

Microwave power dependence of the retrapping current of superconducting nanostrips

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The microwave power density absorbed in the normal state by continuously irradiated superconducting Nb and NbN nanostrips is extracted from their electrical transport properties. The procedure is based on the reduction of the retrapping current (i.e., the minimum applied current required to sustain a dissipative region inside a superconducting microbridge) that results from the microwave dissipation. The power effectively absorbed by the nanostrips varies linearly with the input power level and falls in the $\mu\text{W}\mu\text{m}^{-3}$ range. At a given microwave frequency, the relation between the input power and the absorbed power does not depend on the coolant temperature. In addition, the upper limit of the detection range is given by the heat removal capabilities through the substrate. When the absorbed microwave power exceeds this temperature-dependent heat removal threshold, normal hotspot domains are stabilized down to zero bias current. The determination of the microwave power absorbed by superconducting samples in the normal state may be of practical interest in the field of incident power detection. © 2011 American Institute of Physics. [doi:10.1063/1.3632982]

I. INTRODUCTION

Many practical applications that involve the microwave response of a granular superconducting film are limited by deviations from the linear regime when the input power is increased. This nonlinear behavior often originates from the microwave dissipation that arises when the heat removal capabilities are not sufficient to balance the microwave power. The microwave heating may be either uniform throughout the whole sample (global heating) or concentrated within localized defects (local heating). In the latter case, the heat is preferentially transferred away along the defects¹ and the local Joule heating often manifests itself by the formation of hotspot domains at the weak-links of the granular thin films. By studying the frequency-driven resonance response of NbN strip line microwave resonators, Abdo *et al.*^{2,3} have reported a wide variety of nonlinear features that arise above an input microwave power threshold. The multiple and sharp variations of the reflection parameter, as well as the hysteretic behavior in the vicinity of the jumps, have been attributed to the local heating of the weak-links that form at the boundaries of the NbN columnar structure. The metastable nature of the jumps was demonstrated by the repetitive switch of the reflection parameter between two well-defined values. The transitions between bistable states have also been reported by Ghigo *et al.*⁴ in their investigation of the switching response of MgB₂ resonators. From the analysis of the scattering parameter, the system was found to oscillate between two stable states when the input power is sufficiently high. The all-important feature of their model — which is based on the formation of hotspots at the intergranu-

lar weak-links — is that the abrupt transitions are directly related to the thermal bistability condition. Indeed, both states in the resonance curves were shown to be equivalent to the current densities j_* and j^* , which define the interval of the thermal bistability in the current-biased conditions.^{5,6} The interplay between the microwave dissipation and the heat removal capabilities was also highlighted by Pukhov *et al.*,^{7,8} who have theoretically studied the power-induced switching of thin high-temperature superconductors deposited onto a thermally stabilized substrate. The heat transfer conditions between the sample and its surroundings appear to be the main factor that determines the microwave power threshold required to switch the film into the normal state. The authors further notice that the presence of defects reduce the power threshold required to initiate the breakdown phenomenon. The distinction between local and global heating has also been examined by Cohen *et al.*,⁹ who have studied the evolution of the resonance curve shape of high-temperature superconducting resonators as a function of the delay time between each frequency step. At a sufficiently high input power, the resonance curves remain symmetric for a delay time of 0.3 s, while a pronounced non-linear behavior arises by increasing the delay time up to 12 s. The authors consider that the non-linear effects arise in the films at a lower frequency threshold due to the longer heating time. The reduction of the frequency resonance was then directly related to a global temperature rise. Even though their theoretical heating model reproduces only qualitatively the experimental results, the global heating was interestingly shown to be generated if the delay time is sufficiently long, i.e., in the second time-scale.

All the above-mentioned results indicate that the microwave heating-induced breakdown of the superconductivity

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has a threshold character, in the sense that the microwave dissipation has to exceed a certain input power in order to overcome the heat transfer capabilities and to lead to a thermal instability. However, in most of the experimental results that focus on the microwave power dependence of a physical property, the fraction of the input power which is effectively absorbed by the samples is not known with precision.^{10–16} The available information is the power level of the input signal — usually expressed in dBm or in arbitrary units — and the results are only compared between different input powers at the same frequency. This is a main limitation which results from the difficulty to determine the microwave field, which is actually coupled with the superconductor. In order to quantitatively compare their samples, Kermorvant *et al.*¹⁰ have introduced an effective microwave reactive power, which depends on the loaded factor of their resonators. Doing so, the physical properties of their films (namely the resonance frequency and the surface impedance) were compared at similar absorbed microwave powers. However, such treatment is not suitable for experiments that deal with the microwave response of superconducting strips biased with a direct current or voltage. In this case, only the input power is considered (for recent works focusing on electrical transport properties, see Refs. 14–18). This is particularly problematic when the sample dimensions are reduced in the nm range, because the fraction of the input power, which is absorbed by the samples, becomes really tiny.

