

Efficient detection of midinfrared photons by phonon trapping in superconducting nanowires

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Phonons not only serve as the fundamental medium underlying superconductivity but also play a critical role in tuning the performance of superconducting nanowires. Here, we present an efficient approach for detecting midinfrared single photons by leveraging enhanced phonon trapping in superconducting nanowires, which arises from intrinsic acoustic mismatch. In the experiment, the nanowires are patterned on nitrogen-doped amorphous tungsten films, which consist of disordered heavy atoms and weakly doped light atoms. This unique structural composition enables the films to exhibit a phonon group velocity that is significantly lower than that of the silicon substrate. The current-voltage characteristics reveal an ultrahigh ratio of the superconducting switching current to retrapping current (~ 22), which is more than three times higher than that of conventional niobium nitride nanowires. We attribute the increased ratio to phonon trapping facilitated by strong intrinsic acoustic mismatch. Furthermore, the fabricated detector achieves saturated internal detection efficiencies across a wavelength range 1.75–6 μm . This work provides a facile strategy for improving the sensitivity of midinfrared single-photon detectors through *in situ* phonon engineering.

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I. INTRODUCTION

Infrared control of quantum states in superconducting nanowires has emerged as a prominent research focus in recent decades, offering intriguing prospects for detector engineering. In particular, quasi-two-dimensional superconducting nanowires exhibit photon-excited nonequilibrium behaviors that significantly alter metastable quantum states and generate measurable signal outputs under a current bias. This remarkable phenomenon provides a theoretical foundation for achieving ultrasensitive single-photon detection in superconducting nanowires. In recent years, efficient midinfrared (MIR) single-photon detection has played a pivotal role in both fundamental physics research and scientific applications, including molecular vibration spectroscopy [1], quantum entanglement studies [2], planetary exploration [3], and high-dimensional MIR imaging [4]. Compared to semiconductor-based detectors, superconducting nanowire detectors exhibit superior performance across multiple metrics, such as intrinsic high sensitivity, ultralow noise [5], high

internal detection efficiency (IDE) [6], high time resolution [7], and high response speed [8].

As a detection technology with superconducting nanowires as the core component, superconducting nanowire single-photon detectors (SNSPDs) typically exhibit an energy gap smaller than 5 meV, theoretically enabling a detection band that extends to the midinfrared and even longer wavelengths [9]. Moreover, their photon-counting capability makes SNSPDs inherently resistant to amplifier noise and current drift, offering superior stability compared with HgCdTe or blocked impurity band detectors [3]. However, experimentally extending the detection wavelength of SNSPDs into the MIR regime still faces challenges because of insufficient energy for Cooper pair breaking and energy loss in the substrate. Previous efforts have improved the detector sensitivity in the MIR region by lowering the detection threshold through various approaches, such as reducing the nanowire cross-sectional area [10], employing materials with a low superconducting energy gap and increasing the sheet resistivity of the superconducting film [11,12]. However, several experimental challenges persist. For example, the fabrication of narrow nanowires poses significant difficulties and restricts the active area [13]. Additionally, both a low superconducting energy gap and high sheet resistivity lead to a reduced bias current, potentially degrading the signal-to-noise ratio and limiting the scalability of detector arrays.

Phonon-mediated energy loss at superconductor/substrate interfaces plays a crucial role in determining both energy resolution [14] and IDE [15]. Effective nanoscale phonon

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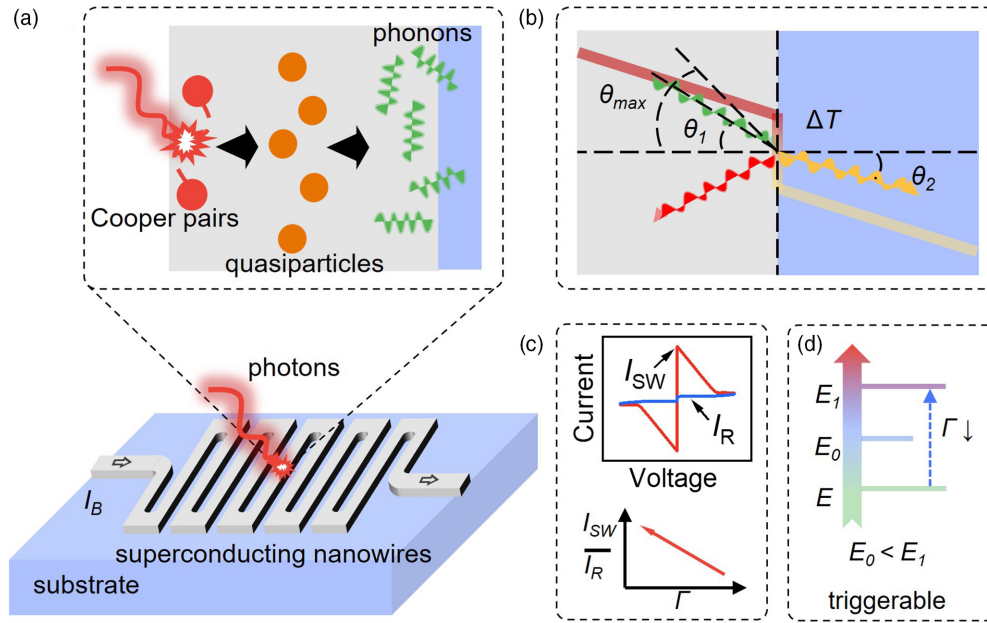


