Fluctuation conductance and the Berezinskii-Kosterlitz-Thouless transition in two dimensional epitaxial NbTiN ultra-thin films

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Abstract. We study on the electric transport properties of epitaxial NbTiN ultrathin films in a range from 2 to 8nm. The films with 4 nm thick shows superconductivity of which mean-field superconducting transition temperature is $T_{C0} = 9.43$ K. The excess conductance due to superconducting fluctuations was measured at temperatures above $T_{C0}$. The paraconductivity shows a two-dimensional like behaviour at close to $T_{C0}$. Experimental results are in good agreement with the sum of Aslamazov – Larkin and Maki – Thompson term for superconducting fluctuation theory. Decreasing temperature below $T_{C0}$, the current-voltage characteristic shows a crossover from linear to nonlinear behaviour. The exponent $\alpha$ of current-voltage relation, $V \sim I^\alpha$ showed universal jump at $T_{C,BKT} = 9.33$ K. As results, we find that there is a consistency between the parametrization of the2D characteristics of fluctuation paraconductivity above $T_{C0}$ and Berezinskii-Kosterlitz-Thouless type behaviour below $T_{C0}$.

1. Introduction

The phenomenon of superconducting fluctuation and Berezinskii-Kosterlitz-Thouless (BKT) resistive transition in two-dimensional (2D) superconducting film has been an interest in both experimental and theoretical research for several decades. Recently, low-dimensional superconductors have attracted considerable attention because of their applications to electronics. For example, niobium nitride (NbN) and niobium titanium nitride (NbTiN) ultrathin films have been extensively investigated for application as superconducting single photon detectors (SSPDs)[1-3]. Although recent studies are focused on understanding the mechanism of photon detection [4,5], investigations of essential characteristics of 2D NbTiN ultrathin films—including their electrical transport and superconducting properties—are required to enhance the performance of SSPDs.

Most experiments have been performed using polycrystalline, granular, and amorphous films to investigate the transport properties of low-$T_C$ ultrathin superconducting films. Regarding epitaxial films, NbN ultrathin films with thickness of 2-5 nm are employed in SSPDs. However, detail discussion on their transport properties have not yet been reported. In this work, to verify the relation
between superconducting properties and crystalline morphology for epitaxially grown NbTiN ultrathin films, we studied the temperature dependence of resistance and current-voltage characteristics. We analyzed the temperature dependence of the resistance of NbTiN ultrathin films using the model given by the Aslamazov-Larkin (AL) and Maki-Thompson (MT) term, which is responsible for the excess conductivity of two dimensional (2D) films.

2. Experimental detail

The ultrathin NbTiN films were prepared by deposition on (100) single-crystal MgO using the dc reactive sputtering method. The base pressure of the deposition chamber was below $2 \times 10^{-5}$ Pa. Before the deposition, the substrate surface was etched by Ar ions to eliminate the contamination. We employed an alloy with 30 wt.% Ti and 70 wt.% Nb as the target material [6]. During the deposition, the total pressure and the dc current were kept at 0.27 Pa and 1 A, respectively. The flow rate of Ar gas was fixed at 100 sccm, while that of N$_2$ gas was of 16 sccm. We neither heated nor cooled the substrate during the deposition. The film thicknesses in this experiment ranged from 2 to 8nm. The crystallographic structures of deposited films were analyzed by X-ray diffraction (XRD). The NbTiN films were patterned to lines of 200 $\mu$m width by a conventional photolithography technique, and etched by reactive-ion-etching with CF$_4$ plasma. The film thicknesses were checked using a step profiler or atomic force microscopy. The samples were mounted on a copper block in an adiabatic cell. The perpendicular magnetic field was applied by a superconducting magnet immersed in a liquid helium bath.

![Figure 1](image)

**Figure 1.** Resistance per square $R_{sq}$ vs. temperature for NbTiN films on MgO substrates. Numerals denote the film thickness. Inset: $R_{sq}$ vs. logarithmic temperature for a 2nm-thick film.

3. Results and discussion

Figure 1 shows resistance per square $R_{sq}$ vs. temperature $T$ of NbTiN films with different thicknesses. $R_{sq}$ for films with 4 and 8 nm-thick shows a monotonic decrease with decreasing temperature and show sharp superconducting transitions. In addition, $R_{sq}$ vs $T$ shows no reentrant behavior as seen frequently for granular superconducting 2D films. In a case of 2nm thick film shown in the inset of Fig. 1, the $R_{sq}$ shows clearly logarithmic temperature dependence. Such results have been reported for 2D normal metal films. According to theories for weak localization and Coulomb interaction effects, temperature dependence of conductance due to quantum corrections in normal metallic films is given by
\[ \sigma_{\text{loc}} = 2 \ln T = \alpha_T e^2/h \quad (1) \]

Here \( F \) is a parameter that describes the degree of electron screening and approaches 1 for strong screening and 0 for weak screening, while \( p \) is the exponent of the temperature term in the inelastic scattering rate \( 1/\tau_{\text{in}} \propto T^p \). By fitting Eq. (1) to data on \( \sigma \) vs. \( \ln T \), we obtained the coefficient \( \alpha_T \approx 1.7 \), which can be explained by theories of weak localization and the Coulomb effect for the two dimensional homogeneous system \([7]\).