In this paper, it is shown that the electrical transport behavior of continuously irradiated superconducting nanostrips allows one to quantify the fraction of the microwave input power which is absorbed in the normal state. The procedure is based on the minimum applied current required to sustain a dissipative region inside a superconducting microbridge. As the absorption of an electromagnetic radiation results in a measurable decrease of this transport current (also called the retrapping current), its evolution allows one to determine the power density effectively absorbed by the nanostrips at each level of the input microwave power. The paper is organized as follows: The experimental details (sample shape and measurement setup) are described in Sec. II. Section III is devoted to the description of the hotspot plateau under an increasing microwave input power. Normal hotspot domains are shown to be stable in an adjustable current range, depending on the input microwave power level. In particular, configurations of normal hotspots are stable when the total dissipation (Joule effect and microwave dissipation) reaches the heat evacuation capabilities. In addition, the ability to extract the microwave density power effectively absorbed by the normal regions of the samples is discussed in Sec. IV. The consistency of the quantitative analysis is discussed in Sec. V, and the conclusions are given in the Sec. VI.

II. EXPERIMENTAL DETAILS

The superconducting thin films used to fabricate the samples were deposited by reactive dc magnetron sputtering at room temperature from a pure (99.9%) Nb target. The Nb thin films were obtained in an Ar gas atmosphere (total pres-

sure: 9.75 mTorr, 1000 W dc power), while an Ar + N₂ gas mixture (total pressure: 8.9 mTorr, N₂ partial pressure of 11.2%, 360 W) was used for NbN. The obtained 75-nm-thick polycrystalline films have a critical temperature of 8.6 K and 11.4 K for Nb and NbN, respectively. The normal state resistivity is around 9 $\mu\Omega\text{cm}$ (Nb) and 1200 $\mu\Omega\text{cm}$ (NbN). The large electrical resistivity of the NbN thin film results from the formation of low-conducting inter-granular regions that noticeably affect the electrical coupling between the grains.¹⁹ These disordered regions essentially come from the room-temperature and low-power sputtering process, which leads to a negligible diffusion of the sputtered atoms at the substrate surface. This is well known to lead to the formation of a columnar structure, whose grains are separated by voids of a few nm.²⁰ Both types of thin films were deposited onto (100 nm SiO₂)/Si substrates. Multicontact structures were obtained by SF₆ reactive ion etching using a 40-nm-thick Al₂O₃ mask patterned with standard e-beam lithography. The scanning electron microscopy image of Fig. 1 illustrates a typical Nb sample, which is composed of two distinct (and parallel) multi-contact configurations. Each of them contains six nanostrips in series, whose length is either 3 μm or 1 μm . All the results reported in this paper were obtained on nanostrips with similar cross-section dimensions (thickness: 75 nm, width: 120 nm) and length (3 μm). The measured multi-probe structures only differ from the ones of Fig. 1 by a smaller nanostrip width.

Electrical transport measurements were performed in a He flow pulse-tube cryocooler with a base temperature of 1.5 K. All the measurement lines were filtered using a combination of RC and LC filters operative up to 40 GHz. Only one nanostrip is biased at a time with a Keithley K2400 programmable current source. The dc current is applied directly to the measured segment, while the resulting voltage is probed using the nearest superconducting contacts on each side (see the contacts referred by the V⁺, I⁺, I⁻, and V⁻ symbols used to measure the third nanostrip of the top multi-probe configuration). The voltage contacts are thus external with respect to the current ones. This is required in order to prevent any spurious transition of the adjacent segment, whose cross-section would be locally reduced. Starting from the perfect superconducting state, such configuration might favor the

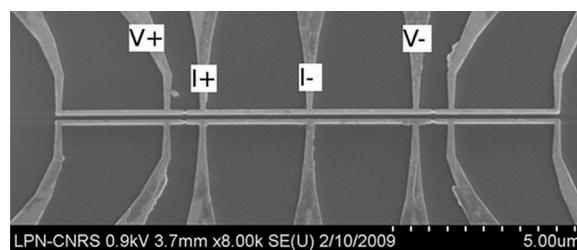


FIG. 1. Scanning electron microscopy image of a typical Nb multi-contact nanostrip configuration. The length of the studied segments amounts to 3 μm . The superconducting leads enable electrical transport measurements. This is illustrated for the third nanostrip of the top configuration. The current bias is applied using the contacts referred by the I⁺ and I⁻ symbols, while the nearest contacts on each side are used to measure the resulting voltage (V⁺ and V⁻ symbols).

