NbN superconducting nanowire single photon detector with efficiency over 90% at 1550 nm wavelength operational at compact cryocooler temperature

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The rapid development of superconducting nanowire single-photon detectors over the past decade has led to numerous advances in quantum information technology. The record for the best system detection efficiency at an incident photon wavelength of 1550 nm is 93%. This performance was attained from a superconducting nanowire single-photon detector made of amorphous WSi; such detectors are usually operated at sub-Kelvin temperatures. In this study, we first demonstrate superconducting nanowire single-photon detectors made of polycrystalline NbN with system detection efficiency of 90.2% for 1550-nm-wavelength photons at 2.1 K, accessible with a compact cryocooler. The system detection efficiency saturated at 92.1% when the temperature was lowered to 1.8 K. We expect the results lighten the practical and high performance superconducting nanowire single-photon detectors to information and other high-end applications.

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A single-photon detector with high detection efficiency is the key enabling technology for quantum information and various applications, including the test of loophole-free Bell inequality violation \cite{1,2}, quantum teleportation \cite{3}, measurement-device-independent quantum key distribution \cite{4}, and linear optical quantum computation \cite{5}. Superconducting single-photon detectors outperform their semiconductor counterparts in terms of not only detection efficiency but also dark count rate, timing jitter, and counting rate \cite{6-8}. In the case of the telecommunication wavelength (1550 nm), the highest system detection efficiency (SDE) greater than 90% has been reported for two types of detectors. One is a transition edge sensor (TES) made of tungsten (W), with an SDE of 95% \cite{9}; the other is a superconducting nanowire single-photon detector (SNSPD) made of amorphous WSi, with an SDE of 93% \cite{10}. However, because of the low superconducting transition temperature of W and WSi, the requirement of sub-Kelvin cryogenics represents a burden for practical applications. Many studies focused on SNSPDs fabricated using different materials and aiming to obtain a high SDE at higher operating temperatures have been reported \cite{11-14}; however, none of these attempts has been

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successful. Regarding another important parameter, timing jitter, a WSi SNSPD and a W TES have values of approximately 150 ps and 50-100 ns, respectively, which limits their use in applications that require low timing jitter.

The SDE of SNSPD ($\eta_{\text{SDE}}$) can be expressed as the product of three contributions [10]: 

$$\eta_{\text{SDE}} = \eta_{\text{ac}} \times \eta_{\text{abs}} \times \eta_{\text{lat}},$$

where $\eta_{\text{ac}}$ is the optical coupling efficiency between the incident photons and the active area, $\eta_{\text{abs}}$ is the absorption efficiency of the nanowires, and $\eta_{\text{lat}}$ is the intrinsic detection efficiency (IDE), which describes the pulse generation probability of the nanowire when a photon is absorbed. To achieve a high SDE, all three parameters must be simultaneously maximized. The $\eta_{\text{ac}}$ is mainly governed by the size of the active area of the SNSPD when the optical alignment method is fixed. The factors that influence $\eta_{\text{abs}}$ include the geometric and optical parameters of the nanowire (e.g., thickness, width, filling ratio, and refractive index) and the optical absorption enhancement structures (i.e., the cavity structures). The $\eta_{\text{lat}}$ is mainly determined by the superconductivity of the nanowire, however, the factors are complicated [15-17]. On the one hand, geometric parameters such as the width and thickness of the nanowire play important roles. On the other hand, the operating parameters (e.g., bias current and operating temperature) can control the $\eta_{\text{lat}}$ directly. In addition, good uniformity of the nanowire with respect to thickness variation and physical constrictions handicaps $\eta_{\text{ac}}$ because it suppresses the maximum bias current. The aforementioned analysis indicates that $\eta_{\text{abs}}$ and $\eta_{\text{lat}}$ are not independent, they are both related to the thickness and width of the nanowire. The correlation between $\eta_{\text{abs}}$ and $\eta_{\text{lat}}$ makes the improvement of SDE complicated. Indeed, a WSi SNSPD with a high SDE is relatively simple because $\eta_{\text{lat}}$ can easily reach 100% with a wide range of nanowire thicknesses and widths because of the lower pair-breaking energy of WSi. By contrast, in the case of an NbN SNSPD, the pair-breaking energy of NbN is nearly double that of WSi. As a result, the room for tuning $\eta_{\text{abs}}$ and $\eta_{\text{lat}}$ is highly limited, which makes it challenging to achieve a high SDE.

