Superconducting NbN Nanowire Photo Switches for Generating Single Flux Quantum Pulses

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Abstract. We investigated superconducting NbN nanowire as a photo switch for generating single flux quantum (SFQ) pulses. Epitaxially grown NbN thin films were prepared on MgO(100) substrates by a dc magnetron sputtering method using gas mixture of Ar + N₂, without substrate heating. NbN thin films showed Tc of 13.6 K for 8 nm, and 10 K for 4 nm. NbN nanowires were patterned using an electron beam lithography with 200 nm thick electron beam resist. To increasing photo-sensitive regions, we fabricated 50 x 50 µm² meander patterns with NbN nanowires. Line width of nanowires was varied from 150 nm to 500 nm. Critical current density of NbN nanowires was varied from 150 nm to 500 nm. Critical current density of NbN nanowires was about 3x10⁶ A/cm² at 4.2 K. We irradiated 850-nm laser pulses via 50-µm multi-mode optical fibers. Repetition frequency and pulse width could be controlled by a pulse pattern generator. The maximum laser pulse power was about 1 mW. Using 150-nm-wide NbN nanowires, half of critical current was suppressed by 1 mW CW laser irradiations. High speed responses were observed for laser pulses with repetition frequency of 1 MHz and pulse width of 2 ns. Besides the NbN nanowire photo switches, we designed an SFQ interface circuit based on Josephson transmission lines. The designed circuit could generate SFQ pulses by input current of 10 µA, 25 GHz current pulses. Dc bias margin of the circuit was ±15% for 60 µA current pulses.

1. Introduction
Single flux quantum (SFQ) logic circuits show ultra fast operating speed and very low energy consumption, would be used for high-end microprocessors[1] and high throughput digital data switches[2] in the near future. To realize those applications using the SFQ logic circuits, high-throughput data transfer between room and cryogenic temperature would be indispensable. For wide-band communications between room temperature and cryogenic temperature, optical communication using optical fibers would be one possible solution because of low thermal conductivity of glass fibers.

Superconducting single photon detectors (SSPDs) have been investigated for fiber-based quantum communication systems and expected to have counting rate exceed to 10 GHz[3]. Combination of the SFQ systems and the fiber-based SSPD would be high-throughput input interface between room and cryogenic temperature.

In this study, we fabricated NbN nanowires as photo switches and examined high frequency performance of NbN nanowire photo switches. We designed SFQ interface circuits generating SFQ pulses using switching current from NbN nanowire photo switches.
2. NbN nanowire photo switches

2.1. NbN thin film

Epitaxially grown NbN thin films were prepared on MgO(100) substrates by reactive dc magnetron sputtering of a 4-inch-diam Nb target (99.95% purity) in a mixture of Ar and N2. Typical sputtering conditions are listed in Table 1. An arc control unit was used to stabilize the discharge state. The unit reversed the applied dc voltage for 5 µs at 30 kHz. A substrate holder was floated from the ground to promote the stimulation of surface diffusion by substrate self-bias[4]. The measured floating substrate self bias was around -40 V.

After film deposition, we examined the orientation of the films using an X-ray diffraction (XRD) method and the in-plane orientation by reflection high-energy electron diffraction (RHEED). Resistivity-temperature curves were measured with a conventional four-probe method. Temperature was determined using a Si diode sensor.

Figure 1 shows an RHEED pattern of an epitaxially grown NbN thin film on an MgO(100) substrate. The pattern is streaky and clearly shows epitaxial growth of the NbN thin film with a smooth surface. Figures 2 show (a) critical temperatures $T_c$ as a function of N2 flow ratio and (b) critical temperatures $T_c$ as a function of NbN film thickness, prepared at 0.80 Pa with N2 flow ratio of 3 %.

