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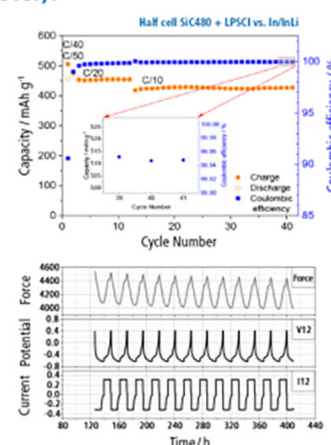
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Graphene-based photodetector with engineered hot-carrier cooling dynamics

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Abstract

Graphene has emerged as a promising material for integration into silicon photonics, owing to its ultrafast and broadband photoresponse without the need for an external bias voltage. This photoresponse relies on the photo-thermoelectric effect created by hot carriers. A key factor underlying the performance of graphene photodetectors is the cooling dynamics of these hot carriers. In this work, we engineer these dynamics in a WSe₂–graphene–WSe₂ waveguide-integrated photodetector. In particular, by introducing proximity screening by a nearby graphite layer to this structure, we prolong the hot-carrier cooling time, leading to an enhanced photoresponse. We characterize the cooling dynamics under continuous-wave laser excitation by employing a photomixing technique, revealing an increase in the cooling time by up to a factor of four. Direct photoresponse measurements show that the internal photoresponsivity improves by approximately 50%. Together, these results demonstrate the potential of proximity screening to enhance the performance of graphene-based photodetectors on an integrated photonics platform.

1. Introduction

Photodetectors facilitate the conversion of optical signals into electrical signals, a capability widely required in both long-haul optical communication systems and short-range data center applications. Graphene is a promising material for photodetection owing to its zero bandgap, high carrier mobility, low electronic heat capacity [1–3], and its ability to generate a direct electron-heat-driven photovoltage signal without requiring an external bias [4, 5]. This strongly reduces the dark current and removes the need for a transimpedance amplifier [6–9]. Graphene-based photodetectors also offer extremely fast operation, up to hundreds of GHz [10]. However, in order to compete with commercial photodetectors, such as those based on germanium, it is necessary

for graphene-based photodetectors to increase their photoresponsivity [11].

To enhance the photoresponsivity of graphene photodetectors, several approaches have been explored, mostly aimed at increasing light absorption in graphene, including optical ring resonators [7] and plasmonic nanostructures [9]. Alternatively, it has recently been proposed that slower cooling of hot carriers, tailored via proximity screening, can lead to an increased photoresponse, as it leads to an increased average carrier temperature [12]. The resulting steeper temperature gradients enhance the thermally driven transport of photo-generated carriers, thereby strengthening the photoresponse. This strategy of increasing the photoresponse through slower hot-carrier cooling requires control over the cooling dynamics, which have been reviewed in [13].

Recent work demonstrated that high-quality WSe₂-encapsulated graphene exhibits longer cooling times than hexagonal boron nitride (hBN)-encapsulated graphene, with the cooling dynamics ultimately limited by the emission of optical phonons [14]. In this scenario, rapid carrier–carrier scattering efficiently re-thermalizes the electronic system, maintaining relatively fast optical-phonon-mediated cooling that occurs on a picosecond timescale [14]. Motivated by very recent work demonstrating the slowing of cooling dynamics in a high-permittivity environment [12], enhanced responsivities in photodetectors based on WSe₂-encapsulated graphene [15], and enhanced quantum mobilities due to proximity screening [16], further improvements to the photoresponse seem to be attainable.