NbN SNSPDs are a promising choice for practical applications because of their high critical temperature, which introduces the possibility of using a compact cryocooler for operation. Unfortunately, the highest SDE at 1550 nm wavelength for an NbN SNSPD is less than 80% [18-22]. Although there is no physical limitation for higher SDE, NbN SNSPD with SDE over 90% has not been demonstrated in the past a few years. The challenges stem from various efforts, such as high absorption, near-unity intrinsic detection efficiency and the efficient coupling.

In this article, we demonstrated an NbN SNSPD with an SDE greater than 90% at 1550 nm. We introduced a distributed Bragg reflector (DBR) mirror onto a Si substrate; the measured reflectance of the mirror was greater than 99.9%, and the calculated absorption of the nanowire was greater than 99%. Excellent front-side single-mode-lens (SML) fiber coupling was ensured by a large sensitive area (greater than $\phi15 \mu m$). By tuning the film thickness, we maximized the $\eta_{\text{abs}}$ and $\eta_{\text{lat}}$ simultaneously. As measured using a dilution refrigerator, the saturated SDE reached 92.1% when the temperature was less than 1.8 K. At 2.1 K, the measured SDE was 90.2% at a dark count rate (DCR) of 10 Hz; we subsequently verified this SDE by cooling the SNSPD using a compacted Gifford-McMahon (G-M) cryocooler. In addition, because of the high switching current of the NbN SNSPD, a relatively small timing jitter of 79 ps was achieved.

## 1 Device design and structure

The design of the SNSPDs that operate at incident photon wavelength of 1550 nm was based on the principle of integrating a DBR mirror into the device to enhance the absorption of the nanowires. Before fabricating the devices, we systematically conducted numerical simulations in which parameters such as the filling factors, thickness, and configuration of the cavity were varied while the nanowire linewidth was fixed to 75 nm empirically to enhance its $\eta_{\text{lat}}$.

We performed the simulation using the rigorous coupled-wave analysis method. The parameters in the simulation, i.e., the refractive index of NbN, $n_{\text{NbN}}=6.50+5.83i$, at 1550 nm were obtained using a spectroscopic ellipsometer, and the refractive index and thickness of the Si substrate were $n_{\text{Si}}=3.46$ and $L=400 \mu m$, respectively.

Figure 1(a) shows the absorption of device ($A_{\text{device}}$) as a function of pitch with a fixed 75-nm width for the nanowires at different thicknesses (5.0-8.0 nm). For the $A_{\text{device}}$ with a thickness of 7.0 nm, maxima greater than 99% appeared at pitches ranging from 130 to 190 nm, corresponding to the filling factor of about 60%-40%. Then, for a thin nanowire, a high filling factor was required to guarantee a high absorption [23]. As the thickness increased, the position of the maxima shifted to a larger pitch, in consistent with the result reported by Yamashita et al. [19]. As shown in Figure 1(b), the $A_{\text{device}}$ with fixed width and pitch (75 and 140 nm) first increased then fell gradually as the NbN thickness increased. $A_{\text{device}}$ reached a maximum greater than 0.99 at 5.5-7.0 nm. Figure 1(c) shows the influence of the antireflection coating (ARC) on a half-cavity (DBR/NbN/Air) design. The ARC designs were tuned through the use of various dielectric materials, including SiO (the SiO refractive index is $n_{\text{SiO}}=1.89$), SiO$_2$ (in SiO refractive index is $n_{\text{SiO}_2}=1.46$), and Ta$_2$O$_5$ (in Ta$_2$O$_5$ is $n_{\text{Ta}_2\text{O}_5}=2.15$). The simulations indicated that the ARC coatings (SiO and SiO$_2$/Ta$_2$O$_5$ bilayer) did not substantially change the absorption around the target wavelengths but resulted in a reduction of the bandwidth. To summarize, a maximum absorption efficiency greater than 99% could be realized with an NbN.
thickness of approximately 7 nm and a filling factor of approximately 0.5 when the NbN film is integrated into a half-cavity.

