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Short Communication

Mid-infrared single photon detector with superconductor $Mo_{0.8}Si_{0.2}$ nanowire

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Mid-infrared (mid-IR) single photon detectors have broad applications in science and technology, such as biomolecular spectrum analysis [1] and astronomical observations [2]. Unfortunately, it is much more difficult than detecting near-infrared photons due to the significantly reduced energy of mid-IR single photon. Superconducting nanowire single photon detectors (SNSPDs) have shown a great potential in mid-IR single photon detection relied on the low energy gap (~meV) of superconductor materials. In 2011, Marsili et al. [3] extended the response bandwidth of SNSPD to 0.5–5 μm band by reducing the width of NbN nanowire to 30 nm, resulting in a saturated internal detection efficiency at wavelengths $\lambda < 3$ μm. The reduced width of 30 nm increased the probability of the transition from the superconducting state to the non-superconducting state. In 2019, Verma et al. [4] reported a SNSPD based on WSi films, a superconductor material with low energy gap, achiving a response cut-off wavelength at 9.9 μm. The lower energy gap of WSi enhanced the efficiency of the photon-induced Cooper pair decoupling. As can be seen above, it is an effective way to develop mid-IR SNSPD through ultra-narrow nanowires patterned on superconductor films with low energy gap.

Recently, the amorphous superconductor MoSi has shown promise as a high-performing material in near-IR SNSPDs [5]. Considering that MoSi also has a low superconductor energy gap similar to that of WSi [6], it is a competitive candidate for mid-IR SNSPDs. Herein, we report a mid-IR SNSPD based on ultra-narrow superconducting MoSi nanowire with high internal detection efficiency.

The mid-IR SNSPD was firstly fabricated by amorphous MoSi film in the experiment, as shown in the Supplementary materials Note S1. The MoSi film was grown on the polished and thermally nitrided silicon wafer by employing the DC magnetron sputtering from an alloy target (4-inch diameter) with the stoichiometry of Mo:Si = 0.8:0.2, also written as $Mo_{0.8}Si_{0.2}$. Considering the poor antioxidant ability of the $Mo_{0.8}Si_{0.2}$ film, ~3 nm-thick Nb_5N_6 grown on the $Mo_{0.8}Si_{0.2}$ film was carried out *in-situ* to prevent the oxidation (Table S1 online). The thickness of $Mo_{0.8}Si_{0.2}$ film was measured to be 6 nm by transmission electron microscopy (TEM; Fig. 1a). The square resistance (R_{sq}) of the $Mo_{0.8}Si_{0.2}$ film was 248.6 Ω/□ and the superconductor critical temperature (T_c) was 4.5 K at 10% R_{20K}. A total active area of 10 μm × 10 μm of the SNSPD was patterned on the $Mo_{0.8}Si_{0.2}$ film by sequential electron-beam lithography (EBL) and reactive ion etching (RIE) steps (Fig. 1b). The active area was composed of $Mo_{0.8}Si_{0.2}$ superconducting nanowires with a width of 30 nm and a pitch of 150 nm, as confirmed by scanning electron microscopy (SEM; Fig. 1c). The nano-fabrication process was carefully optimized to improve the homogeneity in nanowire width (Figs. S1 and S2 online).

The device exhibited a switching current (I_{SW}) of 4.34 μA. The theoretical depairing current density of the $Mo_{0.8}Si_{0.2}$ nanowire at 0 K ($j_{dep}^{KL}(0)$) was calculated to be 3.01×10^{10} A/m^2, which in turn equated to a theoretical depairing current ($I_{dep}^{KL}(0)$) of 5.48 μA, based on a nanowire cross-section of 1.82×10^{-16} m^2 (Supplementary materials Note S2). The measured switching current (I_{SW}) was slightly lower than the theoretical value (i.e., $I_{SW}/I_{dep}^{KL}(0) = 0.79$) as previously reported NbN SNSPD [7], which was attributed to the loss of superconductivity at the edges of the nanowires.

A free-space coupling strategy was then adopted to evaluate the mid-IR SNSPD (Fig. S3 online). A silicon nitride blackbody source was used to generate broad, and continuous mid-IR spectrum. The mid-IR SNSPD was free-space coupled through a dilution

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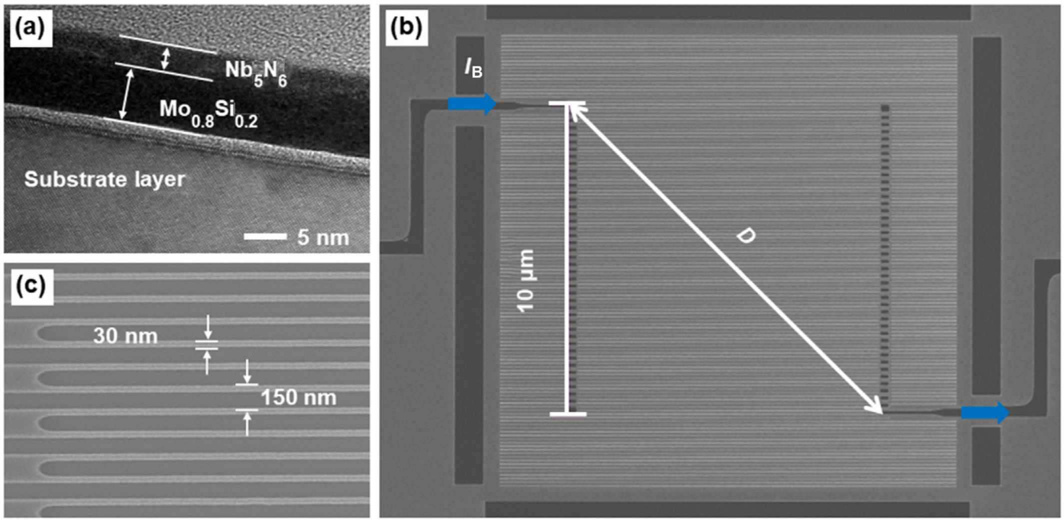

Fig. 1. (a) TEM image of the $Mo_{0.8}Si_{0.2}$ film's cross-section. (b) SEM image of the device active area with 10 μm × 10 μm. The dark blue arrow indicates the direction of the bias current flow. The width of the nanowires on the diagonal line (*D*) has high uniformity in geometry. (c) High magnification SEM image of the nanowires shows the nanowire width and pitch. The image is a zoom-in of an area of (b).

refrigerator set at 80 mK, and then illuminated onto the device. A variable neutral-density (ND) filter was used to fix the attenuation of the incident light to the single-photon level (Fig. S4 online). Additionally, specific wavelength (λ) ranges were selected by using one of seven bandpass filters with bands centered at 1.55, 2.00, 2.25, 3.00, 4.00, 4.26 or 5.07 μm. More details were shown in the Supplementary materials Note S3 and S4.

In the experiment of detecting mid-IR photons, the signal-to-noise ratio (SNR) of response pulse was approximately 8.4, which was large enough for distinguishing true signals from the noise. The internal detection efficiency ($\eta_{internal}$) of the device was also determined, where $\eta_{internal}(\lambda)$ represented the probability of a nanowire absorbing one photon at a determined wavelength (λ) and then generating a detectable electrical signal, which was defined as [8]:

$$\eta_{internal}(\lambda) = PCR(\lambda)/PCR_{saturation}(\lambda). \quad (1)$$

$PCR(\lambda)$ was the photon count rate at the selected wavelength, and $PCR_{saturation}(\lambda)$ was defined as the $PCR(\lambda)$ at the saturated region where the photon count rate was independent of the bias current (I_B). More details about the definition were shown in the Supplementary materials Note S5.

As shown in Fig. 2a, we observed that $\eta_{internal}$ reached saturation within the bias range ($I_B < I_{SW}$) when $\lambda \le 4.00$ μm. Notably, $\eta_{internal}(\lambda)$ still tended to become saturated when $\lambda \ge 4.26$ μm. The maximum $\eta_{internal}(\lambda)$ values attained were 98% at λ = 4.26 μm; and 97% at λ = 5.07 μm. The I_B dependence of $\eta_{internal}(\lambda)$ was then fitted by an empirical sigmoid function (the Supplementary materials Note S5) to characterize the saturation region (ΔI_B) of $\eta_{internal}(\lambda)$ at 1.55–4.00 μm. The fitting results showed that the saturation region width (ΔI_B) decreased as the wavelength increased, and the $\eta_{internal}(\lambda)$ would be saturated at 5.07 μm if the I_{SW} was increased to 4.6 μA. The photon response at $\lambda > 6$ μm has not been characterized currently since the cutoff wavelength of optical window of the dilution refrigerator was no more than 6 μm. Furthermore, the maximum counting rate for 300 K blackbody radiation (*BCR*) of the device was close to 2 Mcps and even showed the onset of saturation. It has demonstrated that the device had a very high photon response rate to 300 K background radiation (Fig. S5 online). Considering the saturated features of the measured counts, we speculated that the mid-IR SNSPD could response to photons up to 10 μm. The high internal detection efficiency was attributed to both reduced cross-section area and low energy gap of $Mo_{0.8}Si_{0.2}$ films.

Quantum efficiency (*QE*) was defined as the ratio between the photon count rate and the number of incident photons on the active area per second, also written as $QE(\lambda)$ because it was wavelength-dependent. The calculation process of $QE(\lambda)$ was shown in Figs. S6 and S7 (online). We could conclude that $QE(\lambda)$ decreased with increasing wavelength (Fig. 2b), which could be attributed to reduced infrared absorption efficiency of the nanowire. The inset in Fig. 2b showed the relative statistical error ($\varepsilon_{QE}(\lambda)$) on the value of $QE(\lambda)$ at each wavelength, which we calculated as the ratio between the standard deviation and the mean of $QE(\lambda)$. $\varepsilon_{QE}(\lambda)$ was shown to increase slightly as the wavelength increased.

The dark count rate (*DCR*) was measured when the mid-IR SNSPD was shielded at 4 K. The *DCR* was always no more than 100 cps (Fig. 2c), and thus it may make the device have potential applications in infrared telescope. We found that the *DCR* was still detected at $I_B < 0.7 I_{SW,}$ which could be attributed to the occasional entry of vortices or phase slips due to random processes in such narrow nanowires.

The noise equivalent power ($NEP(\lambda)$) was further introduced to characterize the sensitivity of the SNSPD as shown in Fig. 2d. The $NEP(\lambda)$ was calculated using the values of the quantum efficiency and the dark count rate at $I_B = 0.9\ I_{SW}$. The error of $NEP(\lambda)$ was calculated from the uncertainty of $QE(\lambda)$. The $NEP(\lambda)$ levels on the order of 10^{-18} W/Hz$^{1/2}$ were calculated in the mid-IR band, which verified the high sensitivity of the mid-IR SNSPD. Improvements in the accuracy of $QE(\lambda)$ measurements in future studies could reduce the $NEP(\lambda)$ error. Nevertheless, the $NEP(\lambda)$ of the mid-IR SNSPD can be improved by increasing the absorption efficiency [9] with an optical cavity and reducing the polarization sensitivity of the nanowire as widely used in the near-IR SNSPD [10].

In summary, a SNSPD composed of 30 nm width $Mo_{0.8}Si_{0.2}$ nanowires was prepared and demonstrated for detecting single mid-IR photons. High internal detection efficiencies in the range of 1.55–5.07 μm wavelength were exhibited at a noise equivalent power on the order of 10^{-18} W/Hz$^{1/2}$. The high sensitivity of the mid-IR SNSPD was benifited from both reduced cross-section area and low energy gap of $Mo_{0.8}Si_{0.2}$ films. Considering the saturated features of measured counts to 300 K background radiation, we speculated that the mid-IR SNSPD could response to photons with

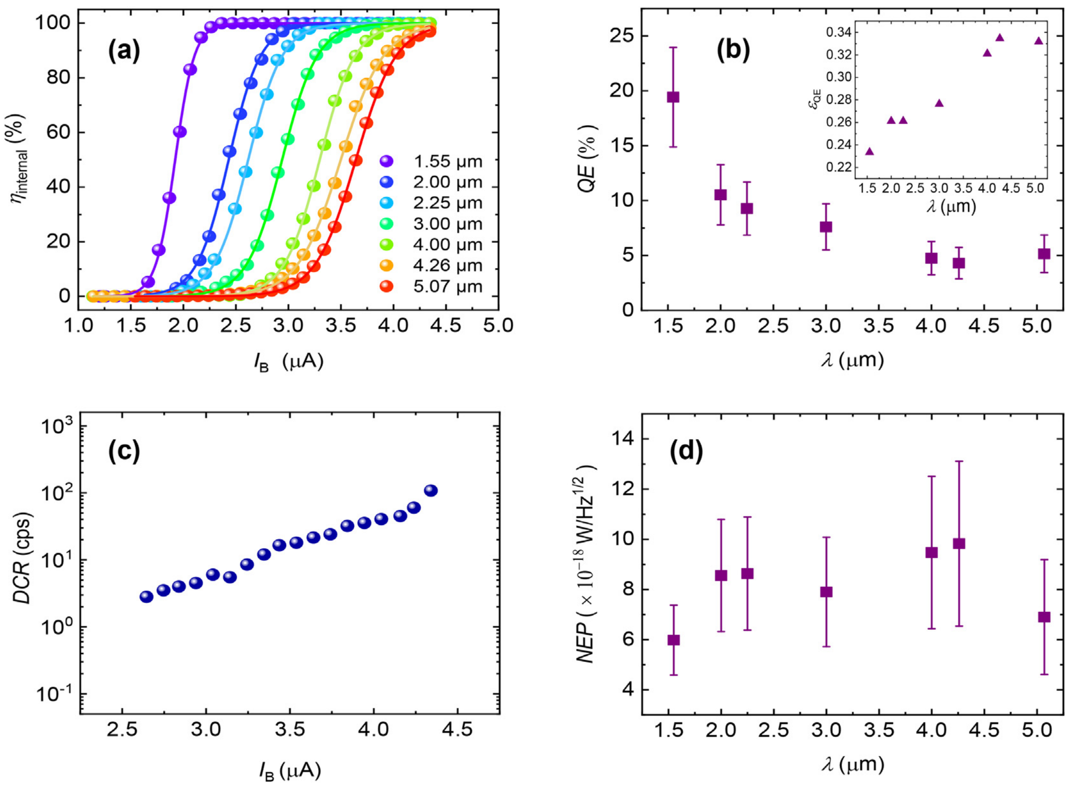

Fig. 2. (a) The relationship between the internal detection efficiency ($\eta_{\text{internal}}(\lambda)$) and the bias current ($I_B$) at 80 mK. Different colors represent different working wavelengths, the solid circles represent the measured data, and the solid curves represent the fitting results. The superconducting switching current (I_{SW}) is 4.34 μA. (b) Quantum efficiency ($QE(\lambda)$) vs. λ of the 30 nm wide $Mo_{0.8}Si_{0.2}$ SNSPD biased at $I_B = 0.9I_{SW}$. The error bars of the quantum efficiency were calculated, propagating the uncertainty on the value of the photon flux due to the precision of the power meter. Inset: wavelength-dependence of the relative statistical error ($\varepsilon_{QE}(\lambda)$) on the value of $QE(\lambda)$. (c) The dark count rate (*DCR*) of the device vs. I_B with 4 K background radiation. (d) Calculated noise equivalent power ($NEP(\lambda)$) of the device with $I_B = 0.9I_{SW}$ at 1.55–5.07 μm wavelength range. The error bars on the value of $NEP(\lambda)$ were calculated from the uncertainty of $QE(\lambda)$.

wavelength up to 10 μm in the future. Thus, this work paves a way to develop mid-IR MoSi SNSPD for potential applications in infrared astronomy.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Labao Zhang conceived and supervised the research. Qi Chen, Rui Ge and Feiyan Li designed and fabricated the SNSPD. Qi Chen, Rui Ge, Feiyan Li, Biao Zhang, Feifei Jin, Hang Han, Xiaoqing Jia, Qingyuan Zhao, Xuecou Tu, Lin Kang, Jian Chen and Peiheng Wu characterized the detection system, analyzed the data and prepared the figures. Qi Chen, Rui Ge, Labao Zhang, Yue Dai, Guanglong He, Yue Fei, Xiaohan Wang and Hao Wang wrote the manuscript. In addition, Xiaoqing Jia, Qingyuan Zhao, Xuecou Tu, Lin Kang, Jian Chen and Peiheng Wu participated in the discussion during the development of the paper. All authors discussed the results and revised the manuscript.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2021.02.024.

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