These encouraging developments make an experimental demonstration of proximity screening effects in graphene photodetectors integrated on a silicon photonic platform highly desirable, in order to demonstrate relevance in real-world applications. However, until now, this has been lacking. In this work, we investigate the influence of proximity screening from a nearby graphite layer on a WSe₂–graphene–WSe₂ waveguide-integrated photodetector. We experimentally compare the cooling dynamics and photoresponse of the exact same device before and after placing the graphite layer, corresponding to the situation without and with proximity screening, respectively. Since the photodetectors of datacommunication and telecommunication applications operate under low-power illumination, we characterize the cooling dynamics using a continuous-wave (CW)-laser-based photomixing technique, based on [17], rather than measurements with ultrashort pulses, as these correspond to high peak powers [13]. Our results show that the introduction of proximity screening leads to an increase in the cooling time by a factor of 2–4, and a 1.5-fold enhancement in the graphene internal photoresponsivity. This shows that engineering the hot-carrier cooling dynamics is indeed a promising strategy for enhancing the performance of graphene-based, silicon-photonics-integrated photodetectors.

2. Results

2.1. WSe₂–graphene–WSe₂ waveguide photodetector

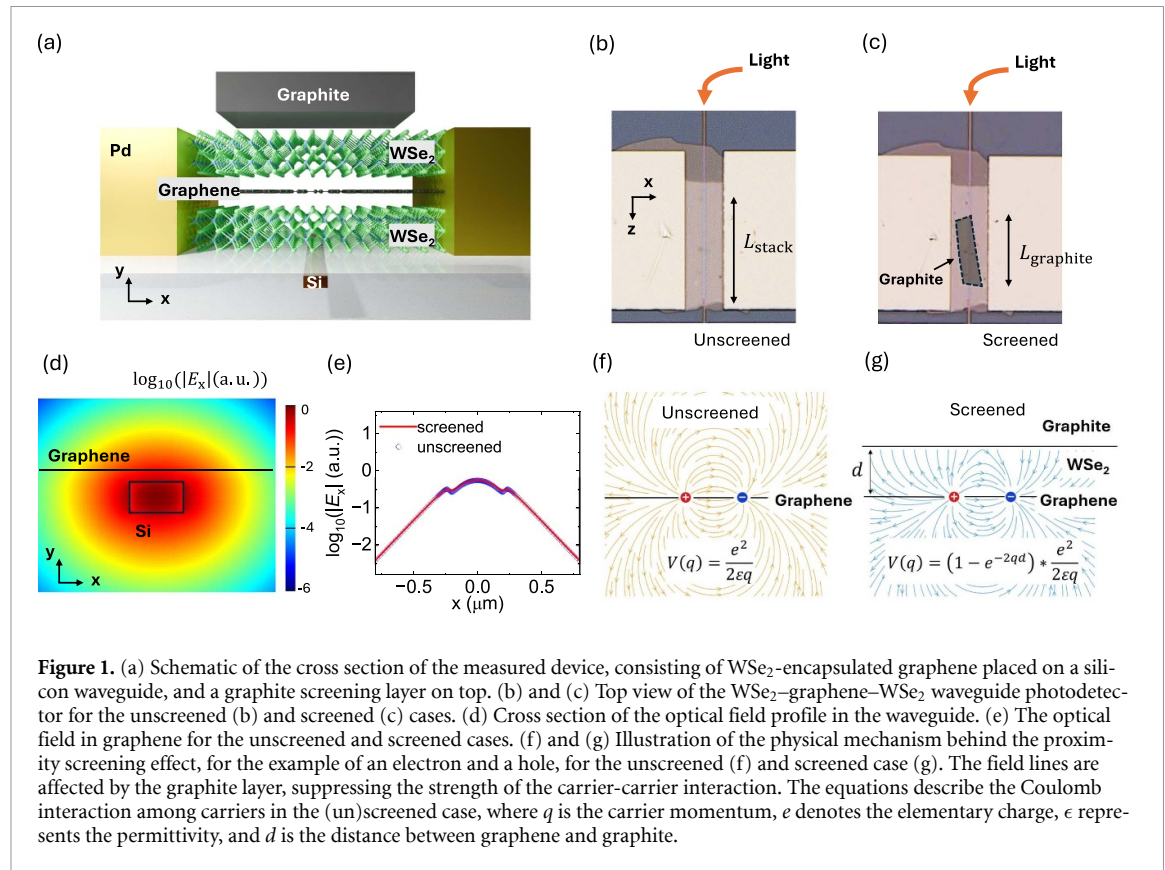
Figure 1(a) shows the schematic of our device, a WSe₂–graphene–WSe₂ waveguide-integrated photodetector with graphite screening layer on top. We prepared a stack of WSe₂–graphene–WSe₂, which we dry-transferred to a silicon optical waveguide designed for operation at the telecom wavelength 1550 nm, forming the channel. The silicon optical waveguide has dimensions of 450 nm × 220 nm and is covered by a few-nanometer-thick