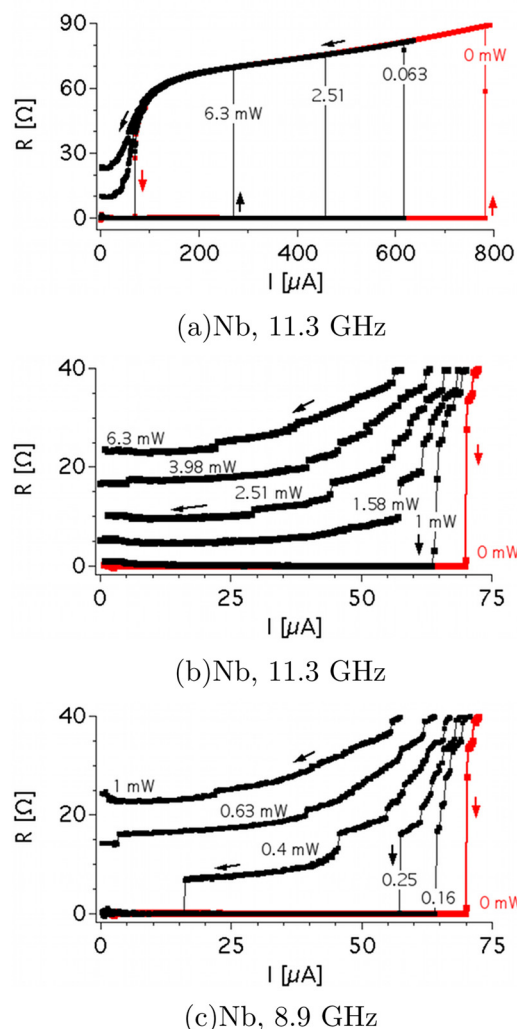


FIG. 2. (Color online) (a) Overall current-driven behavior of the Nb nano-strip under an increasing microwave power ($T_0 = 6$ K, 11.3 GHz). The input power varies from 0 mW to 6.3 mW. (b)-(c): Evolution of the normal-to-superconducting transition of the Nb nano-strip under an increasing microwave power ($T_0 = 6$ K). The microwave frequency is 11.3 GHz and 8.9 GHz, respectively. The microwave input powers are indicated in mW.

nucleation of normal regions at the corners where the current bends. However, the exact location of the first normal region has no impact on the current-induced normal-to-superconducting transition, which is the subject of the present paper. In addition, the electromagnetic radiation was applied through a homemade copper-loop antenna connected to a microwave generator through a semirigid coaxial cable. The antenna — around 9 mm in diameter — was located at approximately 5 mm from the sample holder. The frequency was swept between 10 MHz and 20 GHz.

III. MICROWAVE DEPENDENCE OF THE HOTSPOT PLATEAU

Figure 2(a) illustrates the impact of a microwave irradiation on the overall current-driven characteristic of a Nb nano-strip at fixed coolant temperature ($T_0 = 6$ K) and frequency (11.3 GHz). The curves were obtained at increasing input microwave power, from 0 mW up to 6.3 mW.

Although all the experiments have been performed by monitoring the input power in dBm, it is more convenient to express the microwave input power in a linear scale. Both characteristic currents, namely the superconducting-to-normal (instability) and the normal-to-superconducting (retrapping) currents, are shifted to lower values when the microwave power level increases. In this paper, we focus on the current-driven transition from the normal state to the superconducting state, which is enlarged in Figs. 2(b) and 2(c) at the same coolant temperature and at two microwave frequencies (at 11.3 GHz and 8.9 GHz, respectively). At this coolant temperature, the retrapping transition without a microwave irradiation arises at $70 \mu\text{A}$ (see the rightmost curve). For both frequencies, the hotspot plateau is shifted to lower values when the input microwave power level increases, up to 6.3 mW at 11.3 GHz and up to 1 mW at 8.9 GHz. This means that the current range of stabilization of a resistive domain is shifted to lower values when the input power is increased. Above an input power threshold (between 1 mW and 1.58 mW at 11.3 GHz and between 0.4 mW and 0.63 mW at 8.9 GHz), a normal domain appears to remain stable down to zero applied current. This microwave-dependence of the hotspot plateau is similarly observed on the NbN nanostrips insofar as the input power is sufficiently large. This is illustrated in Fig. 3 with the y-axis displayed in a logarithmic-scale in order to better distinguish between all the intermediate dissipative states. The coolant temperature is $T_0 = 7$ K, and the microwave frequency is 7 GHz. The retrapping current without a microwave irradiation amounts to $11.7 \mu\text{A}$ (see the rightmost curve), while the instability current amounts to $43 \mu\text{A}$ (not shown). Once again, the hotspot plateau is progressively shifted to lower currents when the input microwave power increases. Zero-crossing resistance steps arise (i.e., there is a finite resistance at applied bias current close to zero) when the input power level exceeds a particular threshold.

For both materials, the main features of the microwave-dependence of the hotspot plateau (i.e., the shift to lower currents and the stabilization of normal domains at zero applied

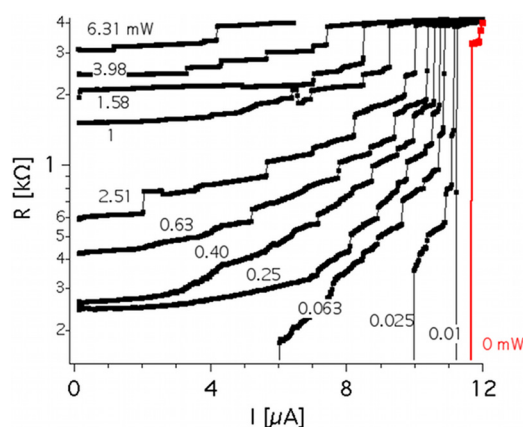


FIG. 3. (Color online) Evolution of the normal-to-superconducting transition of the NbN nano-strip under an increasing microwave power. The microwave frequency is 7 GHz and the coolant temperature is $T_0 = 7$ K. The microwave input powers are indicated in mW.

