurements using lift-off photolithography.

CHARACTERIZATION OF THIN FILMS

The deposited thin films were first characterized using Glancing Incident X-ray diffraction measurements (GIXRD). The electrical resistivity measurements were carried out using the standard four probe geometry patterned on the thin films. A constant current of 20 μA is passed through the sample using a constant current source (Time Electronics Model: 5018 Multifunction calibrator) and the voltage developed across the sample is measured using a nanovoltmeter (Agilant, Model: 34420 A). The sample is fixed firmly on the cooper sample holder mounted on a dipstick. A silicon diode thermometer is mounted on the reverse side of the sample holder for measuring the temperature of the sample. The sample holder is surrounded by a radiation shield to reduce fluctuations of temperature. The temperature of the sample is varied by dipping the sample holder inside a liquid helium dewar which is partially filled. By varying the height of the sample holder above the surface of liquid helium inside the dewar, different temperatures are attained. The resistance and the temperature data is acquired using a labview program and is stored in a computer for subsequent analysis.

RESULTS AND DISCUSSION

Figure 1 shows the GIXRD measurements for a typical NbN thin film deposited on oxidized silicon substrate and indicates the formation of cubic fcc B1 structure. All the NbN thin films deposited were found to be superconducting with a maximum T_c of about 12 K. The plot of resistance versus temperature for the NbN film deposited in accordance with the procedure described above is shown in Fig. 2. The electrical resistivity of the sample is 1254 μΩ-cm at 300 K. The superconducting transition temperature of this film is 11.5 K with a RRR of 0.65 indicating the presence of substantial disorder. The inset in Fig. 2 shows the dependence of resistance on temperature in the range 15 to 30 K. Conspicuous changes in the temperature dependence of resistance have seen below a temperature of 25 K and the down turn in resistance appears at about 20 K. The plots of the first derivative of resistance with temperature and second derivative of resistance with temperature are shown in Fig. 3. The upturn in the first derivative plot with a nearly constant, second derivative is a clear indication of T* and is observed at around 20 K. This shows that in these relatively disordered NbN thin films, the pseudogap

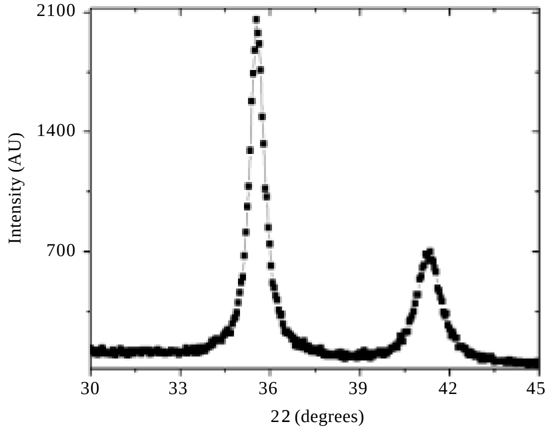

Fig. 1: GIXRD pattern of NbN thin film

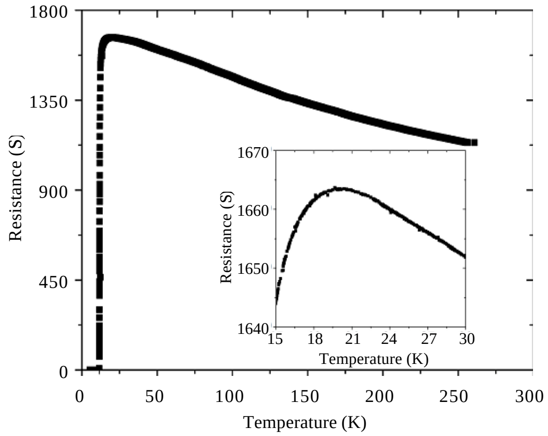

Fig. 2: Measured electrical resistance of the NbN sample with temperature. The inset shows the dependence of the electrical resistance with temperature in the range of 15 to 30 K

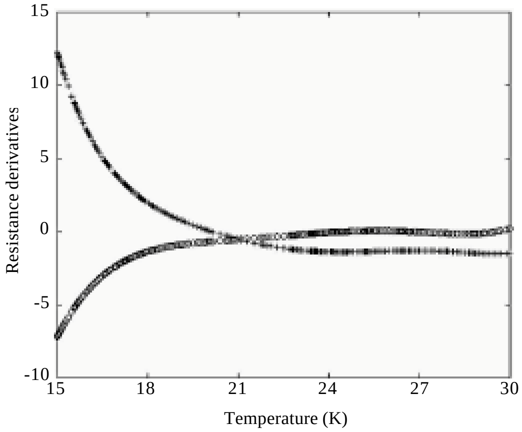

Fig. 3: Dependence of first derivative of resistance with temperature ('+') and second derivative of resistance with temperature ('o') between 15 and 30 K

appears at temperatures of about 20 K while superconductivity (T_c) sets in at a lower temperature of about 11.5 K. The behavior of most of the disordered NbN thin films investigated during the present study conforms to this overall scenario with only marginal variations in T_c and T*.

CONCLUSION

NbN thin films have been deposited on glass and oxidized silicon substrates by reactive DC magnetron sputtering. The NbN thin films have been characterized by GIXRD, which shows the formation of cubic fcc B1 structure. Variation of resistance with temperature from 300 to 4.2 K has been measured using a simple dipstick cryostat. Most of the NbN thin films exhibit a negative temperature coefficient of resistance in the 300 to 20 K temperature range. The NbN thin films were found to be superconducting with a maximum T_c of about 12 K indicating the presence of substantial disorder in these thin films. The electrical resistivity measurements indicate that pseudogap state appears at a temperature of about 20 K, which is higher than the experimentally observed superconducting transition temperature of 11.5 K. Further measurements and detailed analysis of the experimental data are being carried out to look for the existence of such states at even higher temperatures, since the resistivity measurements show anomalous behavior in this temperature range.

ACKNOWLEDGMENTS

We sincerely thank Dr. S. Rajagopalan and Ms D. Sunita for providing the GIXRD data on these thin films. We also thank Ms S. Kalavathi for preliminary GIXRD measurements and for identification of the structure in these NbN thin films. The authors thank Dr. C.S. Sundar for his continued support.

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