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# Superconductor-Metal-Insulator Transitions in two dimensional amorphous $\text{Nb}_x\text{Si}_{1-x}$

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**Abstract.** We report on the study of the two-dimensional Disorder-induced Superconductor-Insulator Transition (D-SIT) in  $\text{Nb}_x\text{Si}_{1-x}$  thin films. In this proceeding, we present new results on the emergence of an insulating state from a 2d metallic state.

## 1. Introduction

Amorphous  $\text{Nb}_x\text{Si}_{1-x}$  is an alloy presenting disorder-driven Superconductor-Metal-Insulator Transitions in three dimension. These transitions can usually be tuned either by changing the composition  $x$  or the thickness of the sample  $t$ . An alternative solution - specific to a- $\text{Nb}_x\text{Si}_{1-x}$  - is to apply a heat treatment which permits to finely tune the transitions.

These transitions have been studied in different materials for several decades now. Nevertheless, it still is a hot topic of condensed matter physics since the competition between a superconducting behavior and disorder effects - inducing localization and enhanced Coulomb interactions - is known to give rise to new phenomena which are far from being understood.

In two dimensions, the lowered dimensionality makes the picture more complex because of enhanced fluctuations. A direct Superconductor-to-Insulator Transition (SIT) is then expected [1][2]. One subject of interest resides in the understanding of the system's behavior in the vicinity of the SIT. Notably what are the mechanisms for the destruction of superconductivity - phase or amplitude fluctuations [3][4] - and what is the nature of the insulating state - fermionic or bosonic [5] - ?

To address these questions, the present work focuses on the emergence of the insulating phase at low temperature by increasing the disorder in a- $\text{Nb}_x\text{Si}_{1-x}$  thin films.

## 2. Experimental details

The samples are deposited onto a sapphire substrate by a co-deposition process in a dedicated e-beam evaporator under ultra-high vacuum. Si and Nb are simultaneously evaporated. The deposition rate of each source is separately controlled by a set of dedicated piezoelectric quartz. The films are then protected by a thin SiO layer. The composition is later cross-checked ex-situ by Rutherford Back-scattering Spectroscopy. Previous measurements [6] have shown that the composition and thickness of a given sample are well controlled and highly reproducible.



Each sample has undergone successive heat treatments that were performed following a systematic procedure. The sample is put into an oven for 1 hour at the considered heat treatment temperature  $\theta$ , with a constant flux of nitrogen to avoid any spurious oxidation. TEM measurements have shown that the heat treatment leaves the film amorphous and homogeneous up to 250°C [7].

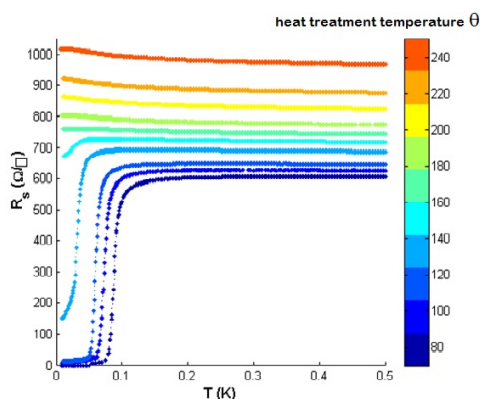
The transport measurements were performed from 300 K to 10 mK using conventional four probes techniques in a dilution fridge. The electrical lines are filtered at room temperature and well thermally anchored at low temperature. The measurements were performed through a low temperature resistance measurement bridge and completed by conventional DC and low frequency AC techniques. All measurements - down to the lowest temperatures - have been checked to be in the Ohmic regime. Moreover, the experimental setup has been carefully designed to prevent any incoming electromagnetic radiation.

### 3. The SIT in a-Nb<sub>x</sub>Si<sub>1-x</sub>

Nb<sub>x</sub>Si<sub>1-x</sub> is an alloy in which the ground state can be tuned by modifying the disorder of the film. In the three-dimensional limit it has indeed been shown, for instance by tuning the composition  $x$ , that a Superconductor-to-Metal Transition occurs at  $x = 12\%$  and a Metal-to-Insulator Transition occurs at  $x = 10\%$  [8]. It has also been shown that a heat treatment of the films allows to finely tune the disorder in our system [7]. Indeed the heat treatment in such binary alloys is - counter-intuitively - increasing the disorder without modifying the morphology of the films [9].

In two-dimensional systems, where the film thickness  $t$  is smaller than the characteristic lengths, and particularly smaller than the superconducting coherence length  $\xi$ , one should expect a direct SIT since metallic states are theoretically forbidden [1]. It has then been widely accepted [2] that the superconductor is characterized by a positive TCR - Temperature Coefficient of Resistance, defined as  $\frac{dR}{dT}$  - and the insulator by a negative TCR at low enough temperature.

