Superconductor-Insulator Transition in Amorphous
\( \text{Nb}_x\text{Si}_{1-x} \) Thin Films. Comparison between
Thickness, Density of State and Microscopic
Disorder.

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Abstract. We report on the study of the Disordered-induced Superconductor-Insulator
Transition (D-SIT) in \( \text{Nb}_x\text{Si}_{1-x} \) thin films. These films, synthesized by electron-beam co-
deposition, are continuous, amorphous, homogeneously disordered and structurally stable for a
wide range of compositions, thicknesses and annealing temperature and thus particularly well
suited for the study of D-SIT.

We present an analysis of the D-SIT induced by three different parameters: the thickness,
the \( \text{Nb} \) composition that changes the electronic density of states and the annealing temperature
that changes the microscopic disorder. The annealing changes quantum interference patterns
that decreases the local conductance. Our results show that the effect of the thickness on the
destruction of superconductivity is very distinct from those of the composition or the annealing.
We point out this material is particularly interesting to disentangle the effect of the parameters
driving this quantum phase transition.

1. Introduction
The understanding of the interplay between disorder and the superconductivity in 2D systems
is a long-standing problem [1, 2, 3, 4, 5], relying on the competition between the disorder
that increases the localization and leads to an insulator and the Cooper pairing that leads to an
infinite conductivity. In 2D systems, this competition is exacerbated as it is the lowest dimension
for both these effects. In these systems, the disorder is evaluated through the measurement of
\( R_\square = \rho/d \) which is proportional to \( 1/k_F l \), \( k_F \) the Fermi wave vector and \( l \) the electronic mean
free path. Since the work of Goldman [1], the thickness has been considered as a parameter for
the study of the disordered-induced SIT. We here report on two other parameters allowing the
tuning of disorder : the density of state and the microscopic disorder.

2. Experimental Setup
The \( \text{Nb}_x\text{Si}_{1-x} \) thin films are synthesized by electron-beam co-deposition process in an ultra-high
vacuum setup \( (10^{-8} \text{ mbar}) \) at room temperature. The samples thickness \( d \) and composition \( x \)
are determined by the Nb and Si deposition rates which are finely controlled in-situ by two pairs of piezo-electric quartz during the deposition process. These parameters are controlled ex-situ by Rutherford Back-Scattering. The Nb$_x$Si$_{1-x}$ thin films were deposited onto a sapphire substrate initially prepared with a 250 Å SiO under-layer. After the deposition, a protective cap of 250 Å of SiO is deposited to avoid the oxidation of the Nb$_x$Si$_{1-x}$ thin film.

The transport measurements were carried with four-probe technique on a dilution fridge down to 7 mK.

Moreover, the samples of composition $x = 13.5\%$ and $x = 18\%$ were studied at different annealing temperature. These samples are annealed under a flowing N$_2$ atmosphere 1 hour at a temperature up to 250°C.

Microscopic measurements show the Nb$_x$Si$_{1-x}$ thin films are continuous, homogeneous in thickness and amorphous even down to 25 Å. This is confirmed by the absence of reentrant behavior of the transport measurement at low temperature. Transmission Electronic Microscope measurement on 25 Å thick sample show no evidence of crystallization up to 500°C where crystallites of Nb$_3$Si appears. For the studied range of annealing temperature, the samples remains homogeneously disordered [6].

3. Experimental Results

With the deposition process, we can probe the Disordered-induced Superconductor-Insulator Transition (D-SIT) on Nb$_x$Si$_{1-x}$ thin films with the composition $x$ or the thickness $d$.

3.1. Disordered-induced Superconductor-Insulator Transition

We observe a D-SIT for the composition-tuned sets (Fig. 1a) or the thickness-tuned sets of samples (Fig. 1b). With the annealing, we observe a linear decrease of the conductivity with the annealing temperature (Fig. 1d). Starting from a superconducting sample, the annealing decreases its critical temperature ($T_c$) (Fig. 1c), leading the sample towards the SIT. According to the Béal & Friedel’s model[7], the annealing of a binary alloy slightly changes the position of the atoms due to the relaxation of the structural stress, this lead to a change of the electronic interference pattern and thus a decrease of the local conductance. No change on the Hall conductivity was observed on Nb$_x$Si$_{1-x}$ system by annealing [8], the annealing has then no effect on the material’s carrier density Our interpretation of the annealing process is that it changes the local disorder of the samples, i.e. its electronic mean-free path, whereas the composition changes the electronic properties and hence $k_F$.

