Supporting Information

Anomalous Negative Resistance Phenomena in Twisted Superconducting Nanowire Yarns

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Twisted NbN-CNT yarn samples showing negative resistance

Table S1. Details of the CNT-templated NbN nanowire yarn samples that exhibited negative resistances in the measurements.

Sample ID	CNT layers [N_{SHEET}]	Nominal NbN thickness (nm) [t_{NbN}]	Superconducting transition temperature (K)		Fitting parameter (K)	
			$R_{90\%}$ (Onset)	$R_{10\%}$ (Offset)	R_C	R_{NbN}
#1	10	200	10.87	9.56	8.2	11.9
#2	10	300	12.78	12.12	11.7	12.6
#3	10	300	12.85	11.92	10.7	12.5
#4	20	200	11.96	8.88	-	-

Definition of the superconducting transition temperature

The onset and offset temperatures of the superconducting transition in CNT-templated NbN nanowire yarns listed in Table S1 are defined as in Figure S1. The onset (offset) temperature corresponds to 90% (10%) of the normal state resistance immediately before the superconducting transition.

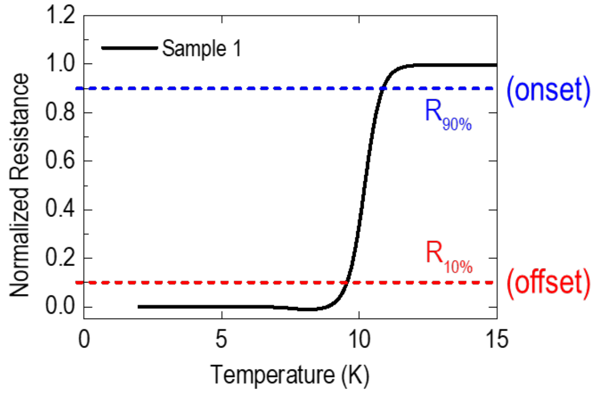

Figure S1. Definition of the onset and offset superconducting transition temperatures of a CNT-templated NbN-nanowire yarn.

Critical temperatures for various NbN-CNT yarn samples with different conditions

The superconducting properties of twisted NbN-CNT yarns were investigated under various conditions. The superconducting transitions and critical currents were studied as a function of temperature. All samples exhibited an abrupt decrease in resistance during the superconducting transition, which is similar to the results shown in Figure 2a (in the main text). The transition temperatures varied according to the nominal NbN deposition thickness (t_{NbN}) and the number of CNT sheets (N_{SHEET}).

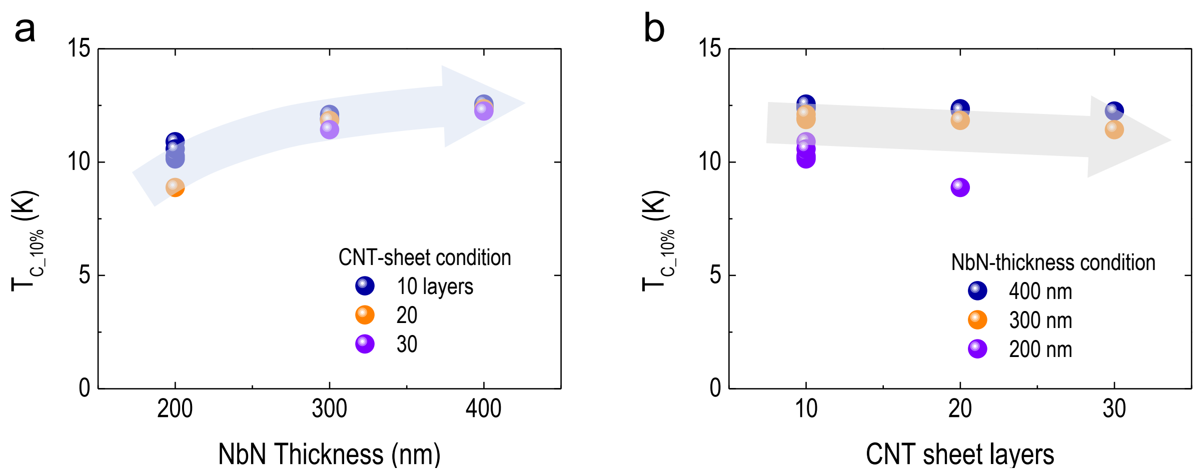

Figure S2. Superconducting transition temperatures of twisted NbN-CNT yarns for different numbers of CNT sheets and nominal NbN thicknesses.