planarized oxide top cladding. We use WSe₂ as the encapsulating material, rather than hBN, because it suppresses hyperbolic phonon mediated cooling, making intrinsic optical phonon cooling the dominant relaxation channel [14, 18, 19]. The graphene is exfoliated from high-quality crystals, to minimize disorder and defects, thereby suppressing supercollision cooling [20, 21]. During the dry-transfer process [22], assisted by polycarbonate/PDMS stamps, we sequentially picked up the flakes to assemble the stack, which was then transferred onto the silicon waveguide. Following the dry-transfer process, plasma etching and metal deposition were performed to form edge contacts [23] to the WSe₂-encapsulated graphene, completing the device for the unscreened case. For the screened case, a graphite layer was deposited on top through an additional dry-transfer step.

Figure 1(b) shows the top view of the device in the unscreened case, where the stack length is $L_{\text{stack}} = 40 \mu\text{m}$. A longer stack leads to increased absorption, yet not necessarily a stronger photoresponse. Figure 1(c) presents the top view of the screened configuration, in which the graphite screening layer, which has a length of $L_{\text{graphite}} = 25 \mu\text{m}$, is placed on top. Light propagates along the z -direction within the silicon waveguide. As it passes through the stacked region, the evanescent field overlaps with the graphene layer and is partially absorbed, generating a photoresponse. The cross-section of the optical field profile in the waveguide is shown in figure 1(d), while figure 1(e) shows the optical field in the graphene channel, highlighting a minimal difference between the unscreened and screened cases. The simulated optical mode profile changes only weakly due to the graphite, indicating that the main role of the graphite layer is proximity screening.

The concept of proximity screening is illustrated in figures 1(f) and (g), for the example of an electron and a hole, where the field lines—including those in between the electron and hole—are affected by the presence of the graphite layer. The Coulomb interaction among carriers is given by $V(q) = e^2/(2\epsilon q)$ (unscreened) and $V(q) = (1 - e^{-2qd}) \cdot e^2/(2\epsilon q)$ (screened), where q is the carrier momentum, e denotes the elementary charge, ϵ represents the permittivity, and d is the distance between graphene and graphite. The presence of nearby graphite imposes a small d , which suppresses the Coulomb interaction via proximity screening. This screening weakens carrier–carrier scattering in graphene, which in turn slows down the re-thermalization processes associated with optical phonon cooling. As a result, the cooling time of photo-generated hot carriers is prolonged, as shown in [12]. Under steady-state optical excitation, this leads to a higher carrier temperature, enhancing the electron-heat-driven photovoltages.

To verify this proximity screening effect on the cooling dynamics and the photoresponse, we



