Determination of depairing current of superconducting thin films by means of superconducting nanowire resonators

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Introduction and Objectives

- Despite the last years achievements in the SNSPD [1-6] field, a complete theoretical model for the photodetection mechanism is still missing. In order to ease the efforts of matching the experimental results with the theoretical models, we present a reliable method to determine one of the key parameters of SNSPDs, the depairing current.
- The aim of this work was to find a optimal and simple way to measure the depairing current of superconducting thin films. Moreover, we report an interesting result concerning the behavior of the constriction factor, C [7] at different operating temperatures.

Methods

- We designed a set of resonators made from nanowire coplanar waveguides (see Fig. 1).
- The nanowires had different widths (55, 80, 100, 120, 140, 160 and 200 nm) and were fabricated in NbN and WSi material systems.
- We measured the resonant frequency both in transmission and in reflection modes (see Fig. 2-3):

$$\|S_{21}(\omega)\| = I\frac{\left(\frac{1}{2}\Gamma\right)^2}{(\omega-\omega_r)^2+\left(\frac{1}{2}\Gamma\right)^2}|1-\xi(\omega-\omega_r)|^2,$$

$$arg\{S_{11}(\omega)\} = -180 + 2\tan^{-1}\left[2Q(1-\frac{\omega}{\omega_r})\right]$$

- We measured the kinetic inductance change of the nanowires using the RLC approximation:

$$\frac{\mathcal{L}_k(q,T)}{\mathcal{L}_{k,0}(T)} = \left[\frac{\omega_r(q=0,T)}{\omega_r(q,T)}\right]^2$$

- Then, by exploiting the kinetic inductance change of the resonator nanowires on basing conditions, we used the fast and slow relaxation models by Clem and Kogan [8] to extrapolate the depairing current:

$$y_{fast}(x) = (1-x^n)^{1/n},$$
$$y_{slow}(x) = y_0 - (y_0-1)(1-x^n)^{1/n}$$

where:

$y = \mathcal{L}_k(q,T)/\mathcal{L}_{k,0}(T)$

$x = |j_s|/j_{dep}(T)$

y_0, n are experimental constants

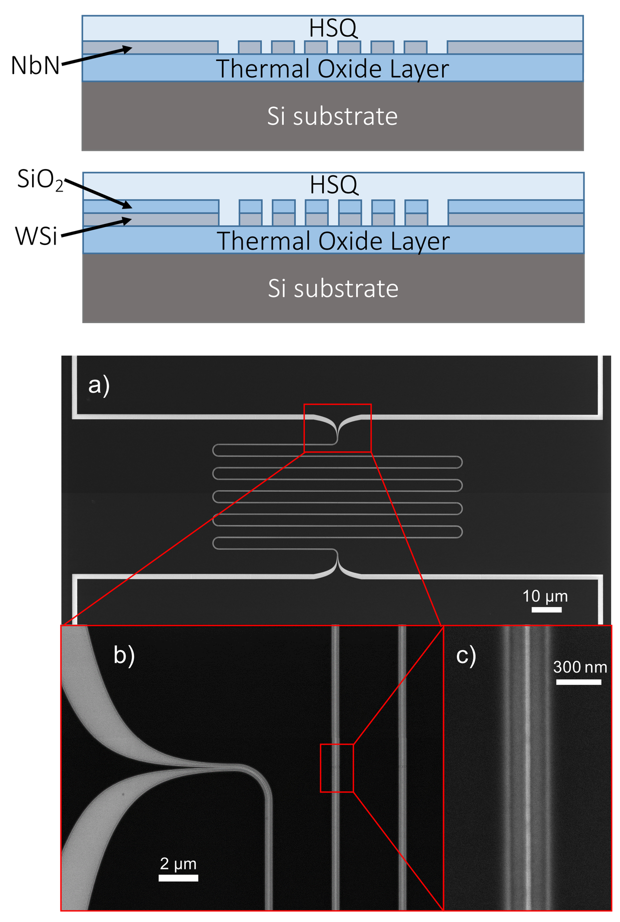


Figure 1: Top: deposited layers of the NbN and WSi resonator. Bottom: and a SEM image of a resonator device fabricated in NbN material system.

