Quantum phase slip and enhancement of superconductivity by magnetic field in NbN nanowires

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Abstract. Transport properties were investigated for quasi-one dimensional superconducting NbN nanowires with width \( w = 20\) nm and thickness \( d = 20\) nm on 3C-SiC substrate. It has been found that 1) the resistance \( R \) shows the broad superconducting transition and the \( R(T) \) characteristic at temperatures below \( T_c \approx 13.6\) K can be well explained by the sum of the thermal activated phase slip and the quantum phase slip (QPS) of the superconducting order parameter. 2) The \( R(T) \) due to the QPS contribution is suppressed to enhance the superconductivity by the external magnetic field \( H \). With decreasing temperature, the \( R(T) \) of short specimen with length 600nm shows nearly zero resistance in the restricted temperature region depending on the magnitude of \( H \) and recovers the QPS resistive state. 3) The critical magnetic field \( H_{c2}(T) \) is fit to the theoretical expression

\[
H_{c2,\text{theo}}(T) = \frac{\phi_0}{4\pi} \frac{\xi_{GL}(T) \times w}{2} \approx (1 - T/T_c)^{1/2},
\]

where the \( \xi_{GL}(T) \) is the Ginzburg-Landau superconducting coherence length. Although the relation

\[
H_{c2,\text{exp}}(T) \propto (1 - T/T_c)^{1/2}
\]

is satisfied, the magnitude of \( H_{c2,\text{exp}}(T) \) is about 5 times larger than that of the theoretical one.

1. Introduction

Recently, one-dimensional (1D) superconducting nanowires (SNWs) are being considered to develop superconducting computing devices.[1] SNW’s can be strongly affected by thermally activated phase slip (TAPS) and/or quantum phase slips (QPS)[2,3] which play an important role in the transport properties of SNW’s. The effect of TAPS to resistance \( R(\Omega) \) sharply decays as a result of the temperature drop below \( T_c \). On the other hand, the QPS represents the residual resistance to suppress the superconductivity at low temperatures even at \( T \approx 0 \). Although numerous studies have been conducted on SNWs, some investigations show no evidence of QPS behavior at very low temperatures.[4] On the other hand, there still are fundamental problems in the effect of external magnetic field on the temperature dependence of resistance \( R(T) \) due to the TAPS and QPS on SNW specimens. Many investigation have reported the interesting field dependence of \( R(T,H) \). [5-7] The
typical behavior is the negative magneto-resistance (NMR) observed at relatively small magnetic fields. Further, recent work reports the magnetic field-enhanced superconductivity due to large NMR.[6] One of reasons for NMR is the presence of the magnetic impurity. Another mechanism is based on the suppression of the non-equilibrium charge imbalance process at normal and superconducting boundaries, namely, at the boundaries between phase-slipped and superconducting regions in SNWs. Although the exact mechanism is not sufficiently understood yet, it is reasonable to consider that the one of the reason for NMR concerns with the existence of phase slip centers originating the behaviors of TAPS and/or QPS.

In order to clarify the effect of the phase slips to the MR in SNWs, specimens are required to be homogeneous and satisfy the condition \( d, w \leq \xi \) to avoid residual resistance due to inhomogeneities at low temperatures, where \( d, w \) and \( \xi \) are thickness, width of the specimen and superconducting coherence length, respectively. In the present work, we investigated mainly the effect of the magnetic field on the SNW specimens prepared from the NbN thin films on the 3C-SiC substrate. We observed large NMR to show the field-induced superconductivity.

2. Experimental Procedure

Superconducting NbN films were firstly prepared by deposition at ambient temperatures on (200)-3C-SiC substrates having small lattice mismatches comparing with MgO substrate. Details of the deposition procedures are previously reported. [3] The NbN SNWs were fabricated from 2D films with \( d = 20 \) nm by a conventional e-beam lithography method and a reactive ion etching method with CF\(_4\) plasma. We prepared two specimens with the same width \( w = 20 \) nm but different length \( L \) between voltage terminals. We measure transport properties by four-probe method with applying a constant current 10nA for all measurements.