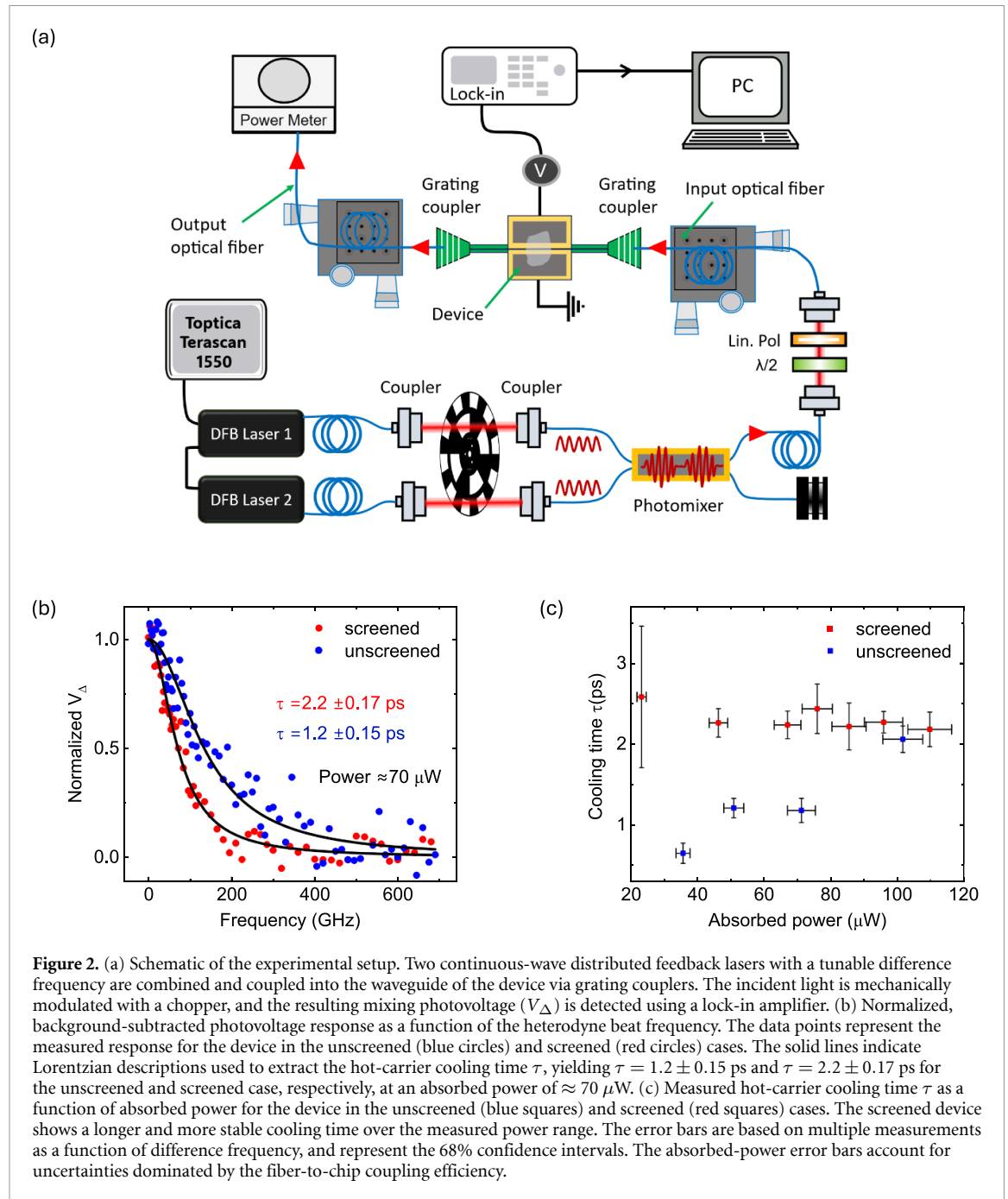
characterized the cooling time on the same device for both the unscreened and screened cases using a CW-laser technique. The measurements used low optical power and gigahertz-scale modulation frequencies, closely mimicking practical data communication and telecommunication operating conditions. In contrast, ultrafast pump-probe measurements typically employ high-power pulsed excitation with megahertz-scale repetition rates. We also performed photoresponse measurements for both the unscreened and screened cases to evaluate if the prolonged cooling time leads to enhanced performance in terms of the responsivity.

2.2. Cooling time characterization

We study the hot-carrier cooling dynamics using heterodyne photomixing (see figure 2(a)). Two CW distributed-feedback (DFB) lasers with a tunable frequency mix to form a beat note, which is then coupled into the optical waveguide of the graphene device through a grating coupler. The optical beat note periodically modulates the absorbed power, causing the carrier temperature to oscillate at the beat frequency, which is given by the relative frequency detuning of the two DFB lasers. Because the photovoltage depends nonlinearly on the carrier temperature, this produces a time-averaged beating photovoltage, which we measure using a lock-in amplifier. At low beat frequencies, the carriers can follow the modulation, whereas at high beat frequencies they

cannot respond fast enough, causing the mixing signal to roll off. The cooling time is extracted from this frequency-dependent roll-off [17]. This CW method probes the device in a low- ΔT regime, where the electron temperature does not increase much beyond the lattice temperature, closer to realistic device operating conditions. It therefore provides direct access to the intrinsic carrier cooling dynamics without strongly perturbing the electron distribution.