Raw data and fitting results for the twisted NbN-CNT yarn shown in Figure 5c

The raw data and fitting results for sample #1 shown in Table S1 and Figure 5c (in the main text) are presented in Figure S3.

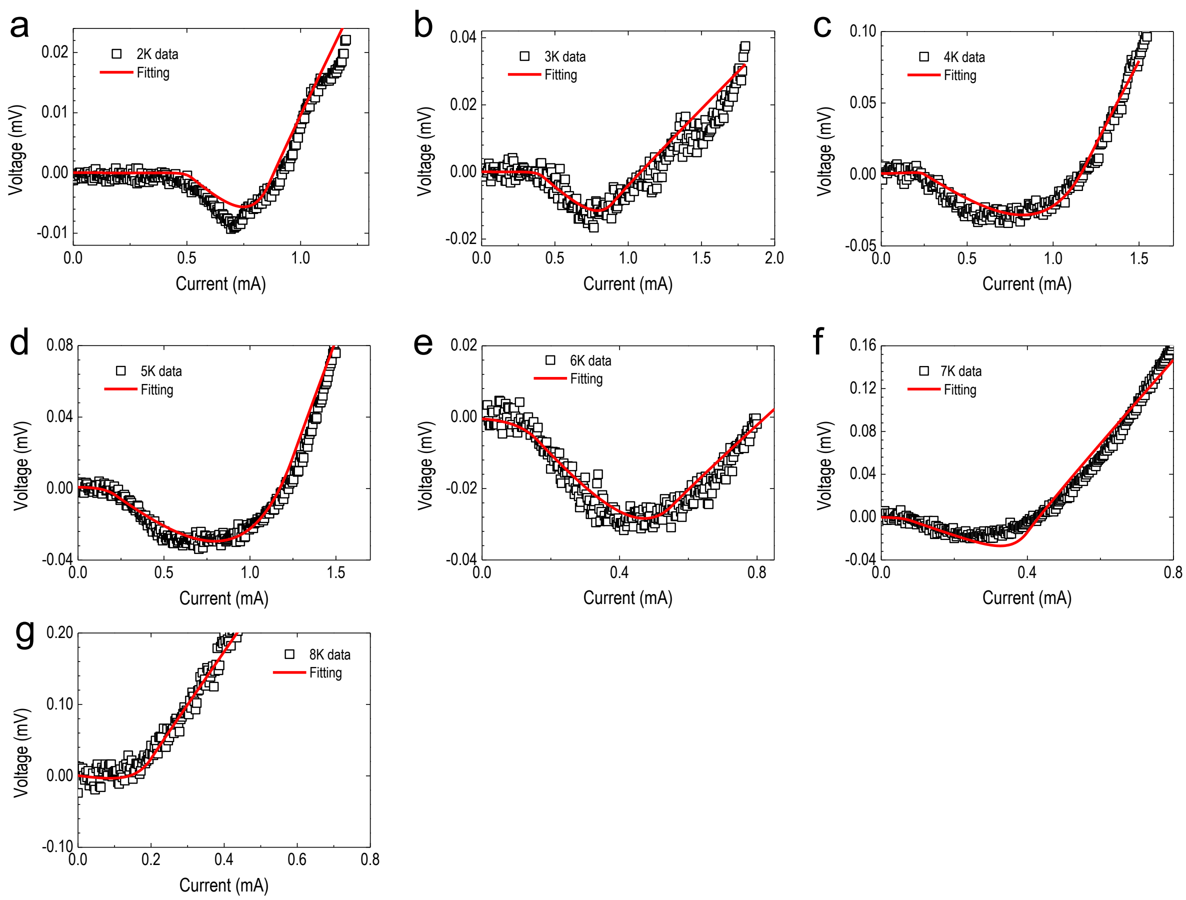

Figure S3. Raw data and fitting results for the data points plotted in Figure 5c (in the main text).

Raw data for other twisted NbN-CNT yarns that exhibited a negative resistance

The raw data and fitting results for samples #2 and #3, as well as the raw data for the non-superconducting sample in Table S1, are presented in Figure S4.

