Manipulation of phase slips in carbon-nanotube-templated niobium-nitride superconducting nanowires under microwave radiation

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We study the manipulation of thermal/quantum phase slips (tpSs/qPSs) in ultra-thin niobium-nitride superconducting nanowires (scNW) grown on carbon-nanotube templates. These NWs exhibit resistive steps in current–voltage (I–V) characteristics, and the number of phase slip centers (PSCs) in an NW can be tuned by the NW length. Under microwave (MW) radiation, emergence of each single PSC can be precisely controlled by varying the MW power. For thin and short scNW, a dip structure between the qPS-dominated low-temperature region and the tpS-dominated high-temperature region were observed owing to anti-proximity effect by electrodes.

Superconducting nanowires (scNWs)¹,² have been attracting interest in the context of modern nanotechnology because of their superconducting properties unique to one-dimensional system. For quantum-device applications, single-photon detectors⁶–⁹, qubits⁷–¹⁰, and quantum current standards¹¹ are promising devices for quantum computing, cryptography, and metrology. In scNW, the quantum or thermal fluctuations give rise to phase slips (PSs)¹²,¹³. The thermal activation of PSs (tPSs) is dominant at high temperatures¹³,¹⁴, and as the temperature is lowered, quantum PSs (qPSs) take place, which are a type of macroscopic quantum tunneling¹⁵–²⁰. Under microwaves (MWs), moreover, a dynamical resistive state, i.e., PS centers (PSCs), emerges²¹–²³. Manipulation of PSCs with such external perturbations has been recently demonstrated²⁴,²⁵.

Here, we investigate the manipulation of tPS and qPS under MWs in ultra-thin scNW grown on carbon-nanotube (CNT) templates. From the resistive steps due to PSC in current–voltage (I–V) characteristics, we found that the number of PSCs in single NW can be tuned by the NW length. We also found that superconducting and PSC states can be switched by MWs and the emergence of each single PSC can be precisely controlled by varying the MW power. In resistance–temperature (R–T) characteristics, moreover, a clear dip structure between the qPS-dominated low-temperature region and the tPS-dominated high-temperature region can be observed owing to strong anti-proximity effect (APE) for the thin and short scNW.

We fabricated niobium-nitride scNWs (NbN-scNW) based on suspended CNT¹⁷,¹⁹,²⁰,²⁶–²⁹. Figure 1a shows the schematics of our NbN-scNW device. The details of the fabrication are given in Ref.²⁹. In this paper, we employ three scNWs, which we call SscNW, LscNW, and TscNW (short scNW, long scNW, and thin scNW, respectively). We exposed two scNWs to MW radiation, which are SscNW (L = 0.55 μm) and LscNW (L = 3.1 μm) with the width W = 35 nm for both. We also studied thin and short scNW (TscNW) without MW radiation with

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L = 0.75 \mu m \text{ and } W = 26 \text{ nm for a comparative study. Figure 1b, c show SEM images of SscNW and LscNW on suspended CNTs, which lead to the estimation of } L \text{ and } W. \text{ All the samples are wired in a four-probe configuration, and their electrical transport properties are measured in a pumped helium cryostat (see also Supplemental Material text and Supplemental Fig. S1). The MW radiation is shown in Fig. 1a schematically. The MW is fed through a coaxial MW line, which is weakly coupled to the device. Here a comment is in order for our sample quality. As was done in our previous paper, our sample quality was reconfirmed by the transmission electron microscope (TEM) image, which implies the roughness of our scNW is comparable with previous studies (e.g. about few nanometers).}

The temperature dependence of resistance is shown in Fig. 2b. PSs become evident away from the critical-fluctuation regime below \( T_c \). PS causes a finite resistance in superconductors, and the superconducting order parameter becomes zero somewhere along the wire, which leads to a relative PS of \( 2\pi \) at some rate and a voltage drop. According to Little’s model, residual resistance arising from thermally activated PS (tPS) below \( T_c \) is given by the following equation:

\[
R_{\text{tPS}}(T) = R_n \exp \left( -\frac{\Delta F(T)}{k_B T} \right),
\]

where \( \Delta F(T) = 0.83 k_B T_c (R_q/R_n) (L/\xi(0))(1 - T/T_c)^{3/2} \) is the superconducting condensation energy (i.e., the energy barrier for PS), \( R_q = h/4e^2 = 6.45 \text{ k} \Omega \) is the quantum resistance for Cooper pairs, \( \xi(0) \) is the GL coherence length at 0 K, and \( k_B \) is the Boltzmann constant. The broken curve in Fig. 2b shows a fit of this model to the data. The tPS fitting curve is obtained with \( L = 0.55 \mu m, R_n = 7.8 \text{ k} \Omega, \text{ and two fitting parameters, i.e., } T_c = 13 \text{ K and } \xi(0) = 4.7 \text{ nm. This value of } \xi(0) \text{ is consistent with that in previous reports (} \xi(0) \approx 5 \text{ nm). The } T_c \text{ is generally higher than the transition temperature of the 2D film, which is here 11.5 K. Although it is well described by the tPS picture in the temperature range down to approximately 11.5 K, our experimental data deviate from the tPS model at lower temperatures (i.e., below 11.5 K), which should be due to dimensional crossover in thicker scNWs. In a thicker scNW, generally speaking, a crossover can take place from 1D to higher dimensions. Such a dimensional crossover has been observed in several quasi-1D superconductors e.g. Ref.\textsuperscript{33}. Instead of t and/or qPS behavior, in the low-temperature limit of such systems, drop to zero resistance can be observed due to crossover from 1D to higher dimensions. We note that these SscNW and LscNW exhibit no qPS behavior because of thicker scNW in contrast to the thinner scNW in Ref.\textsuperscript{29} and TscNW discussed later. As shown in Fig. 2a, the hysteresis fades out above ~ 11.5 K (the blue broken line), where the thermal vortices are deconfined and heating due to residual resistance/thermal fluctuations is enhanced.}