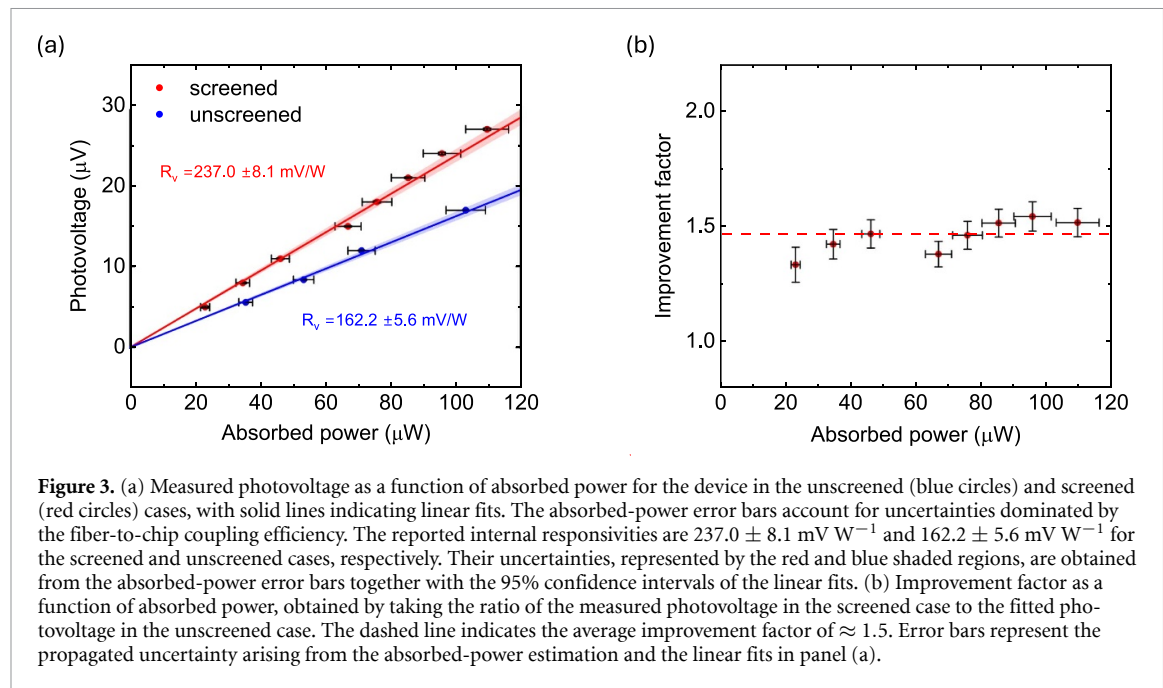
Figure 2(b) shows the normalized heterodyne photovoltage response as a function of beat frequency for the device with and without graphite screening. The solid lines are descriptions with a Lorentzian function of the frequency-domain response of the beating photovoltage, where the width is inversely proportional to the cooling time [17] (see also supplementary note 2). The data shown in figure 2(b) correspond to the same absorbed power of $\approx 70 \mu\text{W}$ in both the unscreened and screened cases. At this power, the extracted cooling time increases from $\tau = 1.2 \pm 0.15$ ps in the unscreened case to $\tau = 2.2 \pm 0.17$ ps in the screened case. In supplementary note 4, we show a detailed simulation of the full experiment, relating the obtained cooling time from the frequency roll-off to a microscopic cooling time that serves as input to the simulation of the experiment. We find that the photomixing technique tends to somewhat underestimate the cooling time, in contrast to time-resolved photocurrent measurements, which tend to somewhat overestimate the cooling time. This means



that the cooling times that we obtain here are lower bounds.