Fisher’s model [2] describes the D-SIT as a Quantum Phase Transition. In the vicinity of the transition, the transport behavior is then described by a scaling law: $R(\delta, T)/R_c = f(\delta T^{-1/\nu z})$, with $\delta$ the distance to the critical point, $\nu$ the correlation length exponent, $z$ the dynamical critical exponent and $R_c$ the critical resistance. The critical point of the transition can be determined by the crossing-point on the $(R_n, d)$ plane, Fig. 2a.

First for the scaling analysis with the thickness as the parameter, we only consider superconducting films close enough of the D-SIT, i.e. where $\delta = \frac{d_{c, n} - d}{\Delta d} < 3$, to be described by the scaling law (Fig 2b). To successfully overlap the $R_\square(T)$ curves, we obtain a critical exponents product $\nu_d z_d = 0.43 \pm 0.03$ for the thickness-tuned SIT which is coherent with previous work at different composition [9]. The thickness-tuned SIT is then coherent with the disordered-induced SIT description of Fisher’s model.

Then we consider the annealing-tuned transition. No superconducting sample undergo the SIT, we thus determine the critical point by extrapolating the linear behavior of the annealing temperature where $T_c$ is canceled. The $\nu_d z_c$ critical exponent product obtained for the best overlap (Fig. 2c) is very close to 1.0. Considering their experimental uncertainty, these product are incompatible and outlines the thickness-induced and the annealing-induced transitions do not belong to the same universality class.
Figure 1. The Nb$_x$Si$_{1-x}$ undergo a Superconductor-Insulator Transition either by tuning the composition $x$ (a), the thickness $d_{\perp}$ (b) or the annealing temperature $\theta_{\text{anneal}}$ (c). (d) The normal state conductivity decreases linearly with the annealing temperature.

Figure 2. a) The crossing point in the ($R_{\square}, d_{\perp}$) plan defines the critical point of the transition (zoom of the crossing point in insert), $x = 13.5\%$. b) The best overlap for renormalized $R_{\square}/R_n$ vs $\delta T^{-1/\nu z}$ is obtained for $\nu z = 0.43 \pm 0.03$, $x = 18\%$, $\theta_{\text{anneal}} = 70^\circ C$. c) Scaling with the annealing temperature as the tuning parameter. The best overlap is obtained with $\nu \theta z_0 = 1.0 \pm 0.1$, here $x = 18\%$, $d = 75\, \AA$, $\theta_c = 520^\circ C$. 
Figure 3. a) We obtain a bi-univocal relation between $T_c$ and $R\square$ (here for $d = 500\,\text{Å}$) either by changing the composition, plot with different shape, and the annealing temperature plot with different color. b) Starting from one reference sample, we cannot obtain the same $T_c$ reduction and the same $R\square$ increase either by changing the thickness (blue to red circles) or the annealing temperature (blue circles to crosses). The thickness has a specific effect compared to composition and annealing.

3.2. Comparison between parameters

One main advantage of the Nb$_x$Si$_{1-x}$ is that we can compare the effect of each of the parameters. We first compare the evolution of the superconducting temperature transition $T_c$ with $R\square$ gathering the different composition and annealing temperature for a given thickness (Fig 3a). All the data align on the same curve, for each thicknesses. This is coherent with our interpretation of the effect of these parameters. As the composition changes the electronic properties ($k_F$) and the annealing affects the local disorder ($l$), they both affect the same disorder parameter $k_F\,l$: they have a joint role on the disorder parameter.

However, this analysis cannot be reproduced with the thickness $d$ and the annealing temperature $\theta_{\text{anneal}}$. Starting from a reference sample (blue circle), we cannot obtain the same $T_c$ reduction with the same $R\square$ increase either by changing $\theta_{\text{anneal}}$ (from blue circle to blue cross) or by the thickness (blue circle to red circle).

4. Conclusion

The structural stability of the Nb$_x$Si$_{1-x}$ material over a wide range of composition, thickness and annealing brings us the ability to tune the samples towards the D-SIT with these three parameters. This allow us to disentangle the effect of these parameters on the disorder. Our results outline the specific role of the thickness compared to the composition and the annealing temperature on the disorder parameter.

References

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