FIG. 1. Interfacial phonon transport engineering diagrams. (a) Schematic diagram of the photon detection procedure. Nanowires of superconducting nanowires emit a number of phonons through electron-phonon interactions after they absorb photons. (b) Schematic diagram of the acoustic mismatch of the superconducting nanowires to the substrate and phonon trapping. When many phonons (green) are incident on the interface, reflection (red) and transmission (orange) behaviors occur. The reflected phonons will be trapped within the superconducting nanowires. (c) Current-voltage characteristics of the superconducting nanowires. The ratio between the switching current (I_{SW}) and the retrapping current (I_R), I_{SW}/I_R , increases with decreasing phonon emissivity, Γ . (d) Schematic diagram of enhanced photon detection by phonon trapping. Intrinsically enhanced phonon trapping reduces Γ and enables more energy to be converted into the electron system. All the gray and light-blue structures represent superconducting nanowires and the substrate, respectively.

engineering is critical for optimizing the thermal and electrical performance of materials, offering new pathways to advance MIR single-photon detection [16]. Recent studies have elucidated the mechanisms governing phonon transport across interfaces and identified key factors that control thermal transport, such as interface abruptness [17], inhomogeneous strain [18], and lattice mismatch [19].

In superconducting nanowires, hot spots arise primarily from two mechanisms: photon-induced nonequilibrium hot spots and self-heating hot spots. When a substantial mismatch exists between the superconductor and its substrate, phonon transmission across the interface is severely suppressed, and phonons excited by photon energy are well trapped [20]. Structures such as phonon blocking layers [21], multilayers with mismatched Debye temperatures [22], and suspended membranes [23] have been successfully implemented to reduce the interfacial thermal conductance. However, these approaches often introduce nanofabrication and optical integration challenges, mainly due to extrinsic insulation layers or defects. Consequently, intrinsic interfacial engineering strategies that suppress phonon loss in detectors without the incorporation of extrinsic insulating layers or defects are urgently needed. Recent work has shown that device dimensions can lead to phonon confinement, reducing heat capacity and potentially slowing heat transport. NbTiN thin films with a polycrystalline granular structure were used to demonstrate this phonon confinement effect [24].

In this work, we demonstrated a phonon engineering approach to strongly enhance phonon trapping in supercon-

ducting nanowires by strengthening the acoustic mismatch between the superconducting nanowire and the substrate. As a proof of concept, we introduced nitrogen-doped amorphous tungsten (NAW), a material characterized by a low Debye temperature due to its heavy atomic mass and strong structural disorder. The introduced NAW film could leverage strong acoustic mismatch with the silicon substrate. It has been verified that suppressed thermal transport fundamentally reduces phonon escape, leading to improved energy conversion efficiency within superconducting nanowires. The fabricated detector exhibited a large ratio of 22 between the switching current (I_{SW}) and the retrapping current (I_R), along with saturated internal detection efficiencies for infrared wavelengths ranging from 1.75 to 6 μm .

II. PHONON ENGINEERING ANALYSIS

For superconducting nanowires toward optical modulation and detection, the photon energy down-conversion procedure is illustrated in Fig. 1(a). Initially, the photon is absorbed by the superconducting nanowire and breaks Cooper pairs (red circles). Subsequently, hot electrons generate multiple electronic excitations (quasiparticles, orange circles) via electron-electron interactions and emit high-energy (Debye) phonons through electron-phonon interactions [25]. The fraction of energy absorbed by quasiparticles contributes to hot-spot formation, whereas the phonon energy dissipates through two primary pathways. Phonons transfer energy back to the electronic system through phonon-electron interactions,

escape into the substrate, and contribute to energy loss via phonon-phonon interactions. The overall photon energy conversion efficiency improves when energy loss is minimized.

In cryogenic conditions, phonon wavelengths and mean free paths are comparable to the thickness of superconducting nanowires. The acoustic mismatch model can be used to phenomenologically explain the phonon trapping mechanism, although it is not as physically accurate as in the description of large systems. Incident phonons may propagate as either longitudinal or transverse modes and may be reflected or refracted at the superconductor-substrate interface, which is governed by an acoustic analog of Snell's law [Fig. 1(b)] [20]. A strong acoustic impedance mismatch at the interface results in a small critical angle, $\theta_{\max}$, which defines the condition for total internal reflection. In other words, phonons incident at angles exceeding these angles are trapped entirely within the nanowires. $\theta_{\max}$ can be given by

$$\theta_{\max} = \sin^{-1} \frac{v_1}{v_2}, \quad (1)$$

where v_1 and v_2 define the phonon group velocities in the nanowire and in the substrate, respectively. If $\theta_{\max}$ is small, an increasing number of phonons are preferentially reflected back into the nanowire to break Cooper pairs before falling below the condensation energy threshold. The average transmission coefficient for phonon waves across the interface can be determined as $\zeta = 4Z_1Z_2 \cos \theta_1 \cos \theta_2 / (Z_1 \cos \theta_2 + Z_2 \cos \theta_1)^2$, where $Z_i = a_i v_i$ is the acoustic impedance for material i , with a and v denoting the mass density and average phonon group velocity, respectively. $\zeta \propto 1/\Delta T$, where ΔT defines the temperature difference across the interface [26]. ζ decreases as the acoustic impedance mismatch increases, which in turn results in an increased ΔT .