The observation of a Berezinskii-Kosterlitz-Thouless (BKT) transition has been reported in a several of 2D superconducting system. In BKT theory, a discontinuous jump in the current–voltage \((I-V)\) exponent such that \( V \sim I^\alpha \) at \( T = T_c^{\text{BKT}} \) and \( V \sim I \) for \( T > T_c^{\text{BKT}} \) is expected \([8]\). Figure 2(a) shows the \( I-V \) characteristics at various temperatures in the superconducting resistive transition region for a 4 nm-thick film. The exponent \( \alpha \) in the expression \( V \sim I^\alpha \) is plotted in Fig. 2(b). Decreasing temperature below 9.38 K, \( \alpha \) increases gradually and shows the steep increment around 9.33K. The observations suggest that a BKT transition occur at \( T_c^{\text{BKT}} \approx 9.33K \) in our NbTIN films with 4nm thick.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{(a) \( I-V \) characteristics of 4 nm-thick film at various temperatures. The blue line for data at \( T = 9.33 \text{K} \) exhibits \( V \sim I^\alpha \) dependence. The red line represents \( V \sim I \) dependence. (b) Exponents \( \alpha \) determined by fitting the \( I-V \) data to a power law.}
\end{figure}

The superconducting fluctuation theory predicts the form of the excess sheet conductance \( \sigma' = 1/R_{sq}(T) - 1/R_{sq}^N(T) \) for a uniform superconducting film in terms of the following fluctuation conductance

\[ \sigma' = \frac{1}{R_{sq}(T)} - \frac{1}{R_{sq}^N(T)} = \frac{e^2}{16\hbar} \frac{1}{\ln \left( \frac{T}{T_c} \right)} + \frac{e^2}{8h} \frac{\ln \left( \frac{T - T_c}{T_c} \right)}{\frac{T - T_c}{T_c} - \delta}, \quad (2) \]

where, \( \delta \) is a pair-breaking parameter, and \( R_{sq}^N \) is the normal state sheet resistance. The first and second terms are due to the AL and MT contributions, respectively. To analyze our data within this context, we use three parameters to describe each curve: \( R_{sq}^N, T_c \) and \( \delta \). We determined \( R_{sq}^N \) from the intercept of the straight line in the plots of \( 1/R_{sq}(T) \) vs \( 1/H \) around \( T_c \).

Figure 3(a) shows normalized inverse fluctuation conductivity \( \sigma' \) as a function of \( T \) for 4 nm-thick film at zero magnetic field. The solid and dotted curves are determined from the only AL term and AL + MT terms, respectively. Experimental data cannot be fitted with only AL term, represented by the solid line. Use of AL + MT term, the data can be explained well by the fluctuation theory. The agreement supports the homogeneity of films. On the other hand, the situation that the fluctuation data of NbN nanowire on Al2O3can be fitted with AL term alone \([4]\) is different from our data. Unfortunately, this difference is still open question. Figure 3(b) shows \( \delta \) as a function of reduced
temperature \((T-T_c)/T_c\). The magnitude of \(\delta\) increases with increasing \((T-T_c)/T_c\) until 0.1. Above \((T-T_c)/T_c \approx 0.1\), \(\delta\) gradually decreases. The value of \(\delta \approx 0.2\) near \(T_c\) is close to that of a single-crystal Nb film [9].

![Figure 3](image-url)

**Figure 3.** (a) \(T\) dependence fluctuation conductivity. The empty circle are experimental data. The solid line means the contribution from only the Aslamazov-Larkin term. The dotted line is a fit to the data using Eq. (2). (b) Reduced temperature \((T-T_c)/T_c\) dependence of \(\delta\).

### 4. Conclusions

Electrical and superconducting properties measurements were carried out on NbTiN ultrathin film prepared by the deposition with reactive sputtering technique. We have analyzed the data on \(R_{eq}(T)\) as follows: (1) Berezinskii-Kosterlitz-Thouless (BKT) transition at low temperatures; and (2) excess conductivity of superconducting films using the AL and MT term. It has been found that the \(R_{eq}(T)\) of the NbTiN ultrathin film is consistent with the theoretical prediction of two dimensional superconducting films.

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