3. Experimental results and discussion

Prior to showing the present data of NbN SNWs on 3C-SiC substrate, Fig.1 (a) shows the \( R(T) \) of NbTiN SNW which has similar characteristics to those of NbN on the conventional MgO. The shape of this NbTiN-SNWT has \( L=500 \) nm and \( w=200 \) nm which are almost the same sizes of the present NbN NWs. Although the anomalous negative magneto resistance (NMR), that is, \( \Delta R=R(H)-R(0)<0 \) typically appears in the low resistive region, \( R(T) \) characteristic at high resistive region, for instance, at \( R=R^c/2 \) shown by arrow, monotonically shifts to low temperatures with increasing of the magnetic field except for low fields. Here the \( R^c \) is the normal state resistance determined at higher temperatures where the resistance is independent of magnetic field. When the transition temperature \( T^c(H) \) is estimated as a temperature where \( R(Tc)=R^c/2 \) is satisfied, the upper critical magnetic field \( H_{c2} \) changes about 4T in a temperature range from 7K to 3.5K. On the other hand, the \( R(T) \) of NbN on3C-SiC shows quite strange characteristics.

Figures 1 (b) and (c) show \( R(T) \) characteristics of NbN NW on the 3C-SiC substrate with (b) \( T_c=12.7 \) K, \( R^c=15 \) k\( \Omega \)and \( L=900 \) nm and (c)\( T_c=13.6 \) K, \( R^c=10 \) k\( \Omega \) and \( L = 600 \) nm, respectively. The arrows corresponding to \( R=R^c/2 \) are also shown as well as in Fig. 2(a). Comparing the \( R(T) \) of (b) and (c) to that of (a) at high resistive regions, it is clear that both SNW have a strong superconducting characteristic against the magnetic field. The large enhancement of \( \Delta H_{c2} = 9 \) T for SNW with \( L=900 \) nm even in a small temperature range between \~12.2 \) K and \~12.7 \) K. As for another difference between SNW* on 3C-SiC and MgO substrates, it is found that the SNW’s on 3C-SiC in the magnetic field show the V-shape \( R(T) \) at the low resistive region, namely, the large NMR appears and then disappears with decrease of the temperature. In NbN NW with \( L=900 \) nm, the V-shape NMR is clearly found and the value of the non-zero minimum resistance increases with increase of the magnetic field. For shorter SNW with \( L=600 \) nm, as shown in Fig.1(c), the minimum resistance due NMR seems to be nearly zero in the error range of the voltage measurements.
Figure 2 shows the details of $R(T)$ characteristics in the low resistive region below 50 $\Omega$ for the SNW with $L=600$nm at various magnetic fields. The solid lines corresponding to each magnetic field above $H=5$ T show the results smoothly connected to data points to clear the characteristics. The resistances $R(T)$ clearly take zero values in the restricted temperature region depending on the magnitude of the external magnetic field. Here it is emphasized that the zero resistive state under any magnetic field $H>9$ T in this measurement recovers to the non-zero resistive state denoted by the QPS at $H=0$ with decreasing the temperature. This re-entrance characteristic suggests the field-induced superconductivity.

In order to clear the effect of the magnetic field on the TAPS and QPS controlling the $R(T)$ characteristics below $T_c$, Figure 3 shows $R(T)$ at $H=0$ (●) and at $H=6$ T (□) as a typical high field. Theoretically, $R_{\text{TAPS}}(T)$ is given as follows, \cite{2}

$$R_{\text{TAPS}} = \frac{\phi_0}{(k_B T / \phi_0)} \exp[-\Delta F / k_B T], \hspace{1cm} (1)$$

where the magnetic barrier $\Delta F$, associated attempt frequency $\Omega$ and GL relaxation time $\tau_{\text{GL}}$ are given by