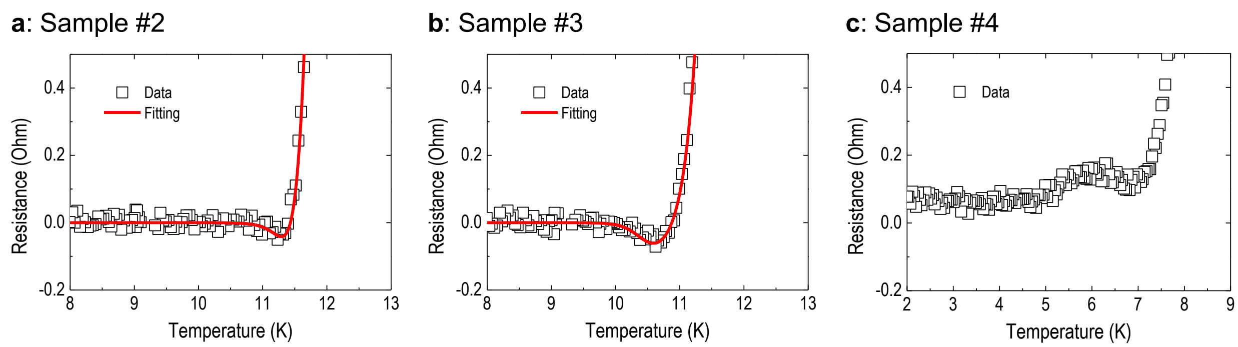

Figure S4. Raw data of the temperature-dependent resistance for the samples that exhibited a negative resistance (samples #2, #3, and #4 in Table S1).

Absolute resistance values at 14 K for all samples in Figure 3

Table S2. Absolute resistance values at 14 K for all samples in Figure 3

Nominal NbN thickness (nm) [t_{NbN}]	200	200	200	400	400	400
CNT layers [N_{SHEET}]	10	20	30	10	20	30
Absolute resistance value at 14 K (Ohm)	69.3	46.3	51.4	55.9	34.9	27.0

The condition of samples showing negative resistance

The analysis of the superconducting transition characteristics of twisted NbN-CNT yarns fabricated at various conditions revealed that they could be mainly classified into four groups of sample preparation condition, as illustrated in Figure S5.

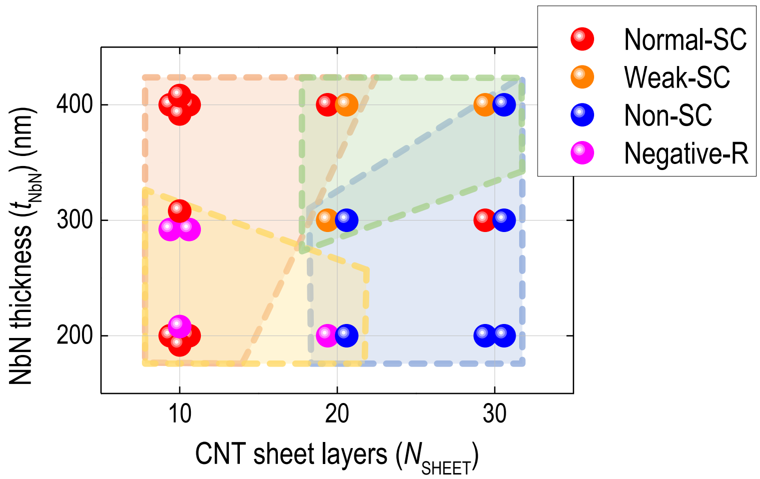

Figure S5. Classification of the superconducting transition behaviors of twisted NbN-CNT yarns fabricated with various NbN thicknesses and numbers of CNT sheet layers.

The first group (denoted as "Normal-SC") exhibited normal superconductor behavior with regard to the resistance–temperature and current–voltage dependences at $T < T_C$, with moderate critical current densities. The second group (denoted as "Weak-SC") exhibited conventional resistance–temperature curves; however, the critical currents of the yarns were too low to sustain the superconducting state during the flow of electrical current. This might have originated from the weak connection of the superconducting states among the NbN-CNT superconducting fibrils. The third group exhibited a superconducting transition corresponding to an abrupt decrease in the resistance; however, the yarns did not reach the zero-resistance state (denoted as "Non-SC"). The fourth group corresponds to the main topic of this study, *i.e.*, the instantaneous absolute negative resistance phenomenon in the vicinity of the superconducting state transition region in the resistance–temperature and current–voltage curves (denoted as "Negative-R"). During the twist-insertion fabrication process of the NbN-deposited CNT sheets, a large number of fractures in the twisted superconducting yarn sample were inevitably formed, leading to various superconducting transition behaviors.