Maximum critical temperature $T_c$ of 13.6 K was obtained at N2 flow ratio of 3 %, as shown in Fig. 2(a). Lower sputtering gas pressures resulted higher deposition rate and higher critical temperature. Critical temperatures $T_c$s were decreased with decreasing NbN film thickness below film thickness of 8 nm and were constant at NbN film thickness thicker than 8 nm, as

| Table 1. Sputtering Conditions for NbN Films. |
|---------------------------------------------|
| Base pressure 2$\times$10$^{-5}$ Pa |
| Sputtering gas Ar(99.999%) N$_2$(99.9999%) |
| Ar flow rate 80 SCCM |
| N$_2$ flow rate 1.2~5.1 SCCM |
| Gas pressure 0.80~0.93 Pa |
| Target-substrate distance 8 cm |
| Dc power 360 W |
| Power density 4.59 W/cm$^2$ |
| Substrate Temp. ambient temperature |
| Dep. rate 20~40 nm/min |
| Thickness 2~20 nm |

**Figure 1.** RHEED image of Epitaxially grown NbN on MgO(100).
Figure 2. Critical temperatures $T_c$ (a) as a function of $N_2$ flow ratio and (b) as a function of NbN film thickness, prepared at 0.80 Pa with $N_2$ flow ratio of 3%.

shown in Fig. 2(b). Epitaxially grown NbN film with a thickness of 4 nm still has a critical temperature of about 10 K. In this study, we used 4 nm-thick and 8 nm-thick NbN thin films for fabricating NbN nanowires.

2.2. NbN nanowires

Measured devices including NbN nanowires were fabricated by electron beam (EB) lithography, conventional photolithography, reactive ion etching (RIE) method and lift-off method. Before fabricating NbN nanowires, Nb contact pads for Al bonding wires and markers for the EB lithography were fabricated using Nb thin films by the lift-off method. Using Nb markers, positions of nanowires were determined. For EB lithography, we used a positive-type EB resist (ZEP520, Nihon Zeon Co. Ltd.) with about 200 nm thickness. Electron beam with 30 kV, 20∼50 pA was used for EB lithography. Typical dose density was 40∼60 $\mu$C/cm$^2$. Through the EB resist mask, NbN nanowires were patterned by RIE using 40 Pa CF$_4$ gas with rf power of 200 W. Finally whole device structures were patterned by the photolithography and the RIE method.

Figure 3 shows (a) an SEM image of 200-nm wide nanowire and (b) critical current of the
IV-curves of 200-nm-wide NbN nanowire (a) without and (b) with VCSEL laser irradiation. To remove hysteresis, the nanowire was shunted by a 40 Ω resistor.

Figure 4. IV-curves of 200-nm-wide NbN nanowire (a) without and (b) with VCSEL laser irradiation. To remove hysteresis, the nanowire was shunted by a 40 Ω resistor.

Figure 5. Suppression ratio of critical current with VCSEL laser irradiation, as a function of the nanowire width. Solid line is guide for eyes.

Figure 6. High-speed optical response of 200-nm-wide NbN nanowire for 190-ns-wide VCSEL pulsed laser irradiation with repetition frequency of 100 kHz.

NbN nanowires at 4.2 K, as a function of the line width of the nanowires. Using our fabrication process, NbN nanowires with line width wider than 100 nm had finite critical currents and critical currents were linearly dependent on the line width and the thickness of the nanowires.

2.3. Photo response of NbN nanowires

Using a 850-nm VCSEL and a multi-mode optical fiber with core diameter of 50 μm, we examined optical response of the NbN nanowire. Maximum output power was 1 mW and laser power could be modulated by a pulse-pattern generator. Using an XY stage, optical fiber was fixed on the nanowires. Typical distance between the nanowires and the optical fiber was less than 500 μm.

Figure 4 shows IV-curves of 8-nm-thick and 200-nm-wide NbN nanowire (a) without and (b) with VCSEL laser irradiation. To remove hysteresis, the nanowire was shunted by a 40 Ω resistor. Critical current of the nanowire was suppressed by VCSEL laser irradiation.