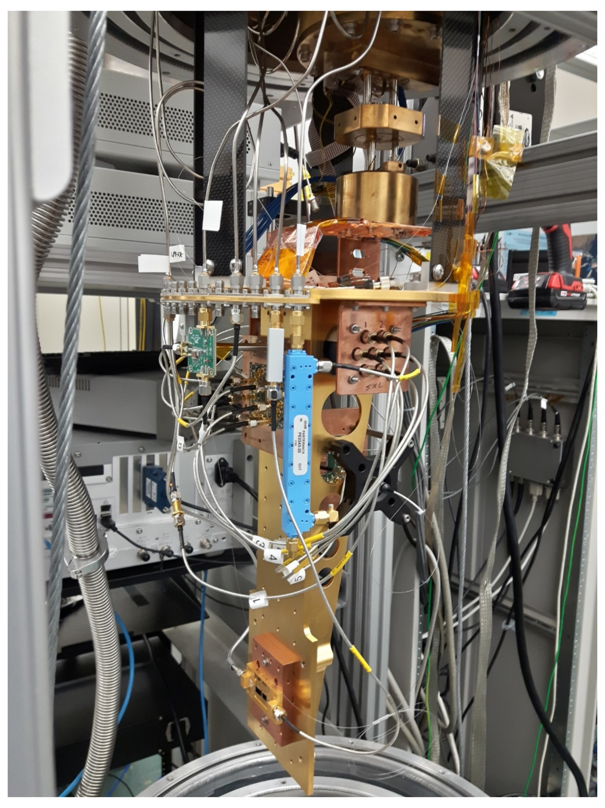


Figure 2: Cryostat setup

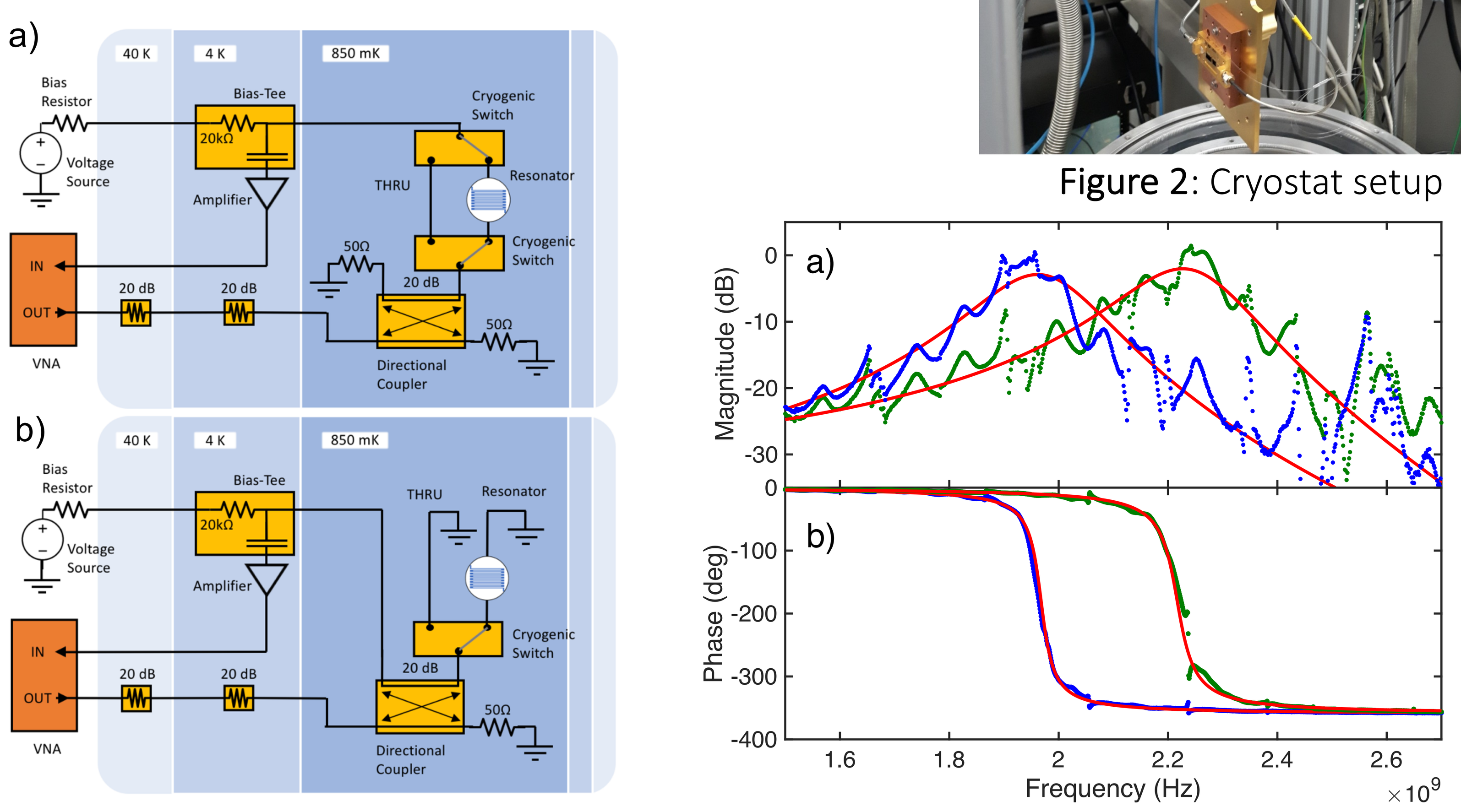


Figure 3: On the left: Setup schematics for the measurements performed in transmission (a) and reflection (b) modes. THRU devices were used for system calibration purposes. On the right: frequency response at zero bias current (in green) and at near-switching bias current (blue) for magnitude in transmission mode (a) and for phase in reflection mode (b).

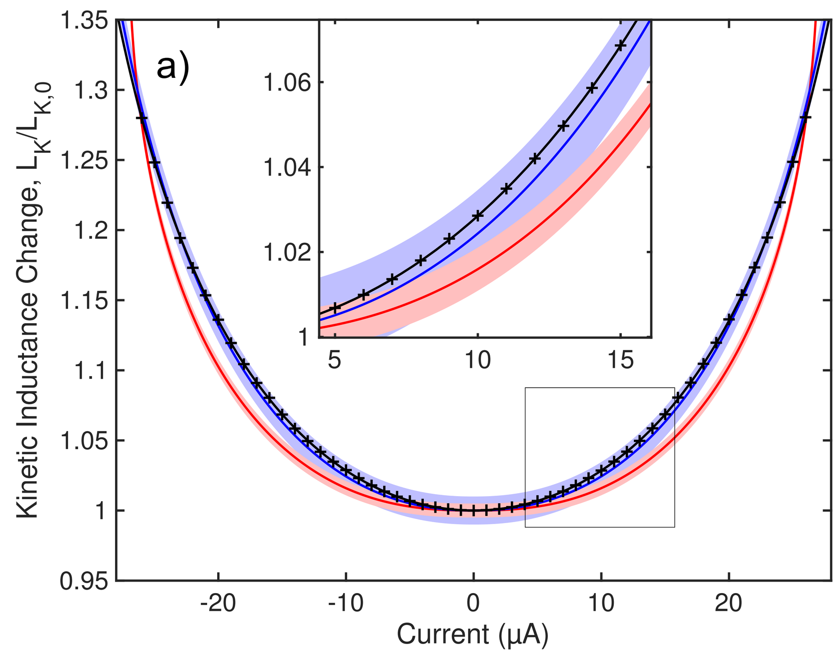
Results

- We fitted the kinetic inductance change with both the fast relaxation (Fig. 4a, in blue) and the slow relaxation (Fig. 4a, in red) models, using the depairing current as the only free fitting parameter. The better fit of the fast relaxation model is in accordance with the theorerical predictions.

Table 1: Depairing current measured with fast and slow relaxation models (from Fig. 4a) for different devices materials and geometries, swtiching