To experimentally validate the simulation results, we prepared SNSPDs by a standard fabrication process (for details on the fabrication see the methods). As shown in Figure 2(a), 15 periodic SiO$_2$/Ta$_2$O$_5$ bilayers were alternately deposited onto a Si wafer using ion-beam assisted sputtering. NbN films with different thicknesses were deposited onto the DBR wafers. The root-mean-square (RMS) roughness of both the DBR substrate and the deposited NbN thin film on the DBR was measured and found less than 0.3 nm (Figure S2, see the supporting information). The measured reflectivity of the DBR substrate was greater than 99.9%, and the absorbance of a 7-nm NbN film on DBR was estimated over 99% at 1550 nm (Figure S3).

The active areas of the SNSPDs were designed with two sizes (∅15 and ∅18 µm), both of which are much larger than the 6.8-µm mode field diameter of a SML fiber for an incident photon wavelength of 1550 nm. The width of the nanowires was fabricated to approximately 75 nm with different pitches of 130, 140, 160, 180, 200, and 230 nm (i.e., filling factors 0.58-0.33). Scanning electron microscopy (SEM) images of the nanowire with a nominal 75-nm width and 140-nm pitch are shown in Figure 2(b); these images demonstrate good controllability of the fabrication process. Figure 2(c) shows a transmission electron microscopy (TEM) image of the DBR structure. The interfaces of each layer are distinguished. The measured thicknesses of the deposited bilayers were observed to vary by ±4 nm from the designed values. Figure 2(d) shows a high-magnification TEM image of a cross-section of a nominal 7-nm-thick, 75-nm-wide nanowire, which has a slightly trapezoidal shape because of the side etching. The TEM image indicates an estimated thickness of approximately 8 nm, which includes an oxidized layer (1- to 2-nm thick) on the top [24].
2 Methods

We fabricated SNSPDs by four subsequent process steps. The first step is the fabrication of DBR substrates. Fifteen periodic SiO$_2$/Ta$_2$O$_5$ bilayers were alternately deposited onto a 400-μm-thick 2-inch-diameter Si wafer using ion-beam assisted sputtering. Their thicknesses were fabricated to be one-fourth of the 1550-nm incident photon wavelength, i.e., 265 nm for the SiO$_2$ layer ($n_{SiO_2}=1.46$) and 180 nm for the Ta$_2$O$_5$ layer ($n_{Ta_2O_5}=2.15$). Then, NbN thin films were deposited at room temperature by a reactive DC magnetron sputtering system with a background pressure of 1.8×10$^{-5}$ Pa. The target was an 8-inch-in diameter Nb plate with 99.99% purity. Before deposition of films, the substrates with the DBR structure on the top were cleaned by argon ion beam in a cleaning chamber. Then, the NbN films were deposited onto the DBR surface in an Ar and N$_2$ mixture under a total pressure of 0.27 Pa, with partial pressures of 79% and 21%, respectively. The flow rates of Ar and N$_2$ were set into 30 and 4 sccm using mass flow controllers. A current control mode was used to maintain the steady discharge state. The NbN films were sputtered at a deposition current of 2.2 A with a deposition rate 8 A/s. The thickness of the films was controlled by the sputtering time and verified by XRD analysis. In the third step, the NbN films were then patterned into a meandered nanowire structure using electron-beam lithography (EBL, JOEL 100 kV, Japan) with a positive-tone ZEP520A electron-beam resist and reactively etched in CF$_4$ plasma. The thickness of the ZEP520A layer was about 70 nm, with a higher etching selectivity (NbN to resist) in contrast to the commonly used PMMA. The width of the nanowires was fabricated to approximately 75 nm with different pitches. Finally, a 50-Ω-matched coplanar waveguide was formed using ultraviolet lithography and reactive ion etching.