current) are qualitatively described by considering a local heating of the normal hotspot domains due to the microwave irradiation. First, one has to keep in mind that a dissipative hotspot domain is sustained in a superconducting sample insofar as the total dissipation (Joule dissipation and microwave dissipation) balances the heat removal capabilities.⁶ As a consequence, less Joule dissipation due to the direct current is required to stabilize a normal domain inside the strip when the input microwave power increases (and thus the power density absorbed by the sample). Accordingly, the retrapping current is continuously shifted to lower currents when the microwave power increases. This is similar to the decrease of the superconducting recovery current observed, e.g., in superconducting Al strips when the total microwave power increases.²¹ Second, the microwave power threshold, above which one observes the zero-crossing resistance steps, basically corresponds to the point above which the local heating due to the irradiation exceeds the heat removal capabilities, so that no applied current is required to stabilize a normal domain. This was already pointed out by Skocpol *et al.*,²² who mentioned that, when the average root mean square of the equivalent ac current generated by the microwave source exceeds the minimum current required to sustain a hotspot, the microbridge latches into the normal state at all current levels. In other words, if the microwave power absorbed by the conduction electrons exceeds the power required to stabilize a N/S interface (equivalently, if the temperature of the conduction electrons raises above T_c due to the microwave power alone), the direct current that has to be applied in order to stabilize a normal domain becomes zero.

An important feature of Fig. 2 is that some dissipative states with exactly the same resistance level are observed at different microwave frequencies, while the input power levels involved in the measurements noticeably vary. This is further highlighted if one compares the curves of Figs. 2(b) and 2(c). Indeed, some curves satisfactorily match together, either in the whole current range (e.g., for $P_{IN}^{11.3\text{GHz}} = 6.3$ mW and $P_{IN}^{8.9\text{GHz}} = 1$ mW) or in a quite large current range (e.g., for $P_{IN}^{11.3\text{GHz}} = 2.51$ mW and $P_{IN}^{8.9\text{GHz}} = 0.4$ mW). This correspondence means that the global microwave dissipation is similar for each pair of superimposed current-biased curves. In addition, the ratio between the input power levels at 11.3 GHz and at 8.9 GHz is close to 6.3. As a consequence, the fraction of the total microwave power absorbed by this sample is around 6.3 times smaller when the applied frequency is 11.3 GHz than when the frequency is 8.9 GHz. Larger input power levels are thus needed at 11.3 GHz to generate the same microwave local heating. Such features highlight that (i) this is not the absolute value of the input microwave power, which is relevant, but the microwave power effectively absorbed by the samples and (ii) that the linear relation between the absorbed microwave power and the input level can noticeably differ from one applied frequency to another. This is, of course, a relevant point, which emphasizes once more that comparing the microwave dependence of a particular property at several frequencies requires determination of the fraction of the input power which is effectively absorbed by the samples. For this purpose, a quantitative analysis of the results is given in Sec. IV.

IV. DETERMINATION OF THE MICROWAVE POWER DENSITY ABSORBED BY NORMAL DOMAINS

In their original work, Skocpol *et al.*²² have studied the stabilization of localized normal domains that are maintained by Joule heating in superconducting microbridges. Their model expresses the minimum current required to sustain a normal domain with a finite length $2x_0$ smaller than the whole sample length. This latter current corresponds to the direct retrapping current, below which a normal domain collapses, or equivalently to the left-side boundary of the thermal bistability current-interval.⁶ It is determined by the heat removal capabilities, which are dominated either by the heat evacuated within the film or by the heat transfer through the substrate. In the former case, i.e., for microbridges much shorter than the thermal healing length η , the main cooling mechanism is the diffusion of the hot electrons out of the bridge (diffusion-cooled regime). At the opposite, the electron-phonon interactions dominate the cooling mechanisms (phonon-cooled regime) for a bridge longer than η . This characteristic length for thermal relaxation corresponds to the length required for the hot-electrons to cool down from the normal domain to the neighboring superconducting regions. It is given by $\eta = \sqrt{D_e \tau_e}$, where D_e is the electron diffusion constant (around $0.1 \text{ cm}^2\text{s}^{-1}$ and $3 \text{ cm}^2\text{s}^{-1}$ for the NbN and Nb nanostrips, respectively) and τ_e is the electron temperature relaxation time (around 100 ps and 1 ns for the NbN (Ref. 23) and Nb (Ref. 24) nanostrips, respectively). Let us note that the electron diffusivity D_e is estimated from the slope of the upper critical field with the temperature using the procedure detailed in Ref. 25. Here, due to the small value of the thermal healing length compared to the total length ($\eta_{\text{NbN}} \approx 50 \text{ nm}$, $\eta_{\text{Nb}} \approx 500 \text{ nm}$), the heat removal essentially depends on the heat transfer through the substrate. As a consequence, the minimum dissipated power required to sustain a normal domain can be basically expressed by the balance between the power dissipated by the direct-current Joule effect and the power removed outside the hot area. This is given by Eq. (1) (in Wm^{-3}):