Existence of negative resistance even at very low temperatures

For the sample having the condition of N_{SHEET} = 10 and t_{NbN} = 200 nm, which is presented in Figure 2, the resistance values estimated from the current-voltage characteristics in Figure 2c are plotted in Figure S6 as a function of temperature at different driving currents higher than 100 μA.

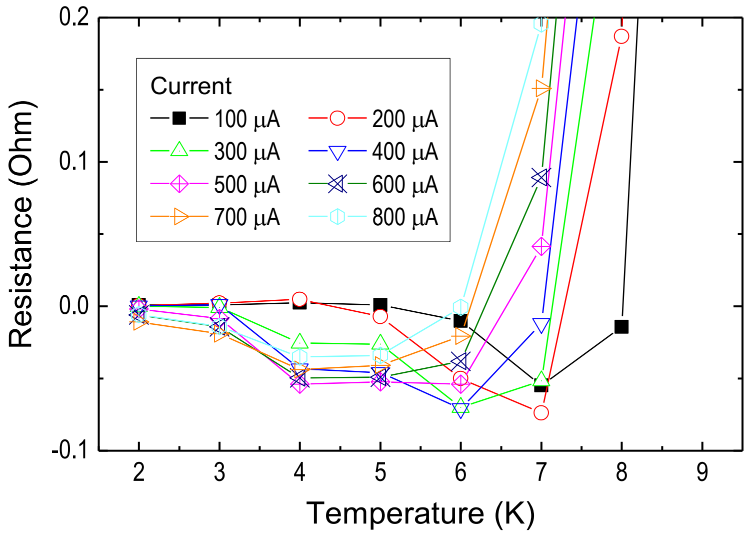

Figure S6. Plot of resistance values as a function of temperature at different driving currents, extracted from the current-voltage characteristics in Figure 2c and Figure 3a. The sample condition is N_{SHEET} = 10 and t_{NbN} = 200 nm.

When we compare the graphs in Figure 2b and Figure S6, the low driving current roughly below 200 μA gives the zero-resistance state at low temperature below 4 K, but the high driving current above 500 μA does not give the zero-resistance and the negative resistance state continues even at 2 K. This originates from the feature of weak superconductivity among NbN nanowires, which is easily broken at high currents. In other words, if the R_C component does not go to proximity superconducting state, the overall resistance values stay negative.

Application of the network analysis model to the other four-probe resistance measurement cases showing negative resistance without concerning superconductivity

