"Development of phase-slip centers in superconducting Sn nanowires"

Michotte, Sébastien ; Piraux, Luc ; Boyer, F ; Ladan, FR ; Maneval, JP

ABSTRACT

By electrodeposition of tin inside the pores of a polycarbonate template, nanowires were grown, out of which a single one was contacted electrically so as to form a quasi-one-dimensional superconductor (diameter: 50 nm). A resistive phase-slip center appears as a response to a pulse of supercritical current. Measuring its resistance, and its time of nucleation, gives access to the electron inelastic lifetime, and to the gap relaxation time, respectively, both in the nanosecond range. Finally, the threshold current for passage into the fully normal state indicates a good thermal contact with the polycarbonate matrix. (C) 2004 American Institute of Physics.

CITE THIS VERSION

Development of phase-slip centers in superconducting Sn nanowires
S. Michotte, L. Piraux, F. Boyer, F. R. Ladan, and J. P. Maneval

Citation: Appl. Phys. Lett. 85, 3175 (2004); doi: 10.1063/1.1804608
View online: http://dx.doi.org/10.1063/1.1804608
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v85/i15
Published by the American Institute of Physics.

Related Articles
Development of 10 kA high temperature superconducting power cable for railway systems
Enhancement of superconducting properties in FeSe wires using a quenching technique
High transport critical current densities in textured Fe-sheathed Sr1−xKxFe2As2+Sn superconducting tapes
Low noise measurement system for determination of the critical currents in superconducting tapes by a pulse method
Rev. Sci. Instrum. 82, 114701 (2011)
Microstructure dependence of the c-axis critical current density in second-generation YBCO tapes
J. Appl. Phys. 110, 083923 (2011)

Additional information on Appl. Phys. Lett.
Journal Homepage: http://apl.aip.org/
Journal Information: http://apl.aip.org/about/about_the_journal
Top downloads: http://apl.aip.org/features/most_downloaded
Information for Authors: http://apl.aip.org/authors

ADVERTISEMENT

HAVE YOU HEARD?
Employers hiring scientists and engineers trust
http://careers.physicstoday.org/post.cfm
Development of phase-slip centers in superconducting Sn nanowires

S. Michotte and L. Piraux
Unité de Physico-Chimie et de Physique des Matériaux (PCPM), Université Catholique de Louvain, Place Croix du Sud 1, B-1348 Louvain-la-Neuve, Belgium and Research Center on Microscopic and Nanoscopic Electronic Devices and Materials (CERMIN), Université Catholique de Louvain, B-1348 Louvain-La-Neuve, Belgium

F. Boyer, F. R. Ladan, and J. P. Maneval
Laboratoire Pierre Aigrain (LPA), Département de Physique, Ecole Normale Supérieure, 24 rue Lhomond, 75231, Paris 5, France

(Received 27 April 2004; accepted 11 August 2004)

By electrodeposition of tin inside the pores of a polycarbonate template, nanowires were grown, out of which a single one was contacted electrically so as to form a quasi-one-dimensional superconductor (diameter: 50 nm). A resistive phase-slip center appears as a response to a pulse of supercritical current. Measuring its resistance, and its time of nucleation, gives access to the electron inelastic lifetime, and to the gap relaxation time, respectively, both in the nanosecond range. Finally, the threshold current for passage into the fully normal state indicates a good thermal contact with the polycarbonate matrix. © 2004 American Institute of Physics. [DOI: 10.1063/1.1804608]