The thermal boundary conductance derived from self-heating in superconducting nanowires usually serves as a key figure of merit for evaluating detection performance, such as the IDE and the dark count rate. The net rate of phonon emission from detectors is quantified by the thermal boundary conductance, which can be studied by analyzing the I_R . I_R is defined as the minimum applied current required to maintain a stable resistive region in a superconducting detector. It is experimentally obtained from *current-voltage* (I - V) curves [Fig. 1(c)]. $\Gamma = (\eta_L/v_{Ls}^2 + 2\eta_T/v_{Ts}^2)(1/v_{Ls}^2 + 2/v_{Ts}^2)^{-1}$, where η_L and η_T are the angle-averaged transmission coefficients for phonons originating in the superconductor film, incident on the interface with the substrate, for longitudinal and transverse phonons. v_{Ls} and v_{Ts} are the longitudinal and transverse phonon velocities, respectively, in the superconductor film [27]. More trapped phonons lead to lower phonon emissivity (Γ), which in turn enhances the IDE for low-energy excitations, such as midinfrared photons. In addition, the derived ratio of the I_{SW} to the I_R can be regarded as another ruler to explore the detection performance of superconducting nanowire detectors. If the ratio is large, the nanowire will be capable of a large bias current (I_B) and high IDE at the same time. This is because $I_B \in [0, I_{SW}]$, and a large I_{SW} increases the upper limit of the I_B . A sufficiently large I_B offers three advantages for superconducting nanowire detectors: reduced noise

susceptibility, simplified readout design, and enhanced array scalability.

In Fig. 1(d), the detection threshold (E_0) represents the minimum energy required to trigger a detectable event, whereas E denotes the actual photon energy converted into the electron system of the nanowire. To detect single photons effectively (under the condition of $E_0 < E$), traditional strategies focus on reducing E_0 , including superconducting energy gap reduction, narrow nanowires, and high-resistivity films [10,11,28]. While these strategies improve the sensitivity, they inadvertently reduce the I_{SW} and impose challenges for large-scale array fabrication (e.g., uniformity, readout complexity). Enhanced phonon trapping in superconductors can break the limit by increasing E to E_1 to greater than E_0 . However, it has seldom been studied in depth. A promising yet underexplored approach involves increasing E to E_1 by enhancing phonon trapping.

III. EXPERIMENTS AND DISCUSSION

The Debye temperature Θ is a characteristic temperature of the highest normal mode of the atomic vibration of a material. Θ is proportional to $(P/m)^{0.5}$, where P denotes the elastic modulus and m is the atomic mass. If P remains constant, heavier atoms will result in a lower Debye temperature. Among element superconductors, tungsten (W) has a large atomic mass. In particular, if W is amorphized, a good reduction in both P and Θ will occur. Amorphous W has a higher transition temperature (T_c) than its crystalline counterpart does, which supports the development of high-performance superconducting detectors [29]. Among various materials, Si is the most widely used and has a high Debye temperature of approximately 640 K [30]. We deposited a NAW film on a Si substrate (see Note 1 in the Supplemental Material [31]). No crystalline peaks of W or WN are observed in the X-ray diffraction pattern of the NAW film. Additionally, there are no obvious lattice fringes in the cross-sectional high-resolution transmission electron microscopy image of the NAW film, and neither diffraction spots nor diffraction rings can be observed in the selected area electron diffraction image. Thus, the NAW film has a standard amorphous structure, and more details can be found in Supplemental Material Fig. S1 [31]. Moreover, X-ray photoelectron spectroscopy confirmed that the main component of the NAW film was amorphous W with only a small amount of doped N atoms [Figs. 2(a) and 2(b)].