$$\Delta F = \sqrt{2\alpha H} \xi_{\text{GL}}(T) / 3 \pi, \Omega = \frac{(L/2 \pi \xi_{\text{GL}}(T) \tau_{\text{GL}})^2}{(3 \pi \Delta F / k_B T)^{1/2}} \text{ and } \tau_{\text{GL}} = \frac{\hbar}{16 k_B (T_c - T)},$$

respectively. The GL coherence length $\xi_{\text{GL}}(T)$ is given by $\xi_{\text{GL}}(T) = (0)(1 - T / T_c)^{-1/2}$. On the other hand, the $R_{\text{QPS}}(T)$ at $H=0$ is given by

$$R_{\text{QPS}} = \frac{h}{4e^2} \frac{h \Omega}{(h / \alpha \tau_{\text{GL}})} \exp[-\Delta F / (h / \alpha \tau_{\text{GL}})]. \hspace{1cm} (2)$$

The dotted and solid lines are calculated from eq.(1) and eq.(2), respectively. The coherence length $\xi_{\text{GL}}(0)=6.3$nm in eq.(1) was determined from the $H_{c2}(T)$ characteristic of the 2D film almost the same thickness and $T_c$ as those of this SNW $L=600$nm. The parameter $\alpha$ in eq.(2) was determined to be $\alpha =0.001$ from well fitting of eq.(2) experimental data $R(T)$ at $H=0$T. This value of $\alpha$ is reasonable to compared that in previous work. The $R(T)$ at high magnetic field seems to be expressed only by the TAPS model. Present analyses suggest that the fields suppress the resistance due to QPS but not due to the TAPS. Even if the resistance due to TAPS does not be suppressed, almost the zero resistive state shown in Fig.3 can be understood because the resistance due to drastically decreases with decreasing of temperature. However, at the present stage, we have no explanation for the reason of the re-entrance to the QPS resistive state at low temperatures.

For 1D superconductors at temperatures near $T_c$ with both magnitudes of width $w$ and thickness $d$ smaller than $\xi_{\text{GL}}$, temperature dependence of $H_{c2}(T) \propto (1-T/T_c)^{1/2}$ is obtained from GL equation. In the
present thin film, we obtained a steep relation of $H_{c2}(T)\sim 47(1-T/T_c)^{1/2} [T]$ as recognized in Figs. 1(b) and 1(c). Although this relation $H_{c2}(T)$ obtained experimentally is not satisfied until absolute zero, there is a possibility that it exceeds the Pauli limit $H_p(0)=1.86 \times T_c[T]$~25T.[8] On the other hand, we can get a relation $H_{c2}(T)=\varphi_0/[2\pi\xi(T)w] \sim 8.2 (1-T/T_c)^{1/2} [T]$ with use $\xi(T) = 6.3(1-T/T_c)^{-1/2}$ above mentioned. Experimental data are about 5 times as large as theoretical ones estimated from above relation. Taking account for the above relation $\xi(T)$ for the present SNW, in the experimental temperature range of $H_{c2}(T)$, namely, 13 K<T<13.6K, the ratio $\xi/w$ is expected to exceeds ~2 and reach to ~200. Further understanding the reason for the extremely large $H_{c2}$, it is necessary to investigate the flux distribution in SNW near $T_c$.

4. Conclusions

For the NbN SNW’s prepared on the 3C-SiC substrates, we observed the broad superconducting transition. The $R(T)$ characteristics in the absence of the magnetic field $H$ can be well explained by the quantum phase slip model. Under the large magnetic field, however, $R(T)$ drastically decreases with decreasing the temperature. This $R(T)$ characteristic suppressed to nearly zero resistance can be well explained by the thermal activated phase slip model. This behavior indicates the occurrence of the field induced superconductivity in the present SNW. As for the upper critical magnetic $H_{c2}(T)$, Experimental data experimental results are about 5 times as large as that estimated from GL relations with use of the suitable value of the diffusion constant D. This fact suggests that there is a possibility of exceeding the Pauli limit $H_p(0)$.

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