$$\rho_N j_{r0}^2(x_0) = \frac{h_{T_c}(T_c - T_0)}{d}, \quad (1)$$

$$= K_{x_0}(T_0),$$

where ρ_N is the normal state resistivity, $j_{r0}(x_0)$ is the current density required to dissipate enough heat at x_0 in order to maintain a stable N/S interface in the absence of microwave, h_{T_c} is the heat-transfer coefficient per unit area to the substrate [$\text{Wm}^{-2}\text{K}^{-1}$] estimated near the critical temperature, T_0 is the substrate temperature (assumed to be the measured coolant temperature), and d is the thickness of the bridge. The notation $K_{x_0}(T_0)$ is introduced to emphasize that, for a given sample and a given hotspot length, the power removed outside the hot area only depends on the substrate temperature. Figure 4 shows the temperature dependence of $K_{x_0}(T_0) \equiv \rho_N j_{r0}^2(x_0)$ for the Nb ($\bullet$) and the NbN ($\square$) samples. The linear evolution of $K_{x_0}(T_0)$ with respect to the temperature difference $T_c - T_0$ between the nanostrip in the normal state and the substrate reinforces the use of Eq. (1) to characterize

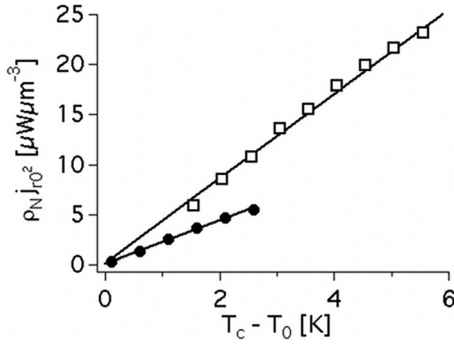


FIG. 4. Evolution of the heat removal capabilities $K_{x_0} \equiv \rho_N j_{r0}^2$ with respect to the difference $T_c - T_0$ between the critical temperature and the coolant temperature. The data are depicted for the Nb (●) and the NbN (□) samples.

the heat transfer between the normal domains and their surroundings. The varying slope reflects different thermal resistances at the interface between the substrate and the thin films.²⁶ The heat-transfer coefficient per unit area to the substrate close to the critical temperature (h_{T_c}) can be estimated from Fig. 4. It amounts to $1.6 \times 10^5 \text{ Wm}^{-2}\text{K}^{-1}$ and $3.8 \times 10^5 \text{ Wm}^{-2}\text{K}^{-1}$ for the Nb and the NbN samples, respectively. The heat removal capabilities also highlight the current range over which the current-induced return to the superconducting state takes place. A major point is that the (Joule) dissipation term of Eq. (1) is set by the heat removal capabilities. The retrapping current density j_{r0} follows from the normal state resistivity of the material, which therefore impacts the current range involved in the electrical transport measurements of Figs. 2 and 3 (i.e., the larger is the ρ_N , the lower is the retrapping current $\propto j_{r0}$). Strictly speaking, the presence of low-conducting inter-granular regions in the columnar structure of the NbN nanostrip results in a reduction of the transport current required to stabilize a normal hotspot domain. Comparing with the much less resistive Nb sample, the current-induced transition from the normal state to the superconducting state arises at smaller currents, while the Joule dissipation is very similar for both materials (as the heat transfer is mainly dominated here by the comparable quality of the substrate/film interface).

Furthermore, the current-induced return to the superconducting state of the Nb and NbN nanostrips spreads over a finite current interval. The numerous intermediate dissipative states result from the localization of the normal domains boundaries, whose motion is prevented by the unavoidable nanoscale modulations of the sample cross-section (the nanoscale width modulations amount to $\sim 10 \text{ nm}$, i.e., the mean grain size of the polycrystalline thin films). Indeed, for a given applied current, the stabilization of a normal domain depends on whether or not the *local* current density exceeds the current density threshold for the propagation of the N/S boundaries (in other words, it depends on whether or not the Joule dissipation exceeds the heat removal).^{6,27} The exact location and the morphology of the nanoscale modulations therefore impact the length and the number of the normal domains. However, the sample geometry is not sufficient by itself to address the issue of the hotspots configurations, especially because it requires us to distinguish between sin-

gle or many hotspots originating in different parts of the sample. As it was discussed by Eichele *et al.*,²⁸ applying the voltage is the most favorable way to stabilize a multiplicity of normal domains, especially when the thermal healing length is small. In this latter case, the interactions between neighboring hotspots are weak and the coalescence is less probable. The situation differs in the present work because the propagation and the coalescence of normal domains are favored when an external current bias is imposed. The stabilization of a large number of individual hotspots is here highly unlikely. When the transport current is reduced, the width modulations play a relevant role to define the successive lengths of the normal hotspot domain (equivalently to define the resistance level of the numerous intermediate dissipative states observed in the resistance versus current curves).