Finkel'stein modeled the transition temperature, T_c , as a function of the sheet resistance (R_{sq}) for disordered superconducting materials. The reduction in T_c follows the relation [32]

$$\frac{T_c}{T_{c0}} = e^{\gamma} \left(\frac{\frac{1}{\gamma} + \frac{r}{4} - \sqrt{\frac{r}{2}}}{\frac{1}{\gamma} + \frac{r}{4} + \sqrt{\frac{r}{2}}} \right)^{1/\sqrt{2r}}, \quad (2)$$

where T_{c0} denotes the transition temperature of the bulk film and $T_{c0} = 4.4$ K, $r = R_{sq}e^2/(\pi h)$, and γ is the only fitting parameter, $\gamma = \ln[h/(k_B T_{c0} \tau)]$, and h , k_B , and τ are the Planck constant, the Boltzmann constant, and the electron scattering time, respectively. Figure 2(c) shows a plot of T_c versus R_{sq} for the NAW films and the fitting curve. The fitting yields $\gamma = 7.44$. From the value of γ , we extract $\tau = 1.02 \times 10^{-15}$

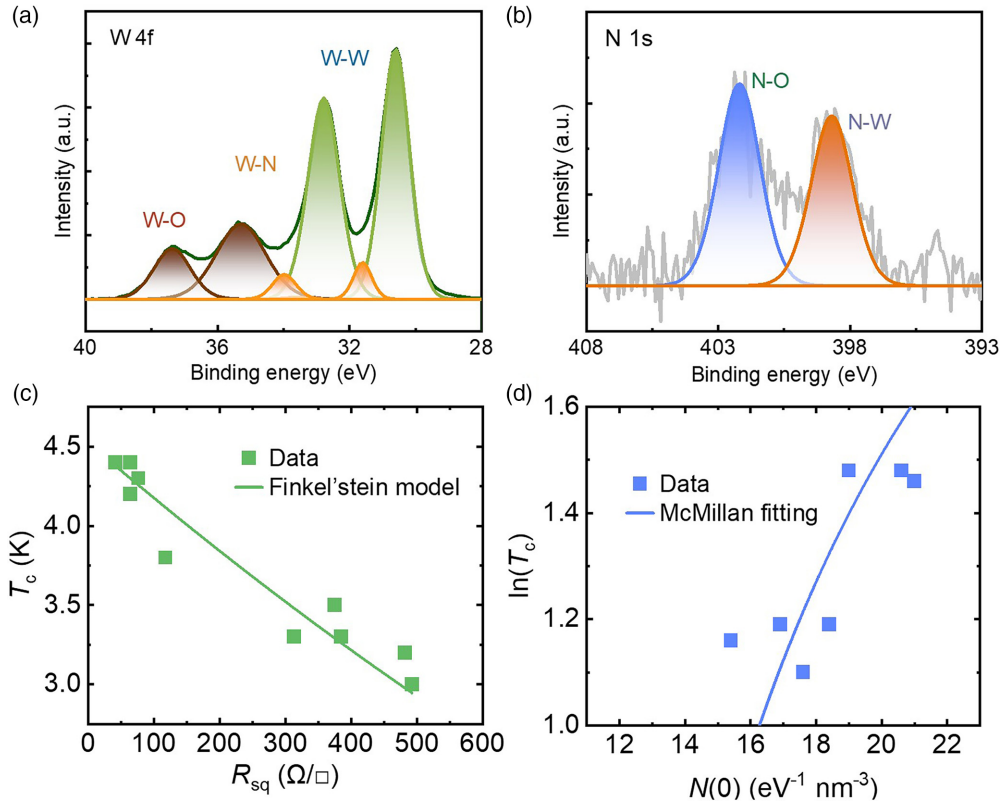


FIG. 2. Analysis of x-ray photoelectron spectroscopy results, transition temperatures, and acoustic characteristics. (a) W–W bonds dominate the spectroscopy results, whereas W–N bonds account for only a small portion. W–O bonds form on the surface of the NAW film, protecting the film from oxidation. (b) N–O bonds dominate the spectrum, whereas N–W bonds account for only a small portion. All the data in (a) and (b) were measured from newly grown NAW films, which is different from the results reported previously [29]. (c) Relationships between T_c and R_{sq} . The green line represents the Finkel'stein fitting model, which gives an adjusted R^2 coefficient of 0.92. (d) $\ln(T_c)$ as a function of $N(0)$. The blue line shows the McMillan fitting results.

s. The electron density $n = m_e / (R_{sq} d \tau e^2)$, where m_e is the electron mass, d is the thickness of the film, and e is the electron charge. The n was estimated to be $1.18 \times 10^{28} / \text{m}^3$ for the film. To understand the dependence of T_c on the spin density of states at the Fermi level, $N(0)$, we analyze the measured data within the framework of the McMillan model, as shown in Fig. 2(d). Within the theoretical model, T_c is given by [33]

$$\ln(T_c) = F - \frac{1.04[1 + KN(0)]}{KN(0) - \mu^*[1 + 0.62KN(0)]}, \quad (3)$$

where $F = \ln(\Theta/1.45)$, $KN(0)$ is the electron-phonon coupling constant, $N(0) = (2e^2 D R_{sq} d)^{-1}$, e is the electron charge, D is the electronic diffusion coefficient, $D = 0.6 \text{ cm}^2/\text{s}$, R_{sq} is the sheet resistance, and d is the film thickness. μ^* accounts for the electron-electron repulsive interaction ($\mu^* \sim 0.2$ for amorphous films). The Debye temperature and K are the same for all the films measured because of the stable and large disordered performance. We fit the variation in $\ln(T_c)$ with $N(0)$ using $\ln(\Theta/1.45)$ and K as fit parameters. The fitting value $K = 0.05$ results in electron-phonon coupling constants ranging from 0.8 to 1 for different NAW films deposited in the experiment, which indicates that the amorphous NAW films can be regarded as strongly coupled superconductors with s -wave pairing. Furthermore, the

Ioffe-Regel parameter ($k_F l \sim 3m_e D / \hbar$, where k_F is the Fermi wave vector, l is the electron mean free path, and $\hbar$ is the reduced Planck constant) is calculated to be greater than 1, which is an indication of a homogeneously disordered film. In addition, the best fitting result of Θ is 144 K, which is much lower than the Debye temperatures of other typical materials, such as NbN, WSi, and MoSi [34].