After the fabrication, the devices were packaged with the SML fiber in a copper box. The fiber was aligned to the center of the active area using a microscope at room temperature, and the alignment error was estimated to be ±3 μm. The fiber was designed with a focal distance of approximately 145 μm, an ARC target wavelength of 1550 nm, and reflectance less than 1%. In the temperature dependence of SDE and DCR measurement, a CDR was adopted, as shown in Figure 3. The fiber-coupled package was mounted onto an Au-plated oxygen-free Cu platform thermally connected to the mixing chamber of the CDR with a base temperature of 10 mK. The sample temperature was indicated by a RuO$_2$ resistance thermometer positioned at the bottom of the mixing chamber. The dilution unit was inside a refrigerated dewar mounted onto a vibration-attenuated stage. The temperature was tuned using a proportional-integral-derivative (PID) controller. The temperature stability varied by region: $T$≤1 K, ±0.001 K; 7≤1.8 K, ±0.04 K; 7≤2 K, ±0.06 K; 7≤2.3 K, ±0.03 K. After the ultra-low temperature measurements, the device 02#F9 was mounted in a (2.125±0.005) K G-M cryocooler.

Spliced fibers and 50-Ω coaxial cables were connected from the top of the fridge to the SNSPD packages. The coupling loss due to the fiber splicing was typically approximately 0.01 dB. To suppress the blackbody radiation of the fiber [25], the fiber was coiled to a diameter of approximately 30 mm in the mixing chamber. The optical loss due to the coils was carefully checked and was observed to be less than 0.07 dB at an incident photon wavelength of 1550 nm. Two tunable-wavelength continuous-wave (CW) laser diodes (Keysight 81970, USA, 1465-1575 nm; Keysight 81940, 1520-1630 nm) and a supercontinuum white-light laser (NKT photonics, EXB-3, Denmark) were used as the photon sources. The input light was heavily attenuated by three cascaded attenuators so that the photon flux at the input connector of the cryostat was single-photon level. A polarization controller (Agilent N7786B, USA) was inserted in front of the attenuator, together with the power controller, to obtain...
the maximum SDE. Each time the polarization was tuned, the input power was carefully rechecked by switching the input photons to the power meter (Keysight 81624B) port. The split ratio of the micro-electro-mechanical system (MEMS) optical switch (Thorlabs Inc., O5W12-1310E, USA) was 1:(1.002±0.002), which guaranteed nearly identical-input-photon numbers to the power meter and the SNSPD. The number of input photons \(N=5\times10^4\) photons/s) is estimated by an expression of \(N=P_{\text{in}}\times\alpha_1\times\alpha_2	imes R_{\text{opt}}/(1-\gamma)/(1-L_1)/(1-L_2)/E_\lambda\) (see the supporting information for more details). The loss due to fiber bending and splicing has been considered in the calibration of input optical power to avoid the overestimate the SDE. The linearity of the three attenuators were recalibrated using the power meter; they were found to be 0.999±0.001 (Figure S5).

The device was current-biased through the DC arm of the bias tee. The response pulse of the detector was readout via the AC arm of the bias tee using a room-temperature amplifier (RF Bay Inc., LNA650, USA) and photon counter (SRS Inc., SR400, USA). The SDE was defined as SDE=PCR/N, where the photon response rate PCR=CR–DCR, CR is the output pulse count rate of the SNSPD. At each bias current, the output pulse counts and dark counts were collected for 10 s by the photon counter.