Figure 5 shows suppression ratio of the critical current with VCSEL laser irradiation, as a function of the nanowire width. The suppression ratio of the critical current was increased with decreasing the nanowire width. From the NbN film thickness dependence, the suppression ratio seemed to be not dependent on the film thickness in this thickness region. From above results, we need to optimize our fabrication process to get more narrow nanowires.

Figure 5. Suppression ratio of critical current with VCSEL laser irradiation, as a function of the nanowire width. Solid line is guide for eyes.
Figure 7. (a) SFQ interface circuit for generating SFQ pulses by current pulse from the nanowire photo switches. (b) Layout design of SFQ interface design for the CONNECT cell library.

Table 2. Circuit parameters for SFQ interface.

| Parameter | Value 1 | Value 2 |
|-----------|---------|---------|
| J1        | 100 µA  | 0.4 pH  |
| J2        | 150 µA  | 0.6 pH  |
| Vb1       | 2.5 mV  | 13 pH   |
| R1        | 10 Ω    | 3.26 pH |

Figure 6 shows high-speed optical response of a 200-nm-wide NbN nanowire for 190-ns-wide VCSEL pulsed laser irradiation with repetition frequency of 100 kHz. About 300 µV voltage peaks were observed. Moreover, photo response for 2-ns-wide pulsed laser irradiation with repetition frequency of 1 MHz could be observed. Note that observation of more higher optical response was limited by narrow bandwidth of a differential amplifier.

3. SFQ generation circuit design

Adapting the nanowire photo switches for the CONNECT cell library[5] that critical current density is 2.5 kA/cm², we designed SFQ circuits generating SFQ pulses using output current pulse from the nanowire photo switches.

Figure 7(a) shows SFQ interface circuit for generating SFQ pulses by current pulse from the nanowire photo switches. We assumed that the current pulse from the nanowire has similar shape as SFQ pulse but peak current less than 100 µA. Circuit parameters are listed in Table 2. Using the smallest critical current of 100 µA for Josephson junctions, the interface circuit could generate SFQ pulses by the switching current as small as 20 µA. Figure 7(b) shows a layout design for the interface circuit.

If the switching current has enough short rise-up time, but long fall-down time, SFQ interface circuit would generate many SFQ pulses for one photo switching current pulse. To avoid the multiple SFQ pulses generation, we added a differential circuit to the SFQ interface circuit, as shown in Fig. 8. If we choose C₀=2 pH and R₀=10 Ω, cutoff frequency becomes 8 GHz and we can make an SFQ interface circuit with resonable 2-dimensional size, using NEC 2.5 kA/cm² standard process II. Figure 9 shows bias margins for SFQ interface circuits with and without a differential circuit, as a function of input current from the nanowire photo switch. SFQ interface circuit without differential circuit has bias margins larger than ±15 % at the input current larger than 60 µA, but that with differential circuit has a little bit smaller bias margin.

Considering above result of the interface circuits, we need much higher critical current for the NbN nanowire with keeping suppression ratio high enough. We suggest that parallel nanowire switches would be one solution for increasing critical current. Further experiment will be
necessary for this.

4. Conclusions
We investigated superconducting NbN nanowire as a photo switch for SFQ pulses. Epitaxially grown NbN thin films were prepared on MgO(100) substrates and NbN nanowires were patterned using an EB lithography. Critical current density of NbN nanowires was about 3x10^6 A/cm^2 at 4.2 K. We irradiated 850-nm laser pulses via 50-µm multi-mode optical fibers. Using 150-nm-wide NbN nanowires, half of critical current was suppressed by 1 mW CW laser irradiations. High speed responses were observed for laser pulses with repetition frequency of 1 MHz and pulse width of 2 ns. Besides nanowire experiments, we designed an SFQ generation circuit. The designed circuit could generate SFQ pulses by at least 10 µA, 25 GHz current pulses. Calculated dc bias margin of the circuit was ±15% for 60 µA current pulses.

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