Detecting single infrared photons with 93% system efficiency

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Single-photon detectors1 at near-infrared wavelengths with high system detection efficiency (>90%), low dark count rate (<1 c.p.s.), low timing jitter (<100 ps) and short reset time (<100 ns) would enable landmark experiments in a variety of fields2–6. Although some of the existing approaches to single-photon detection fulfil one or two of the above specifications5, to date, no detector has met all of the specifications simultaneously. Here, we report on a fibre-coupled single-photon detection system that uses superconducting nanowire single-photon detectors and closely approaches the ideal performance of single-photon detectors. Our detector system has a system detection efficiency (including optical coupling losses) greater than 90% in the wavelength range 1,520–1,610 nm, with a device dark count rate (measured with the device shielded from any background radiation) of ~1 c.p.s., timing jitter of ~150 ps full-width at half-maximum (FWHM) and reset time of 40 ns.

Superconducting nanowire single-photon detectors (SNSPDs)7,8 have outperformed other near-infrared single-photon detector technologies in terms of dark count rate, timing resolution and reset time1. However, after over ten years of research, the system detection efficiency (SDE, which includes the efficiency of the optical coupling to the detector) of SNSPDs has been limited to 36% at a wavelength λ of 1,550 nm (ref. 9) because (i) the superconducting material used (typically, polycrystalline NbN) has limited compatibility with the structures that enhance the optical coupling and absorption of the detectors, and (ii) the internal detection efficiency (the probability that the absorption of one photon in a nanowire results in a response pulse) of typical SNSPDs (based on 100-nm-wide NbN nanowires) does not show saturation as a function of the bias current \(I_B\). The superconducting properties of NbN films depend on the crystal phase of the films10 and are affected by crystal defects11, which limits (i) the fabrication yield of large-area devices12, (ii) the choice of substrates for fabrication and (iii) the design parameters of optical structures that would enhance absorption in the nanowires. Furthermore, although 30- and 20-nm-wide NbN nanowires have demonstrated saturated detection efficiency at \(\lambda = 1,550\) nm (ref. 13), the fabrication of large-area SNSPDs (which allow efficient optical coupling) based on such narrow nanowires remains challenging. We recently reported on the fabrication of SNSPDs based on a different superconducting material, amorphous tungsten silicide (\(W_{0.75}Si_{0.25}\), or WSi)14. Because the crystal structure of WSi is homogeneously disordered, WSi superconducting nanowires are more robust with respect to structural defects than NbN nanowires (which allows the fabrication of large-area devices), can be deposited on a variety of substrates, and allow more degrees of freedom in optimizing the optical coupling and the absorption of the detectors. Furthermore, WSi SNSPDs based

Figure 1 | Bias current dependence of SDE, SDCR and DDCR. a, SDE versus bias current \(I_B\) for two different polarizations of light at \(\lambda = 1,550\) nm. The SNSPD used was based on 4.5-nm-thick, 120-nm-wide nanowires with a pitch of 200 nm. The SNSPD covered a square area with dimensions of 15 μm × 15 μm. The dashed lines indicate the cutoff current (\(I_{\text{sw}}\), which is defined as the bias current at the inflection point of the SDE versus \(I_B\) curve15) and the switching current (\(I_{\text{sw}}\), which is defined as the maximum current the device could be biased at without switching to the normal, non-superconducting state) of the device. At \(I_{\text{sw}} = 3\) μA, the average and 1σ uncertainty of the maximum and minimum SDE were SDEmax = 93.2 ± 0.4% (red circle) and SDEmin = 80.5 ± 0.4% (blue circle) (Supplementary sections ‘Estimation of the system detection efficiency’, ‘Estimation of the uncertainty on the system detection efficiency’). The experimental value of the SDE was lower than the design value of the absorption of the SNSPDs (>99%), which we attribute to several possible causes (Supplementary sections ‘Optical simulations of the system detection efficiency’, ‘Refractive indexes of the materials employed in the optical stack’): (i) our imperfect knowledge of the refractive index of the materials used in the optical stack; (ii) fabrication imperfections; (iii) coupling losses; and (iv) the non-unity internal detection efficiency of the SNSPDs. b, SDCR and DDCR versus \(I_B\) for the device in a. The SDEmax, SDEmin and SDCR curves were obtained at \(T = 120\) mK by averaging six subsequent acquisitions of the curves. Error bars for each point are not plotted for clarity, but the uncertainty is described in Supplementary section ‘Estimation of the uncertainty on the system detection efficiency’.

on nanowires as wide as 150 nm have shown saturated SDE versus \(I_B\) curves14 in the near-infrared, probably because the size of the photon-induced perturbation of the superconducting