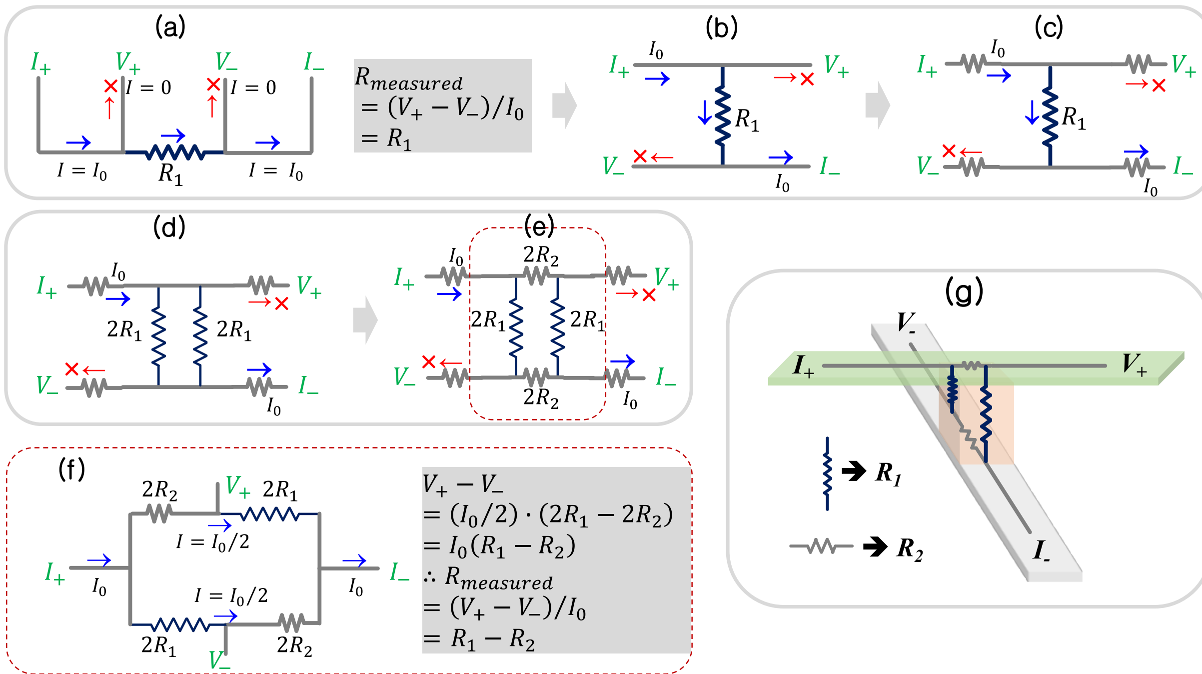

Figure S7. Analysis on the crossed-wire-type four-probe resistance measurement configuration.

The methodology used in this work to explain the negative resistance phenomena can be applicable to the other cases reporting the negative resistance in the four-probe measurement which has nothing to do with superconductivity. Especially in the case of crossed-wire-type four-probe measurement configuration, there are three reports (listed at the end of this document) observing the negative resistance phenomena. Figure S7 shows the possible origin of negative resistance in such cases on the basis of the suggested methodology. Figure S7(a) shows the general definition of four-probe resistance measurement method, where there is no current flow through the voltage probes due to the infinite impedance of the voltmeter. The concept of crossed-wire-type four-probe measurement configuration is developed as in Figure S7(b), which is topologically identical to the case in Figure S7(a). Although there can be a resistance component in the wire as in Figure S7(c), those resistance components do not contribute to the final four-probe resistance value (here, denoted as R_1) because the current passing through the sample does not change due to the resistance components of the wire and no additional voltage drop occurs on the voltage leads because of no current flow through V_+ and V_- probes. Here, it is worthy to note that the sample (having the resistance value of R_1) is assumed to have one-dimensional feature.

If we go further in detail to the real situation, it becomes a little complicated. Because the sample is not truly one-dimensional, the contact area between the electrical lead and the sample can have some finite size(, which is exactly same as the case of crossed-wire-type four-probe measurement configuration in the References S1-S3 listed at the end of this document). In the first approximation, they can be modeled as two resistances connected in parallel as in Figure S7(d). Up to this point, the measured resistance does not change. However, if we further consider the resistance along the electrical leads between those two resistances as in Figure S7(e), it can be analyzed on the basis of the circuit model in Figure S7(f). And it clearly shows that the measured resistance will be equal to R_1–R_2, where R_2 corresponds to the resistance component along the electrical leads in the portion marked with the red dashed line in Figure S7(e). In most cases, the resistance of the electrical leads (R_2) is very small in comparison with the sample resistance (R_1), so that R_2 is negligible. But it can be negative when the wire resistance (R_2) is comparable to or larger than the value of sample (R_1). Figure S7(g) depicts the shape of the sample having the crossed-wire structure conceptually, and it is similar to the cases of the References S1-S3 telling the observation of negative or erroneous resistance. Here, the resistance components of R_1 and R_2 have nothing to do with superconductivity.

References

S1. Pomeroy, J. M.; Grube, H., "Negative Resistance" Errors in Four-Point Measurements of Tunnel Junctions and Other Crossed-Wire Devices. *J. Appl. Phys.* **2009**, *105*, 094503.

S2. Wang, S.; Chung, D. D. L., Apparent Negative Electrical Resistance in Carbon Fiber Composites. *Compos. B. Eng.* **1999**, *30*, 579-590.

S3. Pedersen, R. J.; Vernon, F. L., Effect of Film Resistance on Low-Impedance Tunneling Measurements. *Appl. Phys. Lett.* **1967**, *10*, 29-31.