current, switching-to-depairing current ratio and estimated depairing current at zero temperature by fit (from Fig. 4b) and using the Kupryianov-Lukichev formula.

Device	Fast Relax	Slow Relax	Measured (T = 1K)		Estimated	
	I_{dep}	I_{dep}	I_{sw}	I_{sw}/I_{dep}	$I_{dep}(0)$	$I_{dep}^{KL}(0)$
WSi, 55 nm	4.40	3.32	2.25	54.0%	4.89	6.47
WSi, 80 nm	9.22	6.05	4.75	51.5%	10.06	10.68
WSi, 120 nm	14.82	9.55	7.25	49.6%	16.80	17.41
WSi, 160 nm	20.76	13.82	12.25	63.8%	22.89	23.46
WSi, 200 nm	27.65	21.00	20.50	74.1%	30.29	30.28
NbN, 120 nm	38.19	27.05	26.50	69.4%	39.38	43.30
NbN, 140 nm	46.93	33.09	32.50	69.2%	48.02	50.52

- The depairing current at zero temperature obtained by interpolation (Fig. 4b) differs by less than 5% from the one obtained by the use of the Kupryianov-Lukichev formula.
- We evaluated the ratio between switching and depairing current for different materials and geometries. As shown by Fig. 4c, this ratio tends to decrease with increasing temperature.