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state is larger in WSi than in NbN. In earlier reported work, WSi SNSPDs only achieved SDE ≈ 20% at λ = 1,550 nm because the detectors were fabricated on bare oxidized silicon wafers and were manually aligned to the optical fibre. Here, we report WSi SNSPDs embedded in an optical stack designed to enhance absorption (Supplementary section ‘Fabrication’) at λ = 1,550 nm and coupled to single-mode optical fibres at λ = 1,550 nm with a self-aligned mounting scheme based on silicon micromachining. Using WSi SNSPDs, we constructed a detector system with SDE as high as ≈ 93% around λ = 1,550 nm, a system dark count rate of ≈ 1 × 10^3 c.p.s. (primarily due to background radiation), a timing jitter of ≈ 150 ps full-width at half-maximum (FWHM) and a reset time of 40 ns. The only other single-photon detector that has demonstrated SDE > 90% at λ = 1,550 nm is the transition-edge sensor (TES). However, the TES has orders of magnitude larger recovery time (≈ 1 μs) and timing jitter (the best value to date is ≈ 5 ns; ref. 19) than WSi SNSPDs, and requires a complicated superconducting readout circuit.

We characterized our single-photon detection system by using 28 different SNSPDs from five fabrication runs. We measured SDE > 85% with 50% of the detectors tested so far (Supplementary section ‘List of characterized devices’). Figure 1a shows the bias dependence of SDE (Methods and Supplementary section ‘Estimation of the system detection efficiency’) for our best device. As the detection efficiency of SNSPDs varies with the polarization of the incident light, the polarization state of the light was varied on the Poincaré sphere to maximize or minimize the counts from the detector. We therefore obtained a maximum (SDE\textsubscript{max}, red curve) and minimum (SDE\textsubscript{min}, blue curve) SDE versus I\textsubscript{B} curve. Both the SDE\textsubscript{max} and SDE\textsubscript{min} curves had a sigmoidal shape, and saturated at SDE\textsubscript{max} ≈ 93% and SDE\textsubscript{min} ≈ 80% for I\textsubscript{B} values larger than a cutoff current I\textsubscript{c}. The DDCR was ≈ 1.5 μA and lower than the switching current of the device, I\textsubscript{SW} = 4 μA. Figure 1b shows the bias dependence of the system dark count rate (SDCR, the response pulse count rate measured when the input fibre to the system is blocked by a shutter) and of the device dark count rate (DDCR, the response pulse count rate measured when the fibre is disconnected from the device inside the refrigerator). The SDCR versus I\textsubscript{B} curve has a sigmoidal shape similar to the SDE versus I\textsubscript{B} curves shown in Fig. 1a, and saturated at SDCR ≈ 1 × 10^3 c.p.s. for I\textsubscript{B} > I\textsubscript{c}. The DDCR was ≤ 1 c.p.s. for most of the bias range (I\textsubscript{B} ≤ 0.97I\textsubscript{SW}), which is approximately two orders of magnitude lower than the DDCR of NbN SNSPDs with a similar active area and fill factor. We concluded that the SDCR is dominated by background photons.

Typically, the detection efficiency of SNSPDs varies significantly with the polarization of the incident light (by a factor of ≈ 2 at λ = 1,550 nm; refs 20,22). However, a detector with polarization-insensitive SDE would be desirable for many applications. We therefore characterized the polarization and wavelength dependence of the SDE by mapping the SDE onto the Poincaré sphere in the wavelength range λ = 1,510–1,625 nm (we call these plots Poincaré maps of the SDE). Figure 2a,b shows the Poincaré maps at λ = 1,510 nm and λ = 1,625 nm. The positions of the maxima and minima of the Poincaré maps are approximately the same at

![Figure 2](https://example.com/figure2.png)
however, the ratio between maximum and minimum values of the SDE \( R = \frac{SDE_{\text{max}}}{SDE_{\text{min}}} \) change with wavelength. Figure 2c shows the wavelength dependence of \( SDE_{\text{max}} \) (red squares), \( SDE_{\text{min}} \) (blue squares) and \( R \) (black triangles), which were obtained by extracting the maxima and minima of the Poincaré maps at each wavelength. Although the SDE of our detector showed a non-negligible polarization dependence, the results shown in Fig. 2c suggest that the optical stack could be designed to eliminate the polarization dependence of the SDE at a particular wavelength (which, however, may differ from the wavelength for the maximum SDE).

Most of the readily accessible closed-cycle refrigeration technologies\(^\text{25}\) do not reach a base temperature below 1 K. It would therefore be desirable to operate our detector above 1 K without degrading its performance. As the critical temperature of our SNSPD was \( T_c = 3.7 \text{ K} \), we characterized the performance of the system as a function of temperature by measuring the bias dependence of SDE, SDCR and DDCR in the temperature range \( T = 120 \text{ mK}–2 \text{ K} \). As shown in Fig. 3a, although \( I_{\text{SW}} \) decreases and approaches \( I_{\text{co}} \) with increasing temperature (dark yellow stars on the \( I_B–T \) plane), the SDE versus \( I_B \) curve saturates to \( \approx 93\% \) over the whole temperature range \( T = 120 \text{ mK}–2 \text{ K} \) (dark yellow triangles on the SDE–T plane). As shown in Fig. 3b, the DDCR at the switching current increases with temperature, from \( \approx 20 \text{ c.p.s.} \) at \( T = 120 \text{ mK} \) to \( \approx 10^3 \text{ c.p.s.} \) at \( T = 2 \text{ K} \), and is comparable to the SDCR for \( T > 0.8 \text{ K} \). Although the bias range for efficient, low-dark-count-rate single-photon detection decreases with increasing temperature, the detector shows SDE \( \approx 90\% \) and DDCR, \( \approx 10 \text{ c.p.s.} \) for \( I_B \approx 0.9 I_{\text{SW}} \) over the temperature range investigated (coloured circles in Fig. 3a,b), confirming that we could operate the detector system at relatively high cryogenic temperature without significantly degrading its sensitivity.

We characterized the timing performance of the detector system by measuring the histogram of the inter-arrival time\(^\text{13,26}\) of the response pulses and the timing jitter at \( T = 120 \text{ mK} \). Although in conventional NbN SNSPDs the decay time of the response pulse has been traditionally used as an estimate of the reset time of the detector\(^\text{27}\), in our detector the reset time is significantly shorter than the decay time. As shown in Fig. 4a, the decay time of the response pulse of the SNSPD is \( \tau \approx 120 \text{ ns} \). However, Fig. 4b
The jitter increases with decreasing the detector (I\text{bias} currents. The IRF becomes broader with decreasing system illuminated with a femtosecond-pulse laser for two different shows the instrument response function (IRF) of the detector, detection efficiency at Finally, because of the relatively large bias range with saturated which would allow the jitter of the detector system to be reduced. Decreases from 250 ps at system, which we define as the FWHM of the IRF. The system jitter increases from 250 ps at I\text{co} ≈ 0.97I_{SW} to 150 ps at I\text{co} = 0.97I_{SW}. As the jitter increases with decreasing I\text{co} and I_{SW} decreases with increasing temperature, operating the detector at higher temperature would result in a degradation of its timing resolution. The jitter of our detector system is higher than the values of 30–50 ps typically reported for conventional NbN SNSPDs. However, the system jitter is dominated by the electrical noise of the readout circuit, rather than the intrinsic jitter of WSi SNSPDs (Supplementary section ‘Noise contribution to the jitter’).

In conclusion, our single-photon detector system based on WSi SNSPDs demonstrated SDE ≈ 90% at λ = 1,550 nm and DDCR < 10 c.p.s. up to a temperature of T = 2 K. We expect our detector system to achieve a system dark count rate limited by the device intrinsic dark count rate (SDCR ≈ DDCR < 1 c.p.s.) by improving the filtering of the background photons. In the future, by adopting a parallel architecture (superconducting nanowire avalanche photodetector, SNAP)\textsuperscript{3,28,29}, we expect to reduce the reset time of our SNSPDs to <10 ns and to increase the signal-to-noise ratio\textsuperscript{16}, which would allow the jitter of the detector system to be reduced. Finally, because of the relatively large bias range with saturated detection efficiency at λ = 1,550 nm, WSi SNSPDs have the potential for high fabrication yield across a silicon wafer and broad wavelength sensitivity\textsuperscript{14,30}. These two features will enable two major advancements in the near future: (i) high SDE in the mid-infrared wavelength range, and (ii) large SNSPD arrays with near-unity efficiency from the visible to the mid-infrared spectral regions.

Methods
Detector system and measurement set-up. The experimental set-up used for the optical characterization of our detector system is presented in Supplementary section ‘Measurement set-up’. For the SDE and inter-arrival time measurements, we illuminated the detector using a fibre-coupled continuous-wave tunable laser with tuning range λ = 1,510–1,630 nm. For jitter measurements, we used a mode-locked fibre laser with emission around 1,560 nm, pulse width of <100 fs and repetition rate of ≈ 35 MHz. We controlled the polarization of the light from the lasers with a polarization controller. The light was then coupled to three variable optical attenuators (with nominal attenuation A_1, A_2 and A_3) and to a micro-electromechanical system optical switch. The optical switch diverted the light at its input to the detector system (we call this output the detector port) or to a calibrated (Supplementary section ‘Calibration of the optical power meters’) InGaAs optical power meter (we call this output the control port).

After fabrication, a device could be removed from the wafer\textsuperscript{37} and mounted inside a zirconia sleeve with an optical fibre. Holding both the detector chip and the optical fibre, the zirconia sleeve realized an optical alignment with a typical accuracy of ±3 μm (ref. 17). All of the optical fibres used were silica C-band single-mode fibres. The optical fibre coupled to the detector inside the cryostat (a cryogen-free adiabatic demagnetization refrigerator) was coated with a multi-dielectric-layer anti-reflection coating that reduced the reflectivity at the interface between the silica and the air (or vacuum) below 0.3% in the wavelength range of interest. The fibre coupled to the detector was then spliced to a fibre inside the cryostat. That cryostat fibre was fed out of the cryostat through a vacuum feed-through and then spliced to a fibre coupled to the detector port of the optical switch.

The detectors were wire-bonded to launching pads connected to brass coaxial cables (2 GHz electrical bandwidth at 300 K). The devices were current-biased with a low-noise voltage source in series with a 10 kΩ resistor through the d.c. port of a room-temperature bias-tee (40 dB isolation, 100 kHz–4.2 GHz bandwidth on the radiofrequency port). The readout circuit consisted of a chain of two low-noise, room-temperature amplifiers (100 kHz–500 MHz bandwidth, 24 dB gain, 2.9 dB noise figure) connected to the radiofrequency port of the bias-tee. The amplified signal was connected to a 225 MHz bandwidth counter (for detection efficiency measurements) or to an 8 GHz bandwidth, 20 Gsample/s oscilloscope (for jitter and inter-arrival time measurements).

Estimation of SDE. The SDE was measured as the ratio of the photoresponse count rate (PCR) and the number of photons in the SNSPD fibre (N_{\text{ph}}), where SDE = PCR/N_{\text{ph}}. PCR was estimated as the difference between the response-pulse

![Figure 4](image-url)
count rate (CR), measured with the laser beam attenuated ~80 dB ($A_2 = A_3 = 40$ dB) and coupled to the detector, and the SDCR. We defined the SDCR as the response pulse count rate measured with the laser beam blocked by the shutters of the variable optical attenuators. $N_{\text{Bk}}$ at a particular wavelength $\lambda$ was calculated by using an estimate of the optical power in the SNSPD fibre ($P_{\text{SNSPD}}$) and the energy of a single photon at that wavelength.

The SDE was measured at a particular wavelength with the following procedure. (i) We measured the splitting ratio of the optical switch ($R_{\text{Wk}}$), which we defined as the ratio between the power at the detector and control ports of the switch. (ii) We then measured the real attenuation of attenuator 2.3 ($\alpha_{2,3}$) when the nominal attenuation of attenuator 2.3 was set to 40 dB ($A_2 = A_3 = 0$ dB and $A_{2,3} = 40$ dB). (iii) With the attenuation of attenuator 2.3 set to zero ($A_2 = A_3 = 0$ dB), we varied the attenuation of attenuator 1 ($A_1$) to obtain the desired input optical power in the control port ($P_c$). (iv) We then closed the shutters of the three attenuators and measured the SDCR versus $I_c$ curve. (v) We opened the shutters of the three attenuators, set the attenuation of attenuator 2 and 3 to 40 dB ($A_2 = A_3 = 40$ dB) to reduce the optical power to the single-photon level ($\sim 50 \times 10^3$ photons per second), and measured the CR versus $I_c$ curve. We calculated the optical power in the SNSPD fibre as $P_{\text{SNSPD}} = P_{c}\cdot \alpha_2 \cdot \alpha_3 \cdot R_{\text{SNSPD}}/(1 - \rho)$. Further details are presented in Supplementary sections ‘Estimation of the system detection efficiency’, ‘Estimation of the uncertainty on the system detection efficiency’, ‘Stability of the optical’.

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Author contributions

F.M., V.B.V., J.A.S., A.E.L., B.B., R.P.M. and S.W.N. conceived and designed the experiments. F.M., V.B.V., J.A.S., S.H. and T.G. performed the experiments. F.M. and S.H. analysed the data. J.A.S., I.V., M.D.S. and S.W.N. contributed materials/analysis tools. F.M. wrote the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to F.M. and S.W.N.

Competing financial interests

The authors declare no competing financial interests.