The average phonon group velocity (v) can be given by $v = k_B \Theta (6\pi^2 n)^{-1/3} / \hbar$, where k_B is the Boltzmann constant and $\hbar$ is the reduced Planck constant. We have calculated the v of NAW to be 2127 m/s, which is slower than the average phonon velocities of NbN (~ 5000 m/s), WSi (~ 3200 m/s), and MoSi (~ 3000 m/s) listed in the literature [34]. The longitudinal ($v_{Ls} \approx 8970$ m/s) and transverse ($v_{Ts} \approx 5330$ m/s) phonon velocities of the Si substrate are obtained from the literature [35]. The average phonon group velocity of the Si substrate $v = [3(1/v_{Ls}^2 + 2/v_{Ts}^2)^{-1}]^{0.5}$, which can be given as 6018 m/s. Thus, the critical angle, $\theta_{\max}$, can be estimated when phonons are incident from the superconductor to the Si substrate. Compared with MoSi ($\theta_{\max} = 29.9^\circ$), WSi ($\theta_{\max} = 32.1^\circ$), and NbN ($\theta_{\max} = 56.2^\circ$), the NAW/Si interface has the smallest $\theta_{\max}$ ($\theta_{\max} = 20.7^\circ$) among these typical structures. At the low-temperature limit, the thermal boundary conductance β is proportional to $\int_0^{\theta_{\max}} \zeta \sin \theta \cos \theta d\theta$. Thus, we can predict a very small β for the NAW/Si interface, and

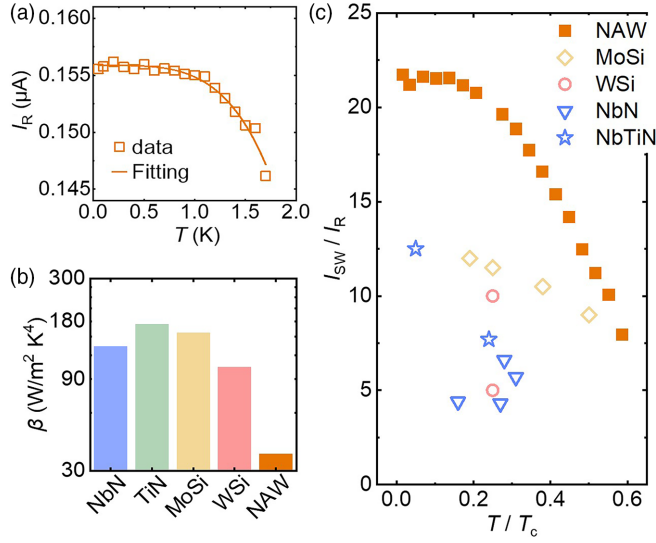


FIG. 3. Self-heating in a superconducting nanowire with intrinsic strong phonon trapping. (a) Temperature-dependent retrapping currents (I_R) of NAW nanowires. The solid red line shows the self-heating model fitting results. (b) Comparison of the generic thermal boundary conductance β of several typical superconducting nanowires on a Si substrate [27]. (c) Temperature-dependent ratios of the I_{SW} to the I_R of different superconductors (MoSi [36], WSi [38], NbN [27,39,40], and NbTiN [41]).

most of the out-of-equilibrium phonons are reflected back into the superconductor at the interface after the NAW nanowires absorb photon energy.

For experimental demonstration, we deposit an 8-nm-thick NAW film on a Si substrate, and the T_c of the film is approximately 3.3 K (Fig. S2). The T_c of the NAW nanowires decreases (0.5–1 K) because of the proximity effect [36]. We then fabricate an NAW detector with an active area of $10\ \mu\text{m} \times 10\ \mu\text{m}$ and a NW width of 80 nm (see Note 2 in the Supplemental Material [31] for fabrication details and Fig. S3 for the NW image). The measured I_{SWs} are approximately equivalent to $0.7I_{dep}$ (I_{dep} is the depairing current), resulting in a constriction factor α of 0.7 [Figs. S4(a)–S4(c)]. This value is greater than that reported previously (constriction factors less than 0.6 in superconducting nanowires with the same nanowire width [37]). A high constriction factor confirms the low probability of defects in such a detector with a large active area. Furthermore, we investigated the length dependence of the I_{SW} . The current fluctuation is $F < 6.5\%$ for nanowires with lengths ranging from 0.03 to 1 mm [Fig. S4(d)]. These results provide evidence that the superconductivity of NAW nanowires is weakly dependent on their geometry and fabrication process.

