Superconductor–Insulator Transitions in Pure Polycrystalline Nb Thin Films
F.Couedo, O.Crauste, L.Bergé, Y.Dolgorouky, C.Marrache-Kikuchi and L.Dumoulin
CSNSM, Univ Paris-Sud, UMR8609, CNRS-IN2P3, Orsay, F-91405, France
E-mail: francois.couedo@csnsm.in2p3.fr

Abstract. We report on a study of the transport properties of Nb thin films. By varying the thickness of the films from 263 Å to 25 Å, we observed a depression of the superconductivity. Magnetic field was also applied up to 6 T, inducing the disappearance of the superconductivity and the onset of an insulating behavior. The results were compared to those we have already obtained on a highly disordered system, a-Nb$_x$Si$_{1-x}$, to understand whether the same mechanisms for the disappearance of the superconductivity could be at play in pure metallic thin films and in highly disordered systems.

1. Introduction
A usual measure of disorder for 2D systems is the sheet resistance $R_s = \frac{\rho}{d}$. By evaporating superconducting films of different thicknesses $d$, such that $d < \xi$ the coherence length, we can vary $R_s$ and thus modify the disorder of the samples [1]. Magnetic field is another well-known way to supress the superconducting coherence in 2D systems [2]. We have studied the effects of these two parameters on Nb films and have compared them to those that have been previously observed in amorphous Nb$_x$Si$_{1-x}$ thin films [3], [4].

2. Experimental Setup
Nb thin films with four different thicknesses (25, 57, 108, and 263 Å) were deposited during the same evaporation onto sapphire substrates by e-beam deposition. Pure metallic thin films evaporated at room temperature are usually polycrystalline [5]. SiO underlayer and overlayer (resp. 370 and 330 Å) were also deposited, respectively to ensure the smoothness of the Nb films and to prevent them against oxidation. Pressure during the evaporation was about $10^{-7}$ mbar for a deposition rate of 2 Å/s. The film thickness was controlled in situ by a set of piezoelectric quartz and ex situ by Rutherford Back Scattering. AFM measurements have been performed ex situ and showed no sign of coarse granularity (average surface roughness of $\sim$ 1 Å), hence guaranteeing the continuity of the films. As we will show, low temperature $R_s(T)$ features do not show any sign of reentrance, characteristic of a granular systems. Nb films are therefore believed to be homogeneous and continuous. Moreover, the 108 Å-thick Nb film has a room temperature resistivity of 100 $\mu\Omega$.cm and a superconducting critical temperature $T_c$ of 3,1 K, which is comparable to other values found in the litterature for polycrystalline Nb thin films [6], [7].

Electrical measurements have been performed in a He-4 cryostat, down to 1,3 K. A magnetic field perpendicular to the film could be applied, operating up to 6 T. DC-resistances were mea-
sured with a standard four-probes method. The normal sheet resistances $R_{s,n}$ were measured at 25 K, where superconducting fluctuations are negligible. The superconducting critical temperature $T_c$ was determined as the midpoint between the temperatures at which the resistance is 10 % and 90 % of the normal sheet resistance.

3. Results and Analyses
From the $R_s(T)$ characteristics of the films, we observe an increase of $R_{s,n}$ together with a decrease of the $T_c$ [Fig. (1a)]. Even for our thinnest film (25 Å) superconductivity persists. The small bumps in the characteristics below $T_c$ are due to edge effects caused by the shadow masks used during the film deposition. They are not considered relevant for our study.

Applying a perpendicular magnetic field to the sample plane is another way to reduce and eventually destroy superconductivity in thin films. By varying the magnetic field up to 6 T, for the different samples, we observed a change of sign of the Temperature Coefficient of Resistance $dR/dT$, revealing a likely destruction of the superconductivity and the onset of an insulating behavior [Fig. (1b)].

When we combine both thickness and magnetic field effects, we can establish the phase diagram for Nb thin films in the $(H, d)$ plane. The $(H_c, d_c)$ experimental points form a single critical line separating the superconducting ground state from the insulating one [Fig. (1c)].

![Figure 1. Sheet resistance as a function of temperature at H=0 for 25 Å- to 263 Å-thick Nb films (a) and for a 25 Å-thick Nb film at different magnetic fields (b). Phase diagram for Nb thin films in the (H, d) plane (c).](image)

In order to compare the behavior of Nb thin films with disorder with that of higher disordered systems, such as previously studied a-Nb$_{2}$Si$_{1-x}$ films ($\rho_{300K} \sim 1000 \ \text{µΩ.cm}$ for a 100 Å-thick Nb$_{0.15}$Si$_{0.85}$ film), we have analysed our results with theoretical models usually considered in the problematic of 2D disordered superconductors [8].