Filamentary superconductors approach the normal state through the creation of phase-slip centers (PSCs) separated by nondissipative zones. Once revealed as steps in the current–voltage (I–V) curves of whiskers, PSCs were more recently found on tin and lead nanowires, which meet more strictly the unidimensionality, or one-dimensional (1D) requirement (transverse size inferior to the pair coherence length ξ). In the quantitative model of Skocpol et al., the zone of longitudinal extension ξ supporting the electron oscillations between the condensed and the normal states is bordered on each side by a quasiparticle diffusion length Λ, dependent itself upon the inelastic lifetime τ\text{in}. In this model, the voltage follows the law V\text{=}R_{\text{p}}(I\text{=}I_{\text{c}}), where the differential resistance R_{\text{p}}\text{=}dV/dI of each PSC can be equated to the resistance of a length Λ of normal material. A second important signature of the PSCs came with the discovery made on aluminum films, and subsequently on indium and high-T\text{c} films, that the PSC voltage excited by a supercritical (I\text{>}I_{\text{c}}) pulse of current arrives delayed with respect to the current. An interpretation of the time delay t\text{d} based on a time-dependent Ginzburg-Landau equation put into evidence a relaxation time, identified as the gap relaxation time τ\text{\Lambda}, subject to a comparison with the former τ\text{in}. Here we report on the transient response to step current pulses of tin nanowires embedded in a polymer matrix. We focus on the observation of PSC voltage response, and on what we believe is evidence of a PSC nucleation time in a nanowire. Independent measurements of R_{\text{p}} and of t\text{d} yield the material parameters τ\text{in} and τ\text{\Lambda}. In our work, a signal is considered a PSC response if (a) it has the form of a voltage jump, stable in time, (b) it arrives late compared to the current step, and (c) it has a constant dV/dI. In contrast, a continuous V(I) relation would be attributed to a different process (activated phase-slips, vortex flow), while a voltage growing with time would be considered as a normal selfspreading hot spot. Tin nanowires were grown in the pores (diameter ~50 nm) of a 50-μm-thick nuclear track-etched polycarbonate membrane (Fig. 1). (Fabrication techniques, including contacting a single nanowire and specifications, were already described in Refs. 5 and 10.) Through scanning electron microscopy with field emission gun, the nanowires show a great regularity in the diameters and uniformity along their length. For electrical measurements, the nanowires were kept inside the membrane. For instance, sample NanoSnP4 had a diameter D\text{=}53 nm and a resistance 2150 Ω at room temperature (165 Ω at 4 K). All samples possess about the same critical temperature (T\text{c}\text{=}\text{3.7 K}), close to the bulk T\text{c} of tin. The relevant transport parameters of a single nanowire are deduced from its low-temperature resistance R_{\text{N}}, its length L, which is just the thickness of the polymer membrane (50 μm), and its diameter D. From the free-electron model, it is easy to show that the electron mean free path ℓ\text{e}\text{=}12\pi\hbar^{2}L/e\text{=}64 nm in nanowire NanoSnP4. For providing the nanosecond rise time pulses, we use a coaxial system having wave impedance Z\text{=}50 Ω, with a 150 ns delay line inserted to allow separate readings of the incident voltage V_{i} and of the reflected voltage V_{r}(t). By reflectometry, and taking appropriate origins of time, the instantaneous voltage across the sample is the sum V(t)\text{=}V_{i}−V_{r}.

FIG. 1. SEM micrograph of a single nanowire obtained by dissolving the hosting polymer membrane. Inset: Top view of the track-etched polycarbonate membrane showing the regularity of diameters.

© 2004 American Institute of Physics
+V_{r}(t)$, while the current is $I(t)=\{1/Z\}[V_{r}-V_{s}(t)]$. Another cable performs a second probing of the voltage, say $V'(t)$, shown in Fig. 2, through a resistive divider connected as a shunt to the sample. (This avoids dumping too much current from the sample). Thus, for each value of $I$, we have at our disposal two determinations $V$ and $V'$, which we check each time for compatibility. The PSC jump, identifiable by its finite and current-dependent nucleation time $t_{N}$ can be viewed either in the reflected pulse (not shown here), or in the voltage $V$ (Fig. 2), which appears superposed to the (constant) signal due to a parasitic resistance of about $(19\pm1)\Omega$ in series with the superconducting nanowire. Because $t_{N}$ is a very sensitive function of the ratio $I/I_{c}$, the temperature-dependent critical current $I_{c}$ must be fixed with accuracy. $I_{c}$ is defined as the current which provides the longest nucleation time admissible in our system (300 ns). Then, the input amplitude was increased from $I_{c}$ by successive removal of calibrated attenuators previously inserted in the drive circuit. Only a limited number of $I/I_{c}$ values could be obtained that way. However, it allowed scanning $t_{N}$ in discrete steps from 300 ns down to about 7 ns, with a precise knowledge on the selected values of $I/I_{c}$. The experiments provide essentially two pieces of information, namely the nonlinear response $V-I$ taken on top of the PSC signal, and the nucleation time $t_{N}$, which we discuss first. Historically, this finite $t_{N}$ was analyzed according to