The SDEs included all losses in the system, and the overall relative errors of the SDE values were estimated to be 2.84% at 1550 nm, resulting from the relative uncertainty of the power meter calibration (2.80%, Agilent 81624B, report of calibration), the relative uncertainty of the splitting ratio (0.20%), relative uncertainty of the attenuation (0.33%), the relative uncertainty of the PCR (0.10%), etc. The dominant uncertainty was from the light power calibration; this uncertainty could be further reduced using the correlated-photon-based method [26] or the Agilent calibration option C05. According to the manual of Agilent 81624B, the PTB (Technische Bundesanstalt, the German national metrology institute) traceable calibration option C05 could reduce the uncertainty down to 0.8%.

3 Results

We characterized different SNSPDs with four film thicknesses (6.5-8.0 nm) fabricated in the same process run (Figure S1 and Table S2, see supporting information). The corresponding \(T_s\) were 7.8-8.6 K and increased monotonically with increasing film thickness (Figure S4). We screened the detectors by selecting those with the highest switching current for the same geometrical parameters. The selected devices were then optically aligned to SML fibers and mounted in a cryogen-free dilution refrigerator (CDR) with a wide temperature operating range and capable of reaching 16 mK.

Figure 4(a) and (b) show the SDEs for an incident photon wavelength of 1550 nm and the DCRs as functions of the bias current \(I_b\) for two devices, 02#F9 (7-nm thick) and 04#E4 (8-nm thick), at various temperatures. For clarity, five curves at five temperatures (3.0, 2.5, 2.1, 1.5 K, and 16 mK) are displayed. In the DCR measurement, the optical-fiber port at room temperature was shielded to eliminate any stray light from the environment. A detailed calibration for the SDE at 1550 nm of the SNSPD can be found in the Methods section and supporting information. As the operating temperature was decreased, the SDE increased and a saturation plateau appeared. When the temperature was less than 3 K, all the SDE \((I_b)\) curves nearly overlapped at the same bias current. At 1.5 K and lower, we observed the highest SDE value of 92.1% for device 02#F9 at a DCR of 10 Hz and saturation plateau indicating that the \(t_{\text{cr}}\) reached approximately 100%. When the temperature was increased to 2.1 K (the lowest temperature that can be achieved with a commercial compact G-M cryo-cooler), an SDE of 90.2% was obtained with a DCR of.
Figure 4 (Color online) (a, b) SDEs and DCRs as functions of the bias current $I_b$ for the 7- and 8-nm-thick, 75-nm-wide, 140-nm-pitch SNSPDs, as measured from 3 K to 16 mK. The filled and open symbols represent the SDE and the DCR, respectively. As the temperature was decreased, a clear saturation plateau emerged. Thinner NbN films resulted in wider saturation plateaus. The maximal SDEs of devices 02#F9 and 04#E4 were 92.1% and 91.7%, respectively, when the devices were operated at a DCR of 10 Hz. (c) temperature dependence of SDEs for devices 02#F9 and 04#E4 when the DCR was set to 10 Hz. For 02#F9, the SDE of 90.2% was obtained at 2.1 K (indicated by the green-dashed line), which is also the base temperature for a G-M cryocooler. The arrows indicate the onset temperature ($T_{os}$), where the SDE nearly saturated with decreasing temperature; (d) the switching current $I_{sw}$ as a function of temperature for devices 02#F9 and 04#E4.

10 Hz. The 8-nm-thick NbN SNSPD (04#E4) exhibited a larger switching current ($I_{sw}$) of 22.5 μA compared to device 02#F9, whose $I_{sw}$ was 15.2 μA; the highest SDE of this device (91.7%) was measured at a DCR of 10 Hz and at 16 mK. However, the SDE decreased to 76.5% at 2.1 K because of the weak saturation of SDE.

The DCR increased monotonously with $I_b$ at all temperatures. Two different regions were clearly distinguished: background blackbody-radiation-dominated DCR (low-bias zone) and intrinsic vortex-related DCR (high-bias zone). The intrinsic DCR logistically increased with increasing $I_b$, which shifted to the high bias current with an increase/decrease of $I_{sw}/$temperature. Its onset $I_b$ depends on the temperature. For example, in the case of device 02#F9 (04#E4) the onset $I_b$ was suppressed to 0.95 (0.97) $I_{sw}$ at the lowest temperature of 16 mK; by contrast, it was 0.89 (0.92) $I_{sw}$ at 3 K. The background DCR curves followed the same curve; however, the highest background DCR slightly increased with increasing/decreasing $I_{sw}$/temperature. The same background DCR value at the bias current can be explained by the consistent SDE at the same bias current and stable background blackbody radiation.

Figure 4(c) shows the temperature dependence of the SDEs for devices 02#F9 and 04#E4 at a DCR of 10 Hz. The green-dashed line indicates the lowest temperature that a commercial G-M cryocooler (e.g., SHI RDK-101D from Sumitomo Inc., Japan [19]) can reach directly. For both devices, the SDE increased with decreasing temperature and saturated at low temperatures. The onset temperature ($T_{os}$) where the SDE reached saturation with decreasing temperature is indicated by the arrow in Figure 4(c). The $T_{os}$ of 02#F9 and 04#E4 were 1.8 and 1.3 K, respectively. Because of the wide saturation plateau, the SDE (7) of 02#F9 exhibited a slow decrease with increasing temperature, in contrast to that of 04#E4. We attributed this different saturation behavior to differences in film thickness, which will be discussed later.

Figure 4(d) shows the temperature dependence of $I_{sw}$ for devices 02#F9 and 04#E4. The measurement error of the $I_{sw}$ values was approximately ±0.05 μA. When the temperature was lower than the $T_{os}$, the $I_{sw}$ gradually reached a maximum. The $I_{sw}$ at $T_{os}$ were 14.5 and 21.9 μA, respectively. The evident difference was observed for the $I_{sw}$ of SNSPDs with different film thickness 7 (02#F9) and 8 nm (04#E4). There are two reasons related to the difference. Firstly, thicker film has a higher critical temperature, which corresponds to a higher critical current density, then a higher $I_{sw}$ considering the larger thickness; secondly, the two SNSPD devices 02#F9 and 04#E4 showed in the figure had different diameters of active area, i.e., 18 and 15 μm, respectively. Larger active area or length of nanowire resulted in less homogeneity (more de-
fects), which might cause a lower $I_{\text{sw}}$ as well. A fitting based on the Bardeen model [27] simplified as $I_{\\text{sw}} = a(1 - (T/T_c)^{\alpha})^{2}$ was applied to the measured $I_{\text{sw}}$ values; the fitting results obtained with $\alpha$ and $T_c$ treated as variable parameters were plotted as solid lines in Figure 4(d). These fitting results are consistent with the measured data, except for a slight deviation in the low-temperature region ($T<1 \text{ K}$). Given the possibility of constrictions in the nanowire, which may limit the maximal $I_{\text{sw}}$, it was found that the measured $I_{\text{sw}}$ was less than the calculated depairing current $I_d$ [28].

To further verify the SDE greater than 90% at 2.1 K, we further examined the SDE of device 02#F9 cooled using a G-M cryocooler (base temperature of 2.13 K), which gave a value of 90.1% at a DCR of 10 Hz, as shown in Figure 5. The SDE of 90.1% was obtained at a DCR of 10 Hz using a G-M cryocooler. To the best of our knowledge, this study is the first report of an NbN SNSPD with an SDE greater than 90%. More importantly, it was achieved using a G-M cryocooler (approximately 2.1 K) and therefore represents a practical and affordable potential solution for single-photon detection for quantum information.