3.1. Analysis of the observed disorder-induced $T_c$ reduction via amplitude fluctuations effects
For 2D homogeneous disordered superconductors, Finkel’stein explained the destruction of the superconductivity by the disorder-induced weakening of the Coulomb interactions dynamical screening [9]. For sufficiently high disorder, Coulomb interactions are so reinforced that electron pairing is not efficient anymore ; the amplitude of the superconducting order parameter $\phi(r) = \Delta e^{i\phi(r)}$ then vanishes. Through renormalization group analysis, Finkel’stein established the evolution of the $T_c$ with disorder :
\[
\frac{T_c}{T_{c0}} = \exp\left(-\frac{1}{\gamma}\right)[(1 + \frac{\sqrt{T_c}}{\gamma - \frac{T_c}{4}})(1 - \frac{\sqrt{T_c}}{\gamma - \frac{T_c}{4}})^{-1}]^\frac{1}{\sqrt{2}}
\]

where \( r = \frac{e^2}{2\pi\hbar}R_{s,n} \), \( \gamma = \frac{1}{\ln\left(\frac{\hbar c}{2m^*k_B}\right)} \), \( T_{c0} \) the bulk \( T_c \) and \( \tau \) the elastic scattering time.

Figure (2a) shows an analysis of the \( T_c \) reduction for both Nb and Nb\(_{x}\)Si\(_{1-x}\) according to equation (1) [3]. The fit are obtained by optimizing \( \tau \) and \( T_{c0} \). These values can be compared to the expected ones, summarized in table (2c). For Nb\(_{x}\)Si\(_{1-x}\) the value of \( T_{c0} \) are in good agreement with the \( T_c \) measured for thick films [10]. The obtained \( T_{c0} \) for Nb is lower than the bulk value (9.22 K) but could be explained by a small oxygen contamination of our films: Nb is very sensitive to oxidation (1 atomic % of O\(_2\) reduces the \( T_c \) by 1 K [11]). However, the fitted values of \( \tau \) are strikingly different from those that can reasonably be expected for both systems. Moreover, Nb\(_{x}\)Si\(_{1-x}\) present a complete destruction of superconductivity for larger values of \( R_s \) than Nb films, thus implying that they are more robust to disorder-induced \( T_c \) reduction, and so despite the lower value of their bulk \( T_c \). This counter-intuitive result may imply that Finkel’stein analysis cannot describe the destruction of superconductivity in both systems.

**Figure 2.** Comparison of \( \frac{T_c}{T_{c0}} \) vs \( R_{s,n} \) for Nb and Nb\(_{x}\)Si\(_{1-x}\) films (a). Symbols and solid lines respectively represent experimental data obtained by varying the film thickness and fits of formula (1). Tables (b) synthesizes the best fitting values and (c) the expected ones. \( v_F \) and \( D \) are taken from the literature or critical field measurements. \( l \) and \( \tau \) are calculated from these values.

### 3.2. Analysis of the H-induced SIT via phase fluctuations effects

An alternative description of the superconductivity destruction in 2D disordered systems was established by Fisher [13]. Enhanced by disorder or magnetic field, phase fluctuations of the order parameter cause the loss of the macroscopic phase coherence, thus inducing a quantum phase transition from the superconducting to the insulating states (SIT). Sufficiently close to the critical point, the system resistance is then expected to obey the scaling relation:

\[
R(\delta, T) = R_c f(\delta T^{-\frac{1}{\nu z}})
\]

where \( \delta \) is the distance to the critical point, \( \nu \) the correlation length exponent, \( z \) the dynamical critical exponent and \( R_c \) the critical resistance.

As previously shown on figure (1a), we do not observe a disorder-induced SIT at zero magnetic field. Therefore, in order to test Fisher’s scenario, magnetic field has been applied to the Nb
films to tune a SIT [Fig. (1b)]. We have plot the sheet resistance as a function of the scaling parameter \((H - H_c)T^{-\frac{1}{\nu z}}\) for different values of the critical exponents to see if the data could exhibit universal behavior. The best optimization, for the 25 Å-thick Nb film, is presented figure (3a), previous results for a 125 Å-thick \(\text{Nb}_x\text{Si}_{1-x}\) film are shown figure (3b) [4]. \(\text{Nb}_x\text{Si}_{1-x}\) data collapse onto two universal curves, representing the superconducting and insulating states, whereas the data for Nb films cannot, whatever the value of \(\nu z\). First let us stress that this result shows that all data cannot be artificially renormalized. It thus reinforced the confidence we have on the universal behavior observed for \(\text{Nb}_x\text{Si}_{1-x}\) films. Second, although the reason for which the scaling procedure fails for Nb films is a subject for future investigations, we note that Fisher’s model implies a strong disorder, a condition which may not be met in polycrystalline Nb films.

Figure 3. Sheet resistance as a function of the scaling variable \((H - H_c)T^{-\frac{1}{\nu z}}\), (a) for a 25 Å-thick Nb film \((\nu z = 0.22)\) and (b) for a 125 Å-thick \(\text{Nb}_{0.15}\text{Si}_{0.85}\) film \((\nu z = 0.67)\).

4. Conclusions
We have presented a study of dc-measurements of Nb films, where thickness and magnetic field have been varied. Comparaison with a higher disordered system, a-\(\text{Nb}_x\text{Si}_{1-x}\), shows that the destruction of superconductivity in both systems can probably not be explained by the same mechanisms, whatever the theoretical model, although there remains to understand why.

5. References
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