The temperature-dependent I_R is fitted by the self-heating model, which defines nanowires cooled by phonon blackbody radiation [Fig. 3(a)] [27].

$$I_R = \sqrt{\frac{\beta w^2}{R_{sq}} (T_{hs}^4 - T_b^4)}, \quad (4)$$

where β is the generic thermal boundary conductance in units of $\text{W/m}^2 \text{K}^4$, and T_{hs} is the temperature of the hot

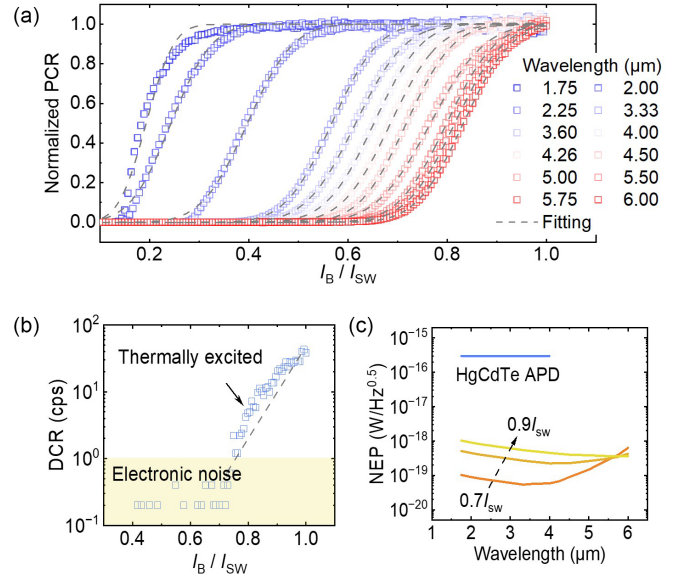


FIG. 4. Midinfrared single-photon detection with high sensitivity. (a) Current-dependent normalized PCR (PCR/PCR_{sat}, where PCR_{sat} is the saturated photon count rate) of the detector at different wavelengths. The operation temperature is 0.5 K, and the dashed black curves are the fluctuation model fitting results. (b) Current-dependent dark count rate (DCR) of the detector. (c) Noise-equivalent powers (NEPs) for the detector at different current biases. The solid blue line shows the reported NEP for HgCdTe APD at midinfrared [47].

spot. Both T_{hs} and β are adopted to be the fitting parameters. The best fitting value of T_{hs} is 3 K. The best fitting value of β is $36.8\ \text{W/m}^2 \text{K}^4$, which is smaller than the values of other typical interfaces in superconductor/Si structures [Fig. 3(b)]. For example, the β value of the NAW/Si structure is approximately one-third that of the NbN/Si structure. This confirms the strong interfacial thermal resistance of the NAW/Si structure.

The ratios of the I_{SW} to the I_R of different superconductors at different normalized temperatures are shown in Fig. 3(c). The ratio is denoted as $I_{SW}/I_R \propto \alpha/\beta^{0.5}$ at very low temperatures (more estimation details can be found in Note 3 in the Supplemental Material [31]). For a simple demonstration, we calculate the ratio difference between the NAW and the MoSi at a low temperature $T/T_c < 0.2$. Figure 3(b) shows that $\beta^{0.5}(\text{MoSi}) \approx 1.9\beta^{0.5}(\text{NAW})$, resulting in a ratio of $I_{SW}/I_R(\text{NAW})$ to $I_{SW}/I_R(\text{MoSi})$ of 1.9, which is comparable to the ratio obtained experimentally (~ 1.8) in Fig. 3(c). Furthermore, the NAW nanowire detector has a very large ratio of 22, which, to the best of our knowledge, has not been found in any other material.

We further demonstrate the broad-spectrum infrared detection capability of the detector through free-space coupling. To increase the signal-to-noise ratio of photon-excited pulses under low bias currents, we employ a low-pass filtering method (see more details in Figs. S5–S7). As shown in Fig. 4(a), the detector successfully responds to infrared photons at different wavelengths, with all the photon count rates (PCRs) exhibiting a monotonic increase with increasing bias current.