It is of the greatest importance to stress that the minimum dissipated power $K_{x_0}(T_0)$ required in the vicinity of the hotspot boundaries to sustain a normal domain is experimentally given by the current-induced transition from the normal state to the superconducting state. Indeed, the retrapping current at a given location is, by definition, the smallest current at which a N/S interface remains stable. The right term of expression (1) can thus be determined without any estimation of the thermal parameters, i.e., only ρ_N and j_{r0} are required. Furthermore, it can be considered constant at a given coolant temperature. This is crucial in order to extend the above-described power balance by considering the alternating currents generated by the microwave irradiation inside the nanostrip. The power balance has to reflect this additional contribution by including the microwave power density absorbed by the nanostrip in the normal state (P_{MW}). This is done in the left term of Eq. (2):

$$\rho_N j_{r,MW}^2(x_0) + P_{MW} = K_{x_0}(T_0), \quad (2)$$

where $j_{r,MW}(x_0)$ is now the retrapping current density at the hotspot boundaries when a microwave is applied. P_{MW} is related to the electromagnetic energy that heats up the quasiparticles at the extremities of the normal domains configuration (by extension, it describes the microwave absorption inside the whole normal region). The radiation photon energy $\hbar\omega$, being small compared to the superconducting gap 2Δ (here, $\Delta_0^{NbN} \approx 2 \text{ meV}$ (Ref. 29) and $\Delta_0^{Nb} \approx 1.5 \text{ meV}$ (Ref. 30)), the paired electrons located far away from the N/S interfaces are not perturbed by the irradiation. No new quasiparticle is created in the superconducting regions at moderate levels of the incident power.³¹ Only the existing quasiparticles move up to the higher energy levels of the excitation spectrum, leading to a nonequilibrium distribution of quasiparticles inside the normal domains.

The knowledge of the retrapping current densities j_{r0} (without irradiation) and $j_{r,MW}$ (with irradiation) is thus sufficient to determine the microwave power density P_{MW} absorbed at each input microwave power P_{IN} . Indeed, P_{MW} is given by the expression

$$P_{MW} = \rho_N [j_{r0}^2(x_0) - j_{r,MW}^2(x_0)], \quad (3)$$

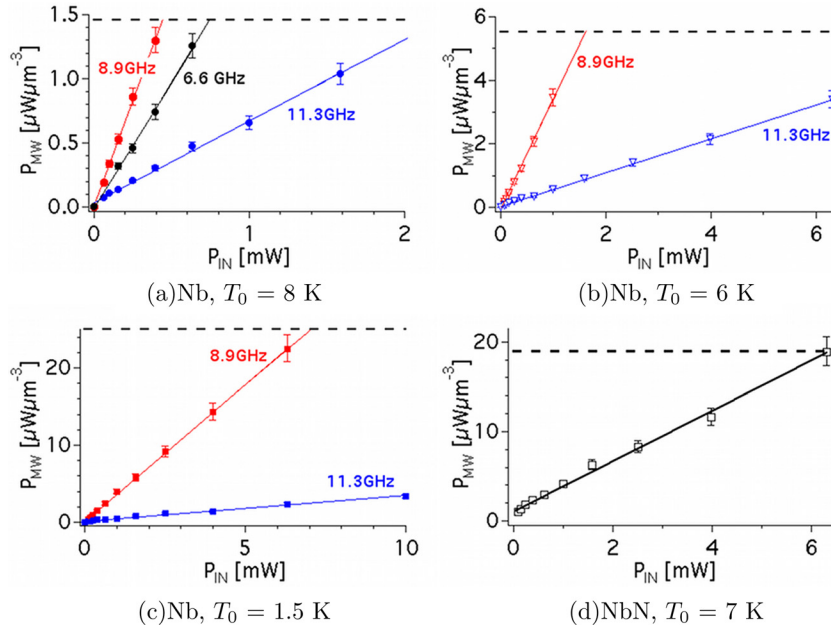


FIG. 5. (Color online) Evolution of the microwave power density absorbed in the normal state P_{MW} with respect to the input power P_{IN} . The data are depicted for the Nb nanostrip at three coolant temperatures $T_0 = 8$ K ($\bullet$, (a)), 6 K (∇ , (b)), and 1.5 K ($\blacksquare$, (c)) and for the NbN ($\square$) nanostrip at $T_0 = 7$ K (d). For Nb, the microwave frequencies are 8.9 GHz and 11.3 GHz, except at $T_0 = 8$ K, where the data are also displayed at 6.6 GHz. For NbN, the microwave frequency is 7 GHz. The dashed horizontal lines mark the heat evacuation capabilities level at the studied coolant temperatures, i.e., $K_{x_0}(T_0) \equiv \rho_N j_{r0}^2$. The errors bars take into account that the local sample width used in Eq. (3) may differ from the nominal one by ± 5 nm.

which is derived from Eqs. (1) and (2). In practical terms, one has to fix a resistance level (R_{crit}) between the perfect superconducting state and the normal state in order to follow the evolution of the retrapping current of equivalent N/S interfaces located at x_0 . Doing so, the comparison is performed for equivalent hotspots length $L_{HS} = L \times \frac{R_{crit}}{R_N}$, where L is the total length and R_N is the normal state resistance.