In order to experimentally study the performance of the optical design, we measured the wavelength dependence of the maximum SDE: and SDE when the polarization of the photons was parallel and perpendicular, respectively, to the direction of the nanowire. The relative uncertainty of the measured SDE was estimated to be 3.67% at the wavelengths of 1200-1700 nm, as shown in Figure 6 with error bars (see the supporting information for the calibration details). For comparison, the simulated absorption $A$ was also given for the wavelength range from 1200 to 1800 nm. The absorption $A_{\parallel}$ showed a broad peak with a value of 99.5% (98.1%) for 7(8)-nm-thick nanowire at an incident photon wavelength of approximately 1550 nm. The measured SDE$s$ were approximately 7% lower than the calculated absorption values, whereas the SDE$s$ were approximately 6% higher than the corresponding calculated absorption values. That is, the measured polarization extinction ratio (PER, defined as $\text{SDE}_{\parallel}/\text{SDE}_{\perp}$) was lower than the calculated PER (defined as $A_{\parallel}/A_{\perp}$). For example, in the case of 7(8)-nm-thick devices, the experimental PER of 3.5(3.2) at 1550 nm was lower than the calculated PER of 4.4 (4.6). This deviation indicates that the practical device differs from the design in geometry and/or material optical parameters. Further optimization of the fabrication process will be helpful in further improving the consistency and the SDE. In addition, an extra ARC upon the nanowire can suppress the PER by a factor of two or more, if necessary (Table S2). However, the SDE decreased faster than the simulated values when the wavelengths were longer than 1600 nm, which can be explained by a non-unity $\eta_{\text{ph}}$ due to the smaller photon energy (Figure S8).

The aforementioned results indicate that the NbN SNSPD exhibited an SDE of 90% at the dark count rate of 10 Hz at 2.1 K. The other important parameter, timing jitter $T_j$, was also measured at 16 mK and 2.1 K. Figure 7 shows the $T_j$ of the SNSPDs (device 02#F9 and 04#E4), as measured at a bias current of 14.5 and 21.5 $\mu$A (both at 0.95$I_{\text{sw}}$), respectively, using a time-correlated single-photon counting (TCSPC) module (SPC-150, Becker & Hickl GmbH, Germany). A 1550-nm-wavelength pulsed laser with a 100-fs pulse width was used, and the input photon flux was attenuated to the single-photon level. For devices 02#F9 and 04#E4, the $T_j$ values defined by the full-width at half-maximum (FWHM) of the histogram were 70.2 and 40.0 ps at 16 mK and increased to 79.0 and 46.0 ps at 2.1 K, respectively, because of the reduction of $I_{\text{sw}}$. Notably, the values of $T_j$ measured using the CDR were a few picoseconds larger than those measured using the G-M cryocooler at the same bias current because of the long
coaxial cable (about 4.5 m) used with the cryogenic system. Nonetheless, the measured $T_j$ of the NbN SNSPD was approximately two times smaller than that of the WSi SNSPD because of its much larger switching current (by a factor of approximately three). Figure 7(b) shows the bias-current dependence of $T_j$. This figure implies that the signal-to-noise ratio plays the key role in determining $T_j$. A comparison of more parameters among the Nb(Ti)N-, WSi-, MoSi-SNSPDs, and W-TES is provided in Table S3, this comparison indicates that our NbN detectors represent a substantial advancement.

4 Discussion

Four of the approaches used in this study contributed to the remarkable improvement of the SDE. The first approach was the DBR cavity design, which ensured near-unity reflectance of 1550-nm photons. The second approach was the removal of the reflection of the substrate in the backside fiber-coupled SNSPDs via front-side SML fiber alignment. Third, the use of SML fiber guaranteed better optical coupling between the nanowire and the incident photons because of a smaller beam size than that achieved with an SM-28e fiber. The fourth approach was to maximize the optical absorption and IDE simultaneously by tuning the thickness while leaving the nanowire linewidth fixed. Optimization was achieved with a nominal film thickness of 7 nm. The absorption reached a maximum, and the IDE approached unity even at 2.1 K. In the case of the 8-nm-thick film, less saturated SDE behavior was observed at 2.1 K, though the maximum SDE was 91.7% at 16 mK. With the thinner film thickness of 6.5 nm, a more saturated SDE behavior was registered for SNSPD at 2.1 K; however, the highest SDE was only 82%, which indicates low optical absorption (Figure S7).