The operation temperature was 0.5 K. We fit all the results with the fluctuation model [42]. The sigmoid fitting function is shown as $\eta = 0.5 \operatorname{erfc}[(I_0 - I_n)/\Delta I]$, where η is the normalized PCR, I_0 is the normalized cutoff current, $I_0 = I_{co}/I_{sw}$, I_{co} is the cutoff current defined as the current at the inflection point of the curve, $I_n = I_B/I_{sw}$, and ΔI is the normalized transition width, where $\Delta I = \Delta I_B/I_{sw}$. Both I_n and ΔI are fitting parameters optimized separately for each wavelength. The normalized PCR curves exhibit saturation across a broad spectral range (1.75–6 μm). The saturation current width increases inversely with the infrared wavelength (i.e., shorter wavelengths yield a wider saturation region). The energy-insensitive current transition width indicates that the mid-IR photon detection procedure may follow the diffusive hot-spot model, $\lambda_c \propto [N(0)(k_B T_c)^2]^{-1}$ [43] (Fig. S8). We compare the cutoff detection wavelengths λ_c between the NAW detector and the $\text{W}_{0.3}\text{Si}_{0.7}$ detector reported previously [12]. The detection energy scales with the characteristic energy density $4N(0)(k_B T_c)^2$. The characteristic energy density and the λ_c of the $\text{W}_{0.3}\text{Si}_{0.7}$ detector are 2.35 $\mu\text{eV}/\text{nm}^3$ and 7.4 μm , respectively. Thus, the predicted λ_c of the NAW detector should be 3.3 μm because of the 5.29 $\mu\text{eV}/\text{nm}^3$ characteristic energy density. However, the measured λ_c is 6 μm , which is larger than the theoretical value without considering phonon trapping. We speculate that intrinsic strong phonon trapping contributes to an increase in the cutoff wavelength [44] (more details can be found in Note 4 in the Supplemental Material [31]). A postprocessing technique based on helium ion irradiation is also being investigated to improve the detector sensitivity, and has been validated on NbN and MgB_2 detectors [45,46]. Helium ion irradiation will introduce high-density, uniformly distributed artificial defects, which serve as efficient detection sites. This mechanism increases both the photon count rate and the cutoff wavelength of the detectors.

Figure 4(b) shows the dark count rate (DCR) of the detector. During the measurement, the detector is packaged in a sealed metal enclosure, resulting in the shielding of external electromagnetic radiation. The origin of the DCR is governed by distinct mechanisms depending on the bias current. Electronic noise dominates at low bias currents ($\leq 0.7I_{sw}$), whereas thermally excited carriers become the primary determinant at high bias currents ($> 0.7I_{sw}$). Noticeably, the maximum DCR remains below 50 cps in Fig. 4(b). The suppression of thermal fluctuations may stem from two main reasons. One is the high homogeneity of the nanowires, and the other is the low operating temperature. Furthermore, traditional detectors always show a linear relationship between $\ln(\text{DCR})$ and I_B/I_{sw} as the bias current increases (the gray dashed line). However, the measured data in this work slightly deviate from it. The deviation may originate from the asymmetry of the interfacial thermal conductance. That is, the interfacial thermal conductance for phonons incident from the NAW superconductor to the substrate differs from that for phonons incident from the substrate to the superconductor owing to the variation in the critical angle $\theta_{\max}$. Therefore, the out-of-equilibrium phonons in the substrate are more easily injected into the superconductor, resulting in fewer extra counts. The asymmetry mechanism is promoted by gated superconducting switches because the switching probability is

improved by the intrinsic strong phonon trapping in superconductors, and the switching voltage is reduced by the high injection rate of out-of-equilibrium phonons. This may be an interesting topic and will be deeply researched in our future work.

Figure 4(c) presents the calculated noise-equivalent powers (NEPs) of the detector across the broad midinfrared band. The NEP for a single-photon detector is calculated as $\text{NEP} = E_\lambda/\eta_D \times (2\text{DCR})^{0.5}$, where E_λ defines the photon energy and η_D defines the detector detection efficiency, which consists of the IDE and the optical absorption efficiency. The optical absorption efficiency is set to an achievable value of $\sim 70\%$. All the NEPs remain below $1 \times 10^{-18} \text{ W/Hz}^{0.5}$ over a wide range of bias currents, and the smallest NEP reaches $\sim 10^{-20} \text{ W/Hz}^{0.5}$. Compared with the widely studied HgCdTe midinfrared detectors, the detector obviously has higher sensitivity. Furthermore, the detector capability was also demonstrated at a relatively high temperature (Fig. S9). When the operating temperature is increased to 1 K, the detector maintains saturated PCRs over the spectral band of 1.75–5.5 μm . The IDE is 94% even at 5.75 μm . It can be speculated that more energy may be transferred into the phonon system if the temperature increases due to the decrease in the C_e/C_{ph} ratio (C_e and C_{ph} are the specific heat capacities of electrons and phonons, respectively) and the increase in the $\tau_{e-ph}^{-1}/\tau_{e-e}^{-1}$ ratio (τ_{e-e}^{-1} and τ_{e-ph}^{-1} are the electron scattering rates and the electron-phonon scattering rates, respectively). Indeed, the condensation energy has a strong nonlinear temperature dependence, which is under discussion and needs more thorough research. The intrinsic strong phonon trapping in the detector improves quasiparticle recombination in hot spots and ultimately weakens the sensitivity of the cutoff wavelength to temperature.