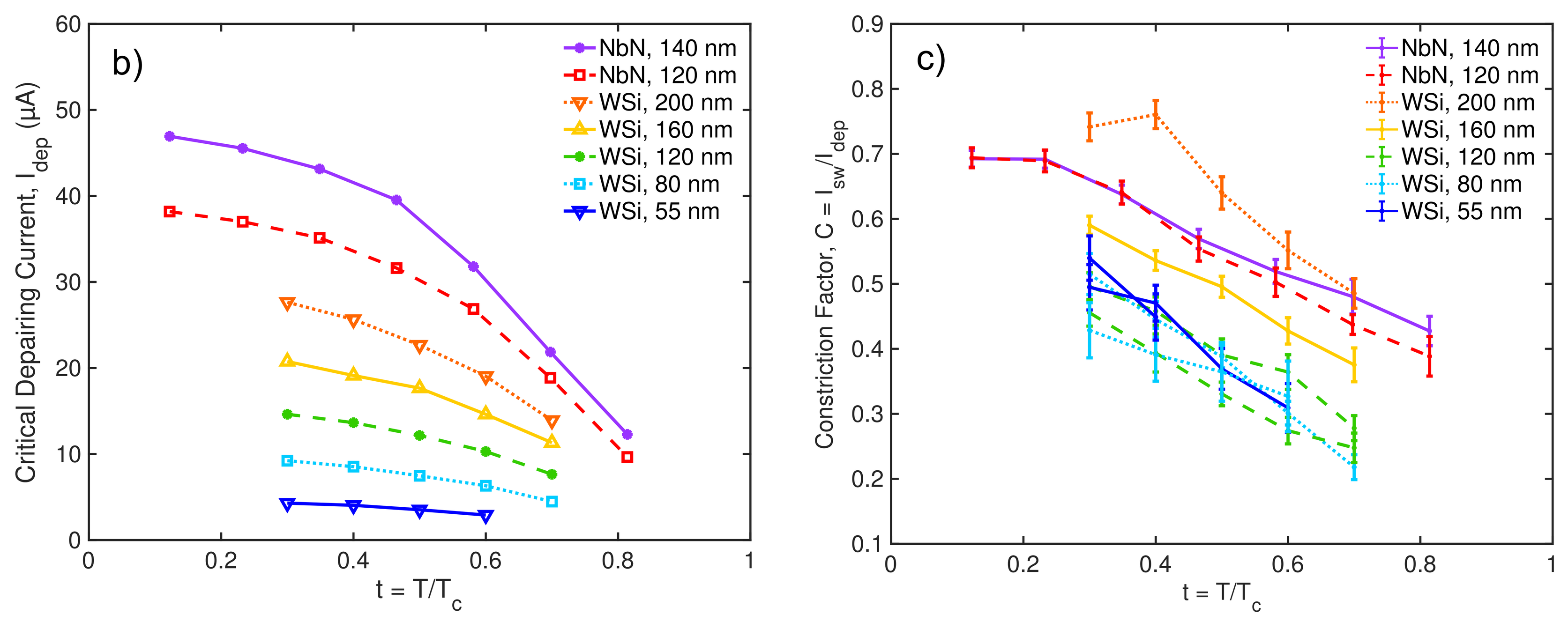


Figure 4: (a) Resonance frequency dependence on bias current flowing through the resonator. Results of an 120 nm wide NbN resonator: fits according to fast (in blue, I_{dep} = 38.19 μA) and slow (in red, I_{dep} = 27.05 μA) relaxation models. (b) Depairing current behavior with respect to different operative temperatures. (c) Switching-to-depairing current ratio for different devices geometries and meaterials at different temperature conditions.

Summary

We have shown a simple and accurate method to directly measure the depairing current of superconducting thin films by means of superconducting nanowires resonators. We also introduce a new parameter, the switching-to-depairing currents ratio, which has the potential to be used as a quality factor of the devices fabrication process.

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