The benefit of a higher detection efficiency (~90% or even higher compared with ~80%) is significant. The single-photon detector (SPD) is integral to optical quantum information sciences. Its performance, most notably the SDE, plays a major role in many scientific advances, such as quantum key distribution [29]. For some fundamental and frontier experiments, SDE over 90% and even unity will be the key enabling technology. For example, two experimental tests of Bell’s inequalities last year removed the last doubts that we should renounce local realism [1, 2]. In both experiments, superconducting SPDs (one is the WSi SNSPD, the other is TES) with DE over 90% played the key role, and were almost prerequisite. Another important application is multiphoton entanglement which is challenging for the optical quantum information. The world record is 10-photon entanglement [30] which used 20 SPDs with DE of 71%, which presented 10-photon count rate of $10^3$ Hz, extremely time-consuming. If SNSPDs with SDE of 90% are adopted, the count rate for the multiphoton entanglement can be increased by 10/100 times for 10-20-photon count rate. Surely, higher SDE close to unity will be the long-term dream for those experiments. On the other hand, 2.1 K is the lowest temperature that the commercial practical and economic compacted two-stage G-M cryocooler (for example, SHI RDK-101D from Sumitomo Inc) could reach. That is the reason why we wish to demonstrate SNSPD at this temperature.

In contrast to the literature published by F. Marsili et al. [10], this manuscript reports SNSPD made of NbN instead of WSi. Firstly, The NbN SNSPD with $T_j$ of ~8 K can operate at higher temperature over 4.2 K, though SDE decreases with increasing temperature. However, WSi SNSPD cannot work at higher temperature since the transition temperature is about 3.7 K. The higher $T_j$ will release the stringency on the cryogenics which makes the SNSPD system more practical. Secondly, though SNSPD made of WSi with 90% efficiency was also obtained at temperatures up to 2 K, the switching current of their detector was only 2 μA, resulting in the jitter

![Figure 7](https://example.com/figure7.png)

Figure 7 (Color online) (a) Timing jitter ($T_j$) measurement of two devices measured at 16 mK. For devices 02#F9 and 04#E4, the corresponding FWHM values of the Gaussian fits of $T_j$ are 70.2 and 40.0 ps, respectively (see solid lines); (b) bias current dependence of $T_j$. The $T_j$ increased to 79.0 and 46.0 ps at 2.1 K (indicated by arrows) because of the reduction of $I_b$ to 13.0 and 19.5 μA for devices 02#F9 and 04#E4, respectively.
of ∼500 ps, which is too high for many experimental applications. As a comparison, NbN SNSPDs have the jitter smaller than 100 ps.

We noticed that two months after our draft [31] first appeared online, another work done by Zadeh et al. [32] reported an over 90% efficiency NbTIn detector at a shorter wavelength of 1310 nm, with a low $T_j$ of 49 ps by using a cryogenic amplifier. The main difference between these two results is the wavelength and cavity structures. We reported SDE over 90% for 1550 nm, while Zadeh et al. reported the SNSPD with SDE over 90% for 1310 nm. We would like to point out that it is more challenging to realize high SDE for 1550 nm than for 1310 nm since the photon energy if 1550 nm is about 20% smaller than that of 1310 nm. They also reported a small $T_j$ of 14.8 ps from another SNSPD with a smaller SDE (maximal SDE of ∼75% at 1310 nm instead of 1550 nm). $T_j$ of our device was mainly attributed to the low SNR caused by small bias current. There is still potential for further reducing $T_j$ of SNSPDs, for example, by reducing the active area of a detector, introducing the cryogenic amplifier and optimizing the readout circuits.

5 Conclusions

We successfully demonstrated that the SDE of an NbN SNSPD surpassed 90% (92%) at a DCR of 10 Hz at 2.1 (1.8) K because of the adoption of a DBR mirror and the simultaneous maximization of the optical absorption and IDE. In addition, the NbN SNSPD exhibited a timing jitter of only 79 ps. We believe some room remains for further improving the SDE to near unity and achieving a higher operating temperature through optimization of the fabrication process and the optical and superconducting properties of the film.

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Supporting Information

The supporting information is available online at http://phys.scichina.com and http://link.springer.com/journal/11433. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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