In addition, the time-dependent dynamic performance of the detector is characterized. The electrical pulse waveform is shown in Fig. 5(a), which has a full width at half maximum (FWHM) of ~ 22 ns. After $\sim 50\,000$ detection events are collected, the normalized counts as a function of time intervals are plotted in Fig. 5(b). The experimental recovery time was determined to be ~ 55 ns by fitting the experimental data to the sigmoid function (the error function). Thus, the maximum count rate (MCR) of the detector can be estimated to be 18 MHz. To perform a more in-depth experimental validation, the variation in the PCR with the input photons was measured (Fig. S10). The results agree well with the linear fit, with a slope of 0.97 (the goodness of fit $R^2 \sim 99.98\%$). The measured MCR is approximately 10 MHz, which is smaller than the estimation. We attribute this to the readout circuit limitation, and subsequent optimization of the circuit will be performed to improve the MCR in our future work. Regardless, phonon trapping does not significantly affect the recovery time. The recovery time is mainly limited by the intrinsic kinetic inductance of the superconducting nanowire and is independent of the interface state.

Furthermore, the time jitter is also statistically presented in Fig. 5(c). The time jitter is measured by a traditional single-mode optical fiber-coupled system. The input wavelength is still set to 1.55 μm because the acquisition of a high-precision midinfrared pulsed laser and accurate power

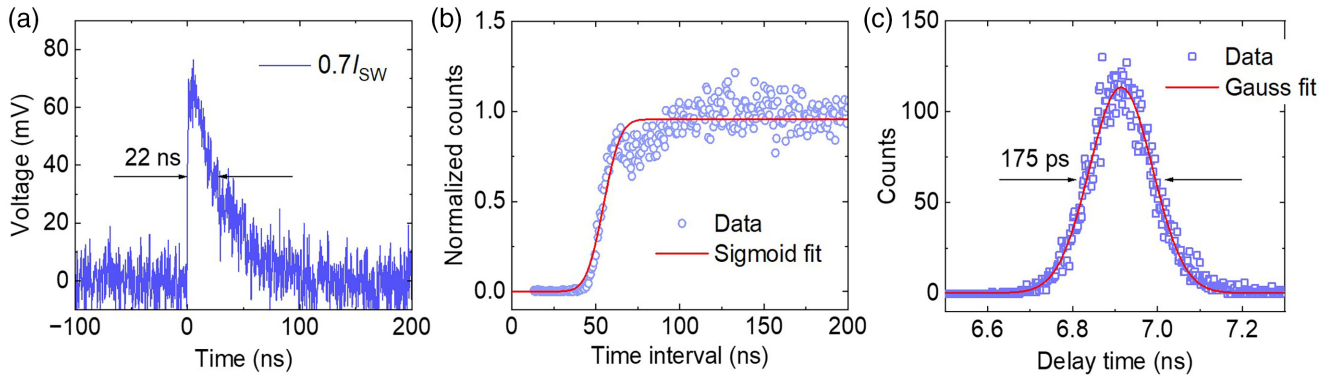


FIG. 5. Characterization of time-dependent dynamic performance. (a) The electrical pulse waveform of the detector at $0.7I_{SW}$, which has a full width at half maximum (FWHM) of ~ 22 ns. (b) Normalized counts of the detector as a function of time after the first detection at $0.7I_{SW}$. The sigmoid fit is performed to determine the recovery time. (c) Time delay statistics of the detector at $0.8I_{SW}$, which result in a time jitter of 175 ps. The red curve represents the Gauss fit results. All the results were measured at a wavelength of $1.55 \mu\text{m}$.

calibration currently present major challenges. The Gauss fit is performed to determine the time jitter. Consequently, a time jitter of 175 ps is measured at $0.8I_{SW}$. As the bias current is reduced, the time jitter continuously increases (Fig. S11). All the results of the time jitters of the detector are comparable to those of the WSi detectors [48], which may stem from their similar disordered structures. The influence of the interface-excited phonon trapping mechanism on the time jitter is not clearly observed in the experiment. We attribute this result to the large photon energy of the $1.55 \mu\text{m}$ wavelength. In our future work, systematic experiments will be conducted to explore the effect of phonon trapping on the time jitter during low-energy photon detection (e.g., mid/long-wave infrared single-photon detection). This will be a fascinating research topic.

IV. CONCLUSION

In summary, this work proposes a scalable interface engineering strategy to suppress thermal transport in superconducting nanowires without incorporating any extrinsic insulating layers or defects. The NAW film exhibits a low phonon group velocity, resulting in enhanced phonon trapping within the nanowire. Consequently, the phonon dissipation is reduced, and the energy conversion efficiency improves after photon absorption. The fabricated superconducting nanowire detector has a high ratio of 22 between the switching cur-

rent and the retrapping current, achieving saturated IDEs across the $1.75\text{--}6.00 \mu\text{m}$ wavelength range. The phonon engineering strategy not only enables saturated MIR single-photon detection but also provides a facile route to modulate superconducting nanocircuits for advanced quantum electronics and beyond.

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L.Z., Q.C., and H.W. proposed and organized this work. Q.C. and L.M. designed and fabricated the samples. Q.C., L.M., H.X., Y.G., and W.Y. worked on the measurement setup and analyzed the data. Q.C., H.W., and L.Z. developed the theory and wrote the paper with inputs from all coauthors. All the experiments were completed under the leadership of L.Z., L.K., and P.W.

The authors declare no competing interests.

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