Figure 2c, d show the \( I-V \) characteristic curves for SscNW and LscNW, respectively. A high bias current induces a set of discrete resistance steps, which should be identified with PSCs due to sample inhomogeneities\textsuperscript{33,34,35}. Moreover, comparing the number of PSCs in SscNW and LscNW, we found that it increases in the longer scNW, indicating that the number of PSCs in one NW can be controlled by the NW length (see Fig. 2c, d). The length...
dependence of the number of PSCs is in reasonable agreement with the theoretical calculation \(^{14}\) by the Skocpol, Beasley, and Tinkham (SBT) model \(^{34,35}\).

We expose the SscNW to MW radiation. A typical \(I-V\) characteristic, \(V(I)\), of our SscNW is shown in Fig. 3a. As shown in Fig. 2a, \(V(I)\) exhibits a hysteretic behavior at low temperatures without MWs, whereas the asymmetry due to hysteresis fades out at high temperatures. Generally, the superconducting state is switched into the normal state at a “switching current” as the current is increased. Then, after becoming the Joule-heated normal state and decreasing the bias current, the state is returned to the SC state again at a “return/retrapping” current. When MWs are applied, the switching current and its stochastic nature are suppressed, the return/retrapping current is basically kept, and the hysteretic behavior fades out. The hysteretic behavior quickly disappears at a certain power, \(P_c\) (\(\sim 3.8\) dBm in Fig. 3a,b). Note that the switching current is basically “stochastic” because of the nucleation of a few or single PS, whereas the return/retrapping current is “deterministic” \(^{23}\). The absence of Shapiro steps implies the absence of phase coherence to synchronize with applied MWs.

As high-power MWs are applied, MW-assisted PSCs take place in the sweeping up current (see Fig. 3b inset and Fig. 3c). At high power, the switching current is reduced and the wire switches into PSC state at a low bias current. Here, Joule heating dissipation in the wire is weak enough not to heat the wire above \(T_c\) in this regime, which leads to the nucleation of PSCs near the switching current, i.e., the emergence of MW-assisted PSCs \(^{21-23}\). In Fig. 3a, we can clearly observe the resistive steps (arrows in Fig. 3a) due to the emergence of the PSCs and can trace them as a function of MW power (see Fig. 3a), which is distinguished from simple heating effects. This indicates that the emergence of every single PSC can be precisely controlled by changing the MW power, which has higher controllability compared with the simple temperature change.
Figure 3. PSC control by MW irradiation in SscNW. (a) Mapping of $dV/dI$ for SscNW as a function of the bias current $I$ and MW power $P$ at the MW frequency $f = 26.57$ GHz and the temperature $T = 1.65$ K. Blue broken lines indicate MW powers of $P = -4.0, -3.8$ dBm used in (b). Arrows indicate the resistive steps due to the emergence of PSCs. (b) $I-V$ characteristics for SscNW at $P = -4.0, -3.8$ dBm (i.e., just below and above $P_c$) indicated by blue broken lines in (a). Inset: a close-up of the $I-V$ characteristics. (c) $I-V$ characteristics as above for SscNW at $T = 1.65$ K and $P = -3.0, 0, 3.0, 6.0, 8.0$ dBm indicated by white broken lines for (a). Dashed arrows correspond to the movement of $I_c$ in (d). (d) “Critical” current $I_c$ curves, which are the voltage steps in (a) due to the emergence of PSC. Phenomenologically, $I_c$ curves are assumed to be $I_c(P) = I_0 - AP$, where $I_0$ is the critical current without applied MWs and $A$ is the coefficient.

Figure 3d shows a “critical” current $I_c$ at which the resistive steps occur because of the emergence of PSCs. Phenomenologically, $I_c$ is assumed to be following equation:

$$I_c(P) = I_0 - AP,$$

where $P$ is the MW power, $I_0$ is the critical current without applied MWs, and $A$ is an adjustable parameter. The solid lines in Fig. 3d show a fit of this formula to the experimental data. Since $I_c(P)$ is proportional to the MW power, it is found that these are correlated to heating by MW irradiation.

We exposed the LscNW to MW radiation. A typical $I-V$ characteristic, $V(I)$, of our LscNW is shown in Fig. 4a, which is basically the same as for the SscNW in the above section except many resistive steps due to many PSCs in a long scNW. In this LscNW, moreover, it is to be noted that “excess voltage” is observed (Fig. 4b)36–38. Near the PSC, the (Bogoliubov) quasiparticle diffuses the distance $\Lambda_0$ away from the PSC. Such an excess voltage has only been observed when the distance between voltage probes is narrow within the quasiparticle diffusion length $\Lambda_0$37. This is not the case in our study, as discussed next, and further theoretical study is needed. The frequency dependence of $R_{PSC}$ is shown in Fig. 4c, where $R_{PSC}$ is the differential resistance of the PSC slightly above $P_c$, as defined in Ref.23. In the SBT model of the PSC34,35, $R_{PSC}/R_n = 2 \Lambda_0/L$, where $L$ is the length of scNW and $\Lambda_0$ is quasiparticle diffusion length. As high-frequency MWs are applied, $\Lambda_0$ becomes longer, which is consistent with the previous study23 and gives the value of $\Lambda_0 = 60–120$ nm for the LscNW ($L = 3.1 \mu$m). In Ref.23, on the other hand, there has been a proposal that a naïve SBT model does not apply in this setting as commented above.

Now we focus on thinner and short scNW (TscNW). Figure 5a,b show SEM images of TscNW ($L = 0.75$ μm and $W = 26$ nm) and the superconducting film used for a reference, respectively. In this thinner device, PSs become evident away from the critical-fluctuation regime below $T_c$. Even though thermally activated PS (tPS) dominates near $T_c$, qPS should play a role at lower temperatures (Fig. 5). These tPS and qPS lead to different temperature dependences. To explain this behavior, we applied the Golubev–Zaikin model15–19,29, which describes the qPS contribution to the residual resistance in scNW:

$$R_{qPS}(T) = B R_q S_{qPS} \frac{L}{\xi(T)} \exp\left(-S_{qPS}\right)$$

$$S_{qPS} = \frac{R_q}{R_n} \frac{L}{\xi(T)},$$
where \( \xi(T) = 0.907\xi(0)(1 + (1 - 0.25t)\xi(0)/t)^{-1/2}(1 - t^2)^{-1/2} \), with \( t = T/T_c \), and \( B \) and \( C \) are adjustable parameters. The blue curve in Fig. 5 represents the fit of (3) with \( L = 0.9 \mu m \), \( R_n = 7.2 k\Omega \), \( T_c = 11 K \), and \( \xi(0) = 3.7 \text{ nm} \) and the two adjustable parameters with values of \( B = 0.0019 \) and \( C = 0.014 \). Here we note that the two adjustable parameters are smaller than a naïve expectation, which is comparable with the result in Ref.5. The red and green curves denote the tPS \( R_{PS} \) and total resistance \( R_{tot} \), respectively19. Note that the slight bump/dip structure in the \( R-T \) curve near 8 K is caused by the change in resistance because of the superconducting transition in the film/electrode, which should be because of a shorter sample than that in Ref.29. As discussed in Ref.29, the APE should also play a role here29,39–42. At ~ 8 K, the film, i.e., the electrode, undergoes a phase transition to the superconducting phase where dissipation in the electrode environment is suppressed (Fig. 5b and the black dotted curve in Fig. 5c). The dissipation in this environment, which is coupled to phase slip events, causes the (de)localization of quantum vortices via the Caldeira–Leggett mechanism and APE43.

In the above, our discussion is based on the ‘phase-slip’ scenario. Here let us comment on another scenario ‘hot-spot’ scenario. The principle of superconducting single photon detectors is conventionally based on the hot spot and phase slips become unstable in such regime44,45. In previous study on NbN scNW as in our devices, on the other hand, such regime does not take place and phase slips were still stable there. Therefore, as discussed above, consistent picture is given by the ‘phase-slip’ scenario for our devices.

Figure 4. PSC control by MW irradiation in LscNW. (a) Mapping of \( dV/dI \) for LscNW as a function of the bias current \( I \) and MW power \( P \) at \( f = 26.57 \text{ GHz} \) and \( T = 1.65 K \). The blue broken line indicates MW power of \( P = 2.2 \text{ dBm} \) used in (b). (b) I–V characteristics for LscNW at \( P = 2.2 \text{ dBm} \) indicated by the blue broken line in (a). Open arrows show excess voltages. (c) Frequency dependence of \( R_{PSC} \) (differential resistance of the PSC slightly above \( P_c \), as defined in Ref.29).
In conclusion, we have studied the superconducting properties of ultrathin nanowires on suspended CNTs. We revealed for the first time the emergence/manipulation of PSs in CNT-templated NbN-scNWs under MW radiation. Dynamical resistive states, i.e., PS centers, are observed via the application of MWs.

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**Author contributions**

K.K, T.T., S.M., H.M. did experiments. K.K., T.T., S.M., H.M. mainly wrote the main manuscript text. K.K, T.T., S.M., H.M. prepared figures. All authors reviewed the manuscript.

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**Competing interests**

The authors declare no competing interests.

**Additional information**

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