Previous studies have shown that, in a-Nb<sub>x</sub>Si<sub>1-x</sub> 2d films, the situation is more complex. As partially shown figure 1, the transport properties near the disorder-driven SIT can present 4 different regimes [10].



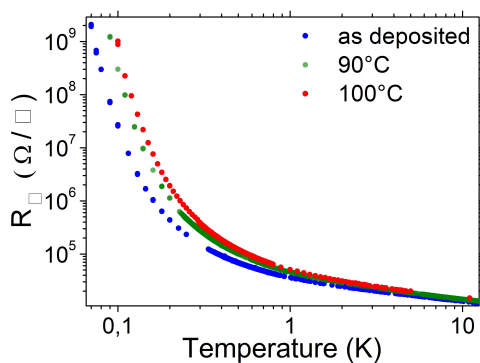
**Figure 1.** Transport characteristics of a single sample of Nb<sub>13.5</sub>Si<sub>86.5</sub> with  $d=23$  nm which sustained several thermal treatments from  $\theta = 70^\circ\text{C}$  to  $\theta = 250^\circ\text{C}$ .

The first regime is a superconducting one, with no dissipation below  $T_C$ . By increasing the disorder, we observe a first metallic-like regime where the conductivity saturates at low temperature and the TCR is positive. These saturations of the resistance are intrinsic and cannot be explained by experimental artifacts, such as heating for example [11]. By increasing the disorder even more, a second metallic-like regime is observed with a negative TCR and a saturation of the conductivity at the lowest measured temperature. Finally this metallic state evolves into an insulating one - with an infinite resistivity at zero temperature.

In this work we will focus on the low temperature transport properties of the two latter states.

#### 4. Results

When the dimensionality is reduced, previous studies have shown that the critical composition  $x_c$  for the transition to occur is dependent on the sample thickness in a-Nb $_x$ Si $_{1-x}$ [12]. In particular, for  $t_c = 15$  nm, the composition corresponding to a change of the TCR sign is  $x_c = 13.5\%$ . We have studied a set of 6 samples of a-Nb $_{13.5}$ Si $_{86.5}$  with thicknesses ranging from 2 to 5 nm lower than  $t_c = 15$  nm, that is to say close to the SIT but with a negative TCR. Initially, the four samples with  $t$  between 2 and 4 nm were on the insulating side of the transition and ones with  $t = 4, 5$  and 5 nm were in the second metallic state described above. Each sample was then progressively driven towards a more resistive state by successive heat treatments. A typical set of data representing the electronic transport properties evolution with the temperature of the heat treatment  $\theta$  is given figure 2 for the 3,5 nm thick sample. Let us now study the evolution of the laws describing the transport properties in the different regimes that we will identify.



**Figure 2.**

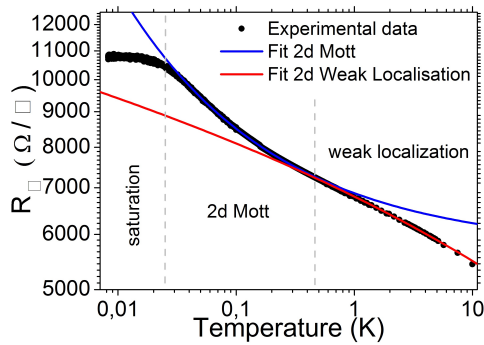
$R_{\square}$  as a function of temperature for a single sample of Nb $_{13.5}$ Si $_{86.5}$  with  $t = 3, 5$  nm before and after sustaining heat treatments at  $\theta = 90^{\circ}\text{C}$  and  $\theta = 100^{\circ}\text{C}$

For each sample, at a given  $\theta$ , we have identified different behaviors depending on the temperature range. For the least disordered sample ( $t = 5$  nm), which is on the second metallic state of the transition, we have found three different low temperature regimes as presented figure 3 where we have plotted the sheet resistance  $R_{\square}$  of the sample as a function of temperature. We observe that the electronic transport for temperature higher than 500 mK can be described by a  $R_{\square} \propto \ln T$  law, corresponding to a two dimensional weak localization process. From 30 to 500 mK, we observe an insulating law such as :