V. DISCUSSION

Through the continuous shift to lower currents of the retrapping current, the use of electrical transport measurements to determine the microwave power density absorbed by the normal domains represents the major result of this paper. Figures 5(a)–5(c) show the evolution of the absorbed microwave power density with respect to the power delivered by the microwave generator for the Nb sample. The data extracted from the experimental current-voltage curves are depicted at three coolant temperatures ($T_0 = 8$ K, 6 K, and 1.5 K) for microwave frequencies of 8.9 GHz and 11.3 GHz (apart from the curves at $T_0 = 8$ K, for which the data are also available at a microwave frequency of 6.6 GHz). The resistance criterion is $R_{crit} = 30 \Omega$. In each case, P_{MW} increases linearly with the input power. This is a major observation that validates the procedure.³² In addition, the fact that the slope depends on the microwave frequency indicates that the local heating of the normal domains does not only depend on the absolute value of the input power, but also on the manner by which the microwaves effectively heat up the conduction electrons. A linear dependence is also observed for the NbN nanostrip, as it is illustrated in Fig. 5(d) ($T_0 = 7$ K, freq: 7 GHz). The resistance criterion used for this sample is $R_{crit} = 3.2 \text{ k}\Omega$.

In addition, each resistive state of the hotspot plateau has been related to the stabilization of the normal domain

boundaries at particular locations along the sample length (see Sec. IV). Therefore, considering a resistance criterion R_{crit} implicitly means that one focuses on N/S interfaces located at a sample width, which slightly differs from the nominal one. However, as the exact width profile is not known with precision, the absorbed microwave power densities are extracted from Eq. (3) using the nominal width as a reference. The nanoscale modulations thus lead to a small uncertainty in the obtained values (the same conclusion holds for the choice of R_{crit}). The error bars of Fig. 5 represent these deviations by considering that the width is ± 5 nm around the nominal one (let us remind that the nanoscale width modulations amount to ~ 10 nm). The relative error is around 15% on the whole microwave power range.

A. Impact of the coolant temperature

The influences of the coolant temperature are manifold. On one side, one sees from Eq. (1) that the heat transfer from the normal domains to the substrate depends on the difference between the hotspot temperature and the coolant temperature. In Fig. 5, the horizontal dashed lines mark the value of $K_{x_0}(T_0) \equiv \rho_N j_{r0}^2$, namely, the heat removal capabilities at the studied coolant temperature. It describes the largest microwave power density that can be detected at these fixed coolant temperatures using the chosen resistance criterion. $K_{x_0}(T_0)$ can thus be viewed as the upper bound of the detection range. As previously discussed, $K_{x_0}(T_0)$ is of the same order of magnitude for both Nb and NbN (i.e., in the $\mu\text{W}/\mu\text{m}^2$ range). The slight difference does not reveal any intrinsic properties of the material, but results from the different quality of the film/substrate interface (and thus different heat transfer through the substrate). On the other side, the electronic temperature at the boundaries of the normal domains is, by definition, close to the critical one at the

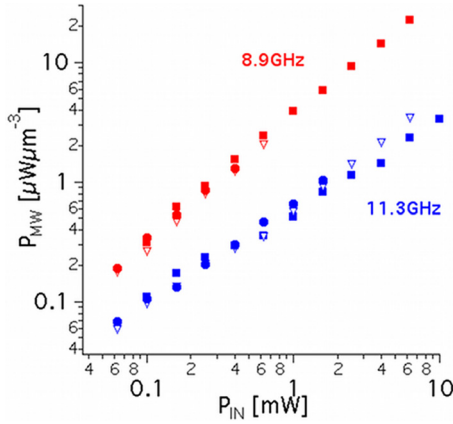


FIG. 6. (Color online) Independence of the absorbed microwave power density with respect to the coolant temperatures, i.e., $T_0 = 1.5$ K (■), 6 K (▽), and 8 K (●) (Nb sample, frequency: 8.9 GHz (top) and 11.3 GHz (bottom)).

retrapping current. As a consequence, the hot electrons are similarly heated — whatever is the coolant temperature — by the microwaves at fixed microwave input power and frequency. The absorbed power is thus expected to vary very slightly with T_0 , on the contrary of the shift of the retrapping current that, according to Eq. (3), will depend on T_0 . This independence of P_{MW} with respect to T_0 is experimentally verified and illustrated for the Nb sample in Fig. 6, which shows that the relation $P_{MW} \propto P_{IN}$ is temperature-independent in the range 1.5 K–8 K. This observation reinforces the validity of the procedure used to determine the microwave density power effectively absorbed by the nanostrips.