$$t_{N}(I/I_{c}) = \tau_{A}\int_{0}^{1} \frac{df}{(4/27)(df)^{2} - df^{4} + f^{6}} \tag{1}$$

brought about from a zero-dimensional time-dependent Ginzburg–Landau equation. Not too close to $T_{c}$, the gap relaxation time $\tau_{3}$ was interpreted either as the electron-phonon inelastic time\(^6\) or, on account of its temperature independence, as the film bolometric time.\(^7,9\) A more complete analysis, especially suitable for nucleation times comparable to the relaxation time $\tau_{A}$, was later proposed by Tinkham,\(^1\) and tested on indium films.\(^5\) It has explicit $T$-dependence and requires too complicated computation to be reproduced here. However, it was found to describe very adequately the experimental results on YBCO\(^7\) and Nb films,\(^7,9\) even far from $T_{c}$, the domain we are interested in here. For instance, the critical current of sample NanoSnP4 was found to be 104 $\mu$A at 1.5 K. Measurements of PSC delay yielded $t_{A}=19$ ns at 1 dB above $I_{c}$ (117 $\mu$A), and 8 ns at 2 dB (131 $\mu$A). Such data well fit Tinkham’s prediction at $T/T_{c}=0.4$ by taking $\tau_{A}=4.3$ ns. Similar measurements between 1.5 and 3.3 K yielded no significant temperature dependence of $\tau_{A}$, and all are encompassed in the result $\tau_{A}=4.3\pm0.5$ ns. We emphasize that after the $t_{d}$ delayed jump into the first resistive state, the voltage is not growing in time (see Fig. 2), therefore excluding a self-spreading hot spot. However, there still exists the possibility that the PSC process is replaced by a nonspreading hot spot if the thermal relaxation time of the system is extremely small. However, due to the low thermal conductivity of the polymer, we believe that this is not the case, though we cannot exclude this process completely because the heat profile in the composite material surrounding the measured nanowire (consisting of polymer and of empty or metal filled nanoparticles) is unknown and therefore the thermal relaxation time of the system can hardly be calculated.

We now turn to the analysis of the $V-I$ relation (Fig. 3), where $V$ and $I$ are taken point by point at the longest available time (300 ns) after the rise of the current pulse. The dynamic $V-I$ isotherms are not essentially different from equivalent curves taken in dc conditions.\(^3\) They can be simplified into four segments: $OA$—which terminates at the critical current $I_{c}$—arises from the series resistance $R_{s}$; PSC formation occurs at the turning point $A$, where the system jumps back in current from $A$ to $B$ along the load line of the passive circuit; on segment $BC$, the slope is $R_{u}+R_{N}$, where $R_{u}$ is the PSC differential resistance; the final part $CD$ starting at current $B$ there corresponds to the transition into the normal, or hot spot (HS) state, whose length grows gradually with $V$. The full resistance $R_{s}+R_{N}$ is only asymptotically reached and we choose to place $C$ at the inflexion point of the $V-I$ curve for definiteness. As an example, sample NanoSnP4 at $T=3.14$ K features: $I_{c}=29$ $\mu$A; $I_{0}=9$ $\mu$A; $R_{s}=19$ $\Omega$; $R_{u}=130$ $\Omega$; $R_{N}=38$ $\mu$A; $R_{N}=155$ $\Omega$. From a large number of measurements at different temperatures, we found $R_{s}=130\pm10$ $\Omega$. We note that the PSC extends over a large portion of the nanowire. Equating the differential resistance $R_{u}$ to the normal resistance of a length $2\Lambda=2(\lambda^{-1}\xi_{v\ell}^{2}T_{m})^{1/2}$, with $d$ the relevant dimension of the system. The question of dimensionality is sound here, as the electron mean free path (64 nm) is comparable to the wire diameter. So, electron transport is governed by boundary scattering, and $d$ should be reduced from its three-dimensional value. We can eventually compute $T_{m}$ from the formula: $T_{m}=dm^{2}v_{f}D^{2}Le^{2}R_{u}^{2}/(48\pi\lambda^{2}R_{s})$, which contains only known or measured parameters. That leads to $T_{m}=3.5$ ns for $d=1$ and $T_{m}=7$ ns for $d=2$, and more for $d=3$. If this time is to be identified with $t_{d}$ derived from nucleation times, we are led to the conclusion that the quasiparticles diffuse unidimensionally, as it happens for electrical transport (compare $\xi_{v\ell}$ =64 nm with $D=53$ nm). In addition, both times are found to have no temperature dependence, a feature noted many times in the literature,\(^4\) even though there is no satisfactory explanation for it. Beyond the PSC state, the quasilinear sec-

FIG. 2. Time dependence of voltage across the nanowire, passed through the resistive divider, in response to a step pulse of current. The nonzero voltage at time $t=0$ is due to contact resistances. The true PSC signal is the positive step arising at $t_{d}=300$ ns. Its apparent rise time is the result of jitter on $t_{d}$ and averaging. (Real rise time—as observed in single shot displays—is much faster).

FIG. 3. $I-V$ characteristic curve measured in the pulse mode, 300 ns after application of the “current” pulse. Branches $OA$, $AB$, $BC$, and $CD$, are described in the text. Due to finite circuit resistance, the PSC formation is not strictly controlled on $AB$. The PSC state is present on the $BC$ branch.
tion (CD) of the I–V curve, extrapolating to zero, corresponds to the passage into the normal state. Its threshold current $I_h$ displays a parabolic dependence upon $T/T_c$ (see Fig. 4), at least within about 1 K from $T_c$, in contrast to the superconducting critical current $I_c$ which behaves like $1 - T/T_c$ to the $-1.9$ power. To proceed further, let us recall that, from linear theory of heat transfer, a hot spot forms when the Joule dissipation is twice the power needed to maintain the metal at $T_c$. In our notations:

$$R_K = \frac{1}{A} \left( T - T_0 \right)$$

is the “Kapitza” resistance which relates the power $P$ transferred from an area $A$ at temperature $T$ to an ambient medium at temperature $T_0$. From our experimental value $I_h = 38 \mu A$ at $T_0 = 3.14 \, K$, corresponding to Fig. 3, we deduce $R_K = 0.43 \, cm^2 \, K/W$. Considering this applies to the intermediate temperature $(T_c + T_0)/2$, this result may be cast into the form $R_K$ (tin-polycarbonate) $\approx 5T^{-2} \, cm^2 \, K^3/W$, if we favor a $T^{-2}$ dependence. We note that our result is about twice lower than $R_K$ measured at helium temperatures between a metal and an organic material, namely $R_K$ (Cu-epoxy) $= 11.2 \times 10^{-1.9} \, cm^2 \, K^{2.9}/W$. In other words, tin has a better thermal contact to polycarbonate than Cu to epoxy resin, which fact may be due to the high density of dangling chemical bonds at the interface produced by the process of electrodeposition. In summary, we have monitored in the time domain the nucleation of phase-slip centers in a strictly 1D superconducting structure. From the delay time, and consistently from the extension of the PSC structure, it emerges a single time constant: ($\sim 4 \, ns$).

The authors thank the “Laboratoire des Hauts Polymères” of UCL for providing the polycarbonate membrane samples used in this study and J-C Villégier from CEA-Grenoble for helpful advice. S.M. is a Research Fellow of the National Fund for Scientific Research (FNRS) Belgium. This work has been partly supported by the Belgian Science Policy through the Interuniversity Attraction Pole Program PAI (P5/1/1) and by the “Communauté Française de Belgique” - “Actions de Recherches Concertées.”