Figure 2(c) summarizes the extracted cooling times as a function of the absorbed optical power in graphene. The absorbed power is quantified by accounting for the excess waveguide propagation losses (see supplementary note 3). These losses are higher in the screened case than in the unscreened case, which is due to optical absorption in the graphite screening layer. The screened device exhibits a longer cooling time than the unscreened device over the measured power range, and its cooling time remains nearly independent of power. This contrasts with the clear power dependence of τ observed in the unscreened case. We attribute the longer cooling

time in the screened case to the proximity screening of carrier–carrier interactions, as proposed in [12]. This weakens carrier–carrier scattering and reduces the efficiency of electronic re-thermalization during the optical-phonon-mediated cooling process, which is the dominant cooling pathway in WSe₂-encapsulated graphene [14]. Consequently, the effective hot-carrier cooling time is increased. In contrast, in the unscreened case, electronic re-thermalization remains efficient, enabling optical-phonon emission and the onset of a hot-phonon bottleneck, as shown in [14], which leads to a stronger power dependence of the cooling time. The long-term stability of the device is supported by the consistent electrical and optoelectronic performance observed before



and after graphite transfer. Over a period exceeding two months, the channel resistance changed by less than 3%. Furthermore, stable operation was observed throughout the extended photomixing measurements which involve repeated frequency and power sweeps.

2.3. Photoresponse

With the cooling time shown to increase after adding a graphite screening layer, we next compare the photoresponse of the device before and after adding the screening layer. As shown in figure 3(a), the device with the graphite screening layer exhibits a higher photovoltage for a given absorbed power, demonstrating a clear improvement of internal photoresponsivity. In both cases, the photovoltage increases monotonically with absorbed power, with no clear saturation over the measured range. The reported internal responsivities are $237.0 \pm 8.1 \text{ mV W}^{-1}$ and $162.2 \pm 5.6 \text{ mV W}^{-1}$ for the screened and unscreened cases, respectively. The corresponding uncertainties are derived from the absorbed-power uncertainties and the 95% confidence intervals of the linear fits. The absolute responsivity is modest compared to that of state-of-the-art ones [6, 7, 9] as we did not carry out any optimization of the geometry and gate configuration for this device. The novelty of the present work lies in demonstrating proximity screening as an additional degree of freedom for device optimization, which can be combined with existing state-of-the-art photodetector concepts, like plasmonic enhancement [9], where the metal gates could potentially be used directly as the screening metal, improving the proximity by reducing the spacing between the gates and the graphene layer. It also applies to resonant cavities and p-n junction engineering by replacing the

graphene gates with a screening layer and bringing it closer to graphene.

Figure 3(b) shows the measured improvement factor, which is approximately 1.5. This improvement factor can be explained by using the measured cooling-time data as input for simulations based on the photothermoelectric effect driven by hot carriers in graphene [5, 13, 24] (see supplementary note 4). It confirms that the measured cooling time data and the measured photoresponse are consistent with our hypothesis that proximity screening suppresses the efficiency of cooling channels, effectively ‘trapping’ heat within the electronic system. While the graphite screening layer enhances the internal photoresponsivity by increasing the hot-carrier cooling time, it also introduces additional optical loss and negatively affects the external photoresponsivity (see supplementary note 3). Therefore, future implementations may benefit from alternative screening materials with lower optical absorption and high free-carrier density, such as transparent conductive oxides [25], which could provide stronger improvements in external responsivity.

3. Discussion

For comparison, table 1 presents a summary of cooling-time results reported from CW photomixing characterization. The screened case exhibits a cooling time of $\approx 2.3 \text{ ps}$. This value is approximately 1.6 times longer than that reported in [17], where high-quality exfoliated graphene was supported on a silicon oxide substrate. It is also approximately 1.8 times longer than that of our unscreened hBN-encapsulated graphene device (see supplementary note 2). We note

Table 1. Summary table of cooling time results of different stacks, characterized with continuous-wave photomixing technique.

Mechanism	Stack (bottom to top)	Graