Characterization of 64 pixel NbTiN superconducting nanowire single photon detectors

Shigehito Miki, Taro Yamashita, Hirotaka Terai
Advanced ICT Research Institute, Nano ICT group
National Institute of Information and Communications Technology
588-2, Iwaoka, Nishi-ku, Kobe, Hyogo 651-2492, Japan
line 4-e-mail address if desired

Zhen Wang
Shanghai Center for SuperConductivity
Shanghai Institute of Microsystem and Information Technology
R3317, 865 Changning Road, Shanghai 200050, PR China

Abstract— **We present the characterization of two-dimensionally arranged 64-pixel NbTiN superconducting nanowire single-photon detector (SSPD) array. NbTiN films deposited on thermally oxidized Si substrates enabled the high-yield production of high-quality SSPD pixels, and all 64 SSPD pixels showed uniform superconducting characteristics within the small range of 7.19–7.23 K of superconducting transition temperature and 15.8–17.8 μA of superconducting switching current. Furthermore, all of the pixels showed single-photon sensitivity, and 60 of the 64 pixels showed a pulse generation probability after photon absorption higher than 90%.**

Keywords— Single photon detectors, superconducting nanowire, single photon detector array

I. Introduction

Recent progress in improving the performance of superconducting nanowire single-photon detectors (SNSPDs or SSPDs [1]) are nothing short of eye-opening. At present, their system detection efficiency (SDE) is reaching unity at a wavelength of 1550 nm with a dark count rate (DCR) lower than 1 kcps [2-4], and a short-system timing jitter of 20–40 ps can be obtained [5]. These values are strikingly superior to those obtained with commonly used avalanche photo diodes (APDs) at telecommunication wavelengths [6]. In fact, practical SSPD systems are already employed in a variety of applications such as quantum key distribution, quantum optics experiments, free space laser communication experiment, and so on [7-13]. However, one remained issue is slow response speed due to large kinetic inductance in superconducting nanowire. To apply SSPDs into high speed free space laser communications, the improvement of response speed is essential. Dividing the sensitive area into the independent multi pixels is an promising configuration to resolve this issue, because the kinetic inductance of each pixel can be reduced by the factor of N and the probability of photon incident also can be reduced by the factor of N, where the N is the number of pixels. As result, the maximum counting rate can be roughly increased by the factor of N^2.

One of the critical issues to realizing large-format SSPD arrays is how to reduce heat flow from room temperature through coaxial cables, the number of which increases as of the number of pixels increases in a conventional readout scheme. Therefore, our primary effort so far has been focused on the development of cryogenic readout electronics using a single flux quantum (SFQ) circuit because the required number of cables can be drastically reduced by implementing SFQ circuits and SSPDs in a cryocooler system. We have confirmed correct SFQ operation with output signals from SSPDs [14], and we have succeeded in implementing a four-pixel SSPD array and SFQ circuit in a Gifford–McMahon (GM) cryocooler system with no serious crosstalk [15]. Accordingly, scaling the number of SSPD pixels should be a next step, which will require significant uniformity of superconducting nanowire characteristics. Because our recent development of single-pixel NbTiN SSPDs prepared on a thermally oxidized Si substrate can provide high SDE devices with high yield [4], it is natural to apply this technology to scale up the SSPD arrays. In this work, we report the development of two-dimensionally arranged 64-pixel NbTiN SSPD array and characterization of electrical and optical properties in a GM cryocooler system.

II. Experimental Procedure

Figure 1 (a) shows the microphotograph and (b) shows the the scanning electron micrograph (SEM) of the 64-pixel NbTiN SSPD device. The NbTiN nanowire pixels were fabricated on a Si substrate with a 250-nm-thick thermally oxidized SiO_2 layer. The fabrication process of the NbTiN SSPDs was basically the same as described elsewhere [4,16]. The 5-nm-thick NbTiN nanowire was formed to be 100 nm wide and 100 nm spaced meandering lines covering an area of 5 × 5 μm, thus configuring one nanowire pixel. The 8 × 8 nanowire pixels were two-dimensionally arranged with spacing of 3.4 μm, covering an area of 63 × 63 μm. The 200-nm-wide interconnection lines were formed using the same 5-nm-thick NbTiN nanowires in the spaces between the nanowire pixels, in which the width of interconnection lines was two times wider than that of the nanowire pixel in order to prevent a response to single-photon incidence. The interconnection lines were then connected to coplanar waveguide (CPW) lines. Since the dc resistance of long (~2 mm) CPW lines could lead to a disturbance of the correct operation of the SSPD, 100-nm-thick NbN films with a superconducting transition temperature (T_c) of ~15 K were used to assure zero dc resistance.

The 64-pixel SSPD array chip was then mounted on the chip-mounting block with a specifically designed printed circuit board (PCB), and each nanowire pixel was wire bonded to a 50 Ω microstrip line on the PCB, as shown in Fig.1 (c). Since the total number of coaxial cables introduced into our cryostat system was nine, we characterized the electrical and optical properties of the 64 nanowire pixels by changing the connections between the microstrip lines on the PCB and the coaxial cables in turn. A single-mode optical fiber for a wavelength of 1550 nm was introduced into the cryocooler system, and the end of the fiber was fixed to the rear side of the chip-mounting block after aligning the incident light from the fiber with the device active area. The distance between the fiber tip and the device active area ($L_{fiber\text{-}sspd}$) were set to 3 mm to observe the incident photon response. The packaged block was cooled with a 0.1 W GM cryocooler system, which can cool the sample stage to 2.3 K [17].

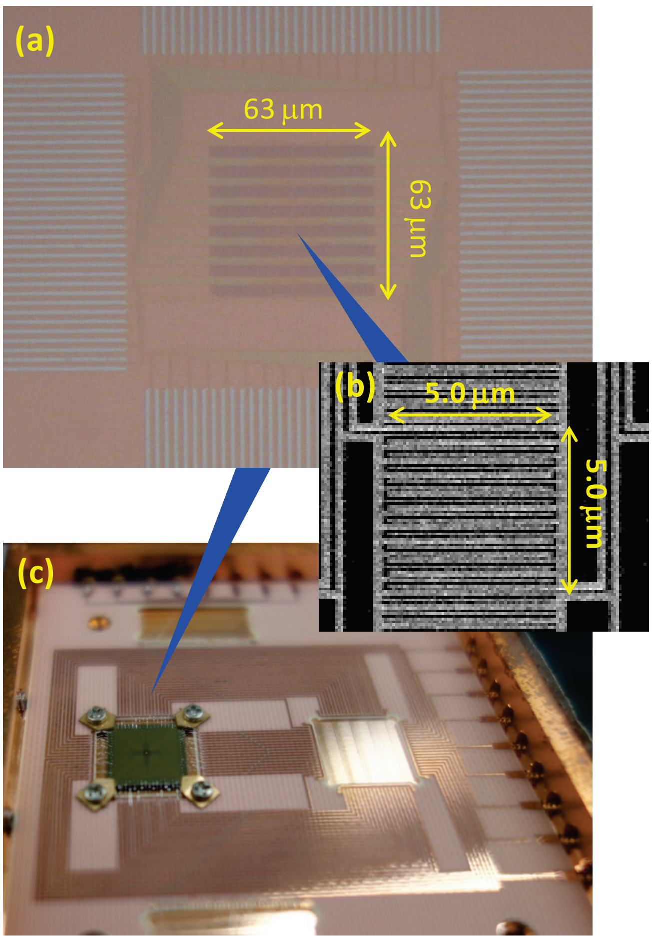

Fig.1 (a) Microphotograph of 64-pixel NbTiN SSPD array. (b) SEM image of one SSPD pixel. (c) photograph of 64-pixel SSPD array chip installed in a mount block.

To measure the SDE, a continuous tunable laser was used as the input photon source. The wavelength of the light source was fixed to 1550 nm and attenuated so that the photon flux at the input connector of the cryostat was 10^9–10^{11} photons/s, where the linearity of the output counts to the incident photon flux were confirmed in advance. A fiber polarization controller was inserted in front of the cryocooler's optical input in order to control the polarization properties of the incident photons so as to maximize the SDE. The SDE was determined by the relation SDE = $(R_{output} - R_{DCR})/R_{input}$, where R_{output} is the SSPD output pulse rate, R_{DCR} the dark count rate, and R_{input} the input photon flux rate to the system. The SDE of each pixel was measured individually by changing the connection of the readout components at the outer side of the cryocooler system.

III. Results

Figure 2 shows the histograms of the observed T_c and Fig. 3 shows the superconducting switching current I_{sw}, for the 64 nanowire pixels. As shown in the figures, both T_c and I_{sw} of all pixels fell within the small ranges of 7.19–7.23 K and 15.8–17.8 µA, respectively. These results indicate that all pixels were fabricated uniformly without significant defects in terms of their electrical properties. We then characterized the optical responses of all pixels. Figure 4 shows the histogram of maximum pulse generation probability in each pixel ($P_{pulse,max}$), where the pulse generation probability is defined as the probability that the detector generate the output signal after photon absorption into the nanowire. The $P_{pulse,max}$ were derived from the fitting from the bias dependencies of system detection efficiency (SDE) using a sigmoid function [4,18]. The sigmoid shape for the bias current dependence of the SDE has been shown empirically, and it is also well fitted to our devices in this work [2,4,19]. As shown in the figure, 60 of the 64 pixels exceeded 90% of approximated P_{pulse}, indicating that our 64 pixel arrays can operate with uniformly high sensitivity.

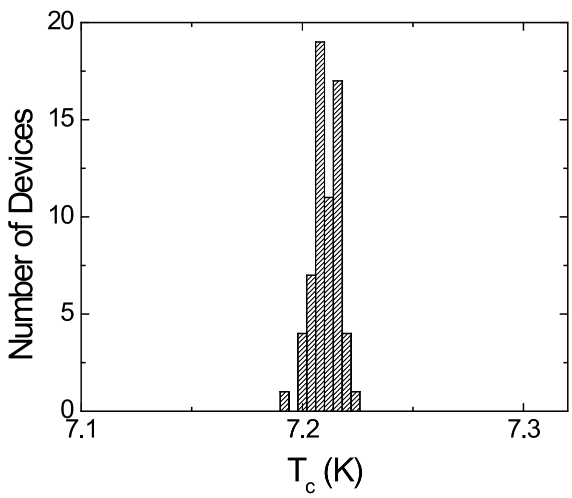

Fig. 2. Histogram of superconducting critical temperature (T_c) of 64 pixel SSPD array.

Note that the system detection efficiencies of 64 pixel arrays in this measurement were quite low (< 10^{-3}%) due to large losses before the absorption to the nanowire. For example, the coupling efficiency between incident light and sensitive area is low (~10^{-3}%) because the $L_{fiber\text{-}sspd}$ is long of ~3 mm and the 3.4 μm-wide spaces between nanowire pixels for interconnections to CPW lines. In addition, optical cavity structure did not attached on the nanowire, resulting in lower absorptance as compared to our standard single pixel devices. We believe if we can reduce these losses, the SDE of 64 pixels can be increased drastically and will reach to the similar values to that with standard single pixel devices.

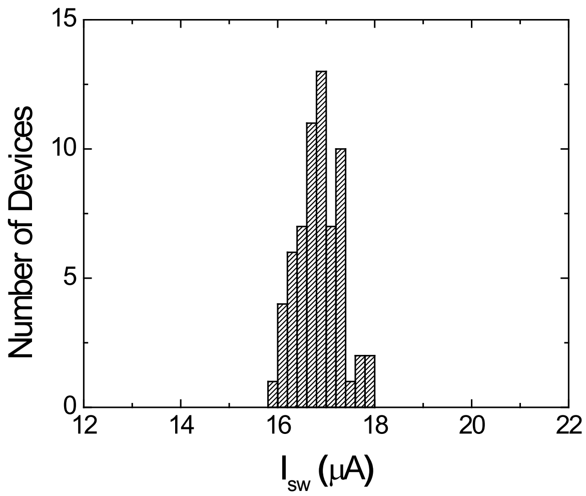

Fig. 3. Histogram of switching current (I_{sw}) of 64 pixel SSPD array.

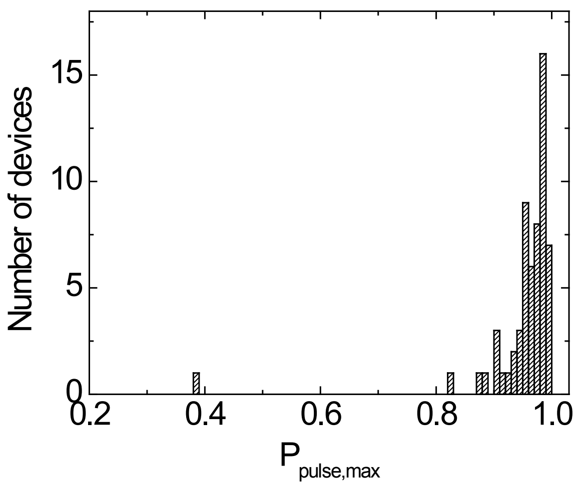

Fig. 4. Histogram of maximum pulse generation probability ($P_{pulse,max}$) of 64 pixel SSPD array.

IV. Conclusions

We characterized the electrical and optical properties of a 64-pixel NbTiN SSPD array prepared on a thermally oxidized Si substrate. Our two-dimensionally arranged 64-pixel SSPD array exhibited uniform superconductivity in all pixels and pulse generation higher than 90% in 60 of the 64 pixels. Our next study will be a simultaneous operation of all of 64 nanowire pixels with an SFQ signal processing circuit for high speed operation. Of course, although further improvement of bias current dependencies in the SDE such as those achieved by WSi-SSPDs at a low operation temperature of ~300 mK is more favorable for retaining the variations of P_{pulse} even at low bias current regions [2], the results of this work provide insights into realizing large-format SSPD arrays even at operating temperatures of 2–3 K.

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