B. Zero-crossing resistance steps

A relevant feature of the microwave-dependence of the hotspot plateau is that, above a particular power threshold, some zero-crossing resistance steps are observed. In Fig. 2, it was highlighted that the input power threshold noticeably depends on the microwave frequency. However, from the point of view of the density power effectively absorbed by the samples, there is only one power threshold, which corresponds to the dissipation required to stabilize the boundaries of the normal hotspot domain. For a given frequency, the intersection between the linear power dependence of P_{MW} ($\propto P_{IN}$) and the heat removal threshold $K_{x_0}(T_0)$ defines the minimum input power required, so that the power density absorbed by the samples becomes sufficient to heat up the electrons above their critical temperature without any Joule heating due to the direct-current. In other terms, it defines from which microwave source power a particular resistance plateau is sustained down to zero bias current. As already mentioned, these plateaus are observed whatever the microwave frequency and the coolant temperature, provided that the power density absorbed by the electrons overcomes the heat evacuation capabilities $K_{x_0}(T_0)$. In addition, let us notice that the resistance criterion R_{crit} can be set above any of the zero-crossing resistance steps. Considering such criterion simply means that the N/S interfaces are stabilized at some locations where the width is slightly larger than the narrowest one. In this latter case, there is no additional uncertainty that

the one which is associated to the nanoscale modulations of the cross-section.

C. Comparison with photonic devices operating in the pulsed regime

Here, all the measurements have been performed under a continuous microwave irradiation, i.e., the nanostrips were continuously irradiated during the whole experiments. This steady-state behavior noticeably differs from the dynamic electron heating regime, which is involved in the photonic devices (either the bolometers^{33,34} or the photon (or quantum) detectors^{35,36}). Indeed, the measure of the energy or the power of an incident radiation is often performed in the pulsed mode in order to detect events that involve a few number of photons. In spite of the apparent gap between the continuous-mode studied here and the pulse-regime involved in photonic devices, the basic mechanism is similar in both cases. Indeed, the subtended feature is the nucleation and the stabilization of a normal hotspot domain when the Joule heating dissipation exceeds the heat removal capabilities. In this sense, one may expect that the radiation power densities involved in both types of experiments take similar values, mainly defined by the manner by which the heat is removed away from the dissipative normal domains. As it was described above, the microwave power levels absorbed by the NbN and Nb nanostrips range between a fraction of $\mu\text{W}\mu\text{m}^{-3}$ up to a few tens of $\mu\text{W}\mu\text{m}^{-3}$ at the lowest coolant temperatures. The power absorbed by a superconducting single photon detector in the vicinity of the hotspot nucleation is given by Eq. (4):

$$P_{ph} = \frac{E_{ph}}{\Delta t V_{HS}} = \frac{E_{ph}}{\Delta t} \times \frac{1}{(\pi \eta^2 d)}, \quad (4)$$

where E_{ph} is the photon energy, Δt is the output pulse duration, V_{HS} is the hotspot volume, η is the thermal healing length, and d is the film thickness. Using usual values for NbN devices²³ ($E_{ph} \approx 1$ eV, $\Delta t \approx 2$ ns, $\eta \approx 50$ nm, and $d \approx 5$ nm), one finds that the density power involved in this latter case ($P_{ph} \approx 2 \mu\text{W}\mu\text{m}^{-3}$) is of the same order of magnitude as in the present experiment. This is a major observation which reinforces the consistency of the quantitative treatment of the results. From an applicative point of view, the evolution of the retrapping current in the continuous mode thus allows one to determine the very small fraction of the input radiation power, which is locally present inside an experimental chamber. In addition to the intrinsic deviations that result from the nanoscale modulations of the sample cross-section, the resolution of the above-described procedure is given by the accuracy of the current source. Indeed, the smallest theoretical power density increment is given by $\frac{(\Delta I)^2}{I_{r0}^2} \times K_{x_0}(T_0)$, where ΔI is the source resolution and I_{r0} is the retrapping current without irradiation. This gives a typical resolution of around $\frac{(5\text{ nA})^2}{(100\mu\text{A})^2} \times 10 \mu\text{W}\mu\text{m}^{-3} \approx 0.1 \text{ pW}\mu\text{m}^{-3}$.

VI. CONCLUSION

In summary, electrical transport measurements are used to determine the microwave power density absorbed in the

normal state by Nb and NbN superconducting nanostrips that are continuously irradiated. The main point is that a normal domain remains stable insofar as the total heat dissipation (Joule heating due to the direct current and microwave dissipation) balances the heat removal capabilities. The reduction of the retrapping current observed when the input microwave power is increased allows one to determine the power effectively absorbed by the nanostrips. The latter varies linearly with the input power level and falls in the $\mu\text{W}\mu\text{m}^{-3}$ range. The upper limit of the detection range is given by the temperature-dependent heat removal capabilities through the substrate. When the microwave power effectively absorbed by the samples exceeds this threshold, some zero-crossing resistance steps are observed at zero applied current. The ability to determine the power density absorbed by superconducting microwave-irradiated samples opens prospects for a complementary understanding of their electromagnetic response, especially their power-handling capabilities. In addition, the knowledge of the microwave power absorbed by Nb and NbN nanostrips in the normal state may be of practical interest in the field of incident power detection, e.g., to determine the small fraction of the input power which is locally available in an experimental chamber.

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