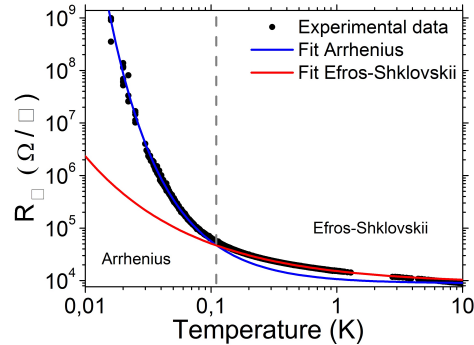
$$R = R_0 e^{(T_0/T)^{1/n}} \quad (1)$$

The precise nature of the insulating law is given by the value of the parameter  $n$ . For instance,  $n=4$  and  $n=3$  correspond respectively to a three dimensional and two dimensional Mott hopping law which are regimes resulting from the disorder-induced localization in the material.  $n = 2$  corresponds to an Efros-Shklovskii hopping law, resulting from localization taking into account electron-electron interactions. Finally,  $n = 1$  corresponds to an Arrhenius regime, reflecting a hard gap insulator. The parameter  $n$  can be determined by using a method described by Zabrodskii et al[13]. We have found that a 2 dimensional Mott regime well fits the intermediate temperature regime on the data presented figure 3. However, at the lowest temperatures, we observed the data systematically deviate from this insulating law. Indeed, in the third regime, the resistance saturates, translating the above-described metallic state. This behavior is intrinsic to the sample, as mentioned above, and the study of this feature is beyond the scope of this paper. However it is noteworthy that - in our system - a metallic ground state emerges from an insulating behavior at higher temperatures.

For more disordered films, on the insulating state, we have identified two low temperature regimes shown figure 4. At the higher presented temperatures we observe a Efros-Shklovskii law, meaning that the transport properties correspond to a hopping law sensitive to Coulomb

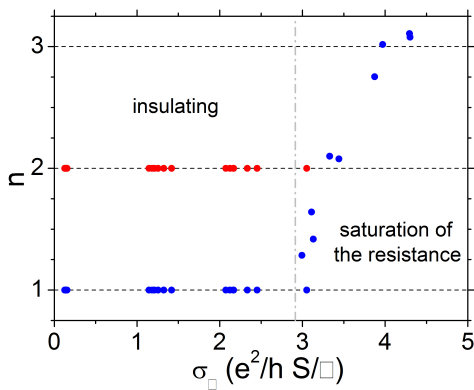


**Figure 3.**  $R_{\square}$  as a function of temperature for a sample of  $Nb_{13.5}Si_{86.5}$  with  $d=5$  nm, as deposited. The sample is on the metallic side of the transition. The gray dashed line corresponds to a crossover between the different identified regimes.



**Figure 4.**  $R_{\square}$  as a function of temperature for a sample of  $Nb_{13.5}Si_{86.5}$  with  $d=4$  nm, as deposited. The sample is on the insulating side of the transition. The gray dashed line corresponds to a crossover between the Arrhenius and the Efros-Shklovskii regimes.

interactions. At the lowest temperatures, the sample evolves towards an Arrhenius-like law corresponding to a hard gap. The existence of this low temperature Arrhenius law seems to be inseparable from the Efros-Shklovskii law at higher temperature.



**Figure 5.**  $n$  as a function of  $\sigma_{\square}$  taken at 4 K. The blue value corresponds to the insulating law recorded at the lowest temperature. The red value corresponds to the insulating law at higher temperature. The gray dashed line corresponds to the limit between the samples which have a saturating resistivity at the lowest temperature and the truly insulating ones. Other dashed lines are guides to the eye.

We can study the transition from the two extreme situations presented above by plotting the evolution of the parameter  $n$  - extracted from the Zabrodskii method and readjusted to perform the best fit of the data - as a function of  $\sigma_{\square} = \frac{1}{R_{\square}} = k_f l \frac{e^2}{h}$ , taken at 4 K, which can be viewed as measure of the disorder. The corresponding plot is displayed figure 5. For metallic samples, the value of  $n$  reported is the one corresponding to the intermediate temperature regime described above. For the insulating samples, two values of  $n$ , corresponding to the low temperature (blue) and the high temperature (red) regimes are plotted. In addition, the vertical line corresponds to the transition between the metallic and the insulating states, defined by the existence (or non existence) of a saturation of the resistance at the lowest measured temperatures. At the transition between the metal and the insulator - as defined section 3, when the disorder is increased, the value of the low temperature  $n$  evolves quickly, but continuously, from 3 to 1. This is consistent with a system evolving towards a more insulating state. This strikingly continuous evolution tends to indicate that this still unexplained metal can be seen as a precursor state for the insulator.

## 5. Conclusion

In this paper, progressive heat treatments enabled us to finely tune the disorder in thin  $\text{Nb}_x\text{Si}_{1-x}$  films between a 2d metallic state and an insulating one. Studying the low temperature properties of this system, we have shown that the insulating state is characterized by an Arrhenius law at low temperature. Metallic samples - in the sense of the second metallic state described section 3 - exhibit an activated 2d Mott law at intermediate temperatures before abruptly saturating at the lowest temperature of the measurements. Furthermore, this hopping law continuously evolves towards a hard gap at the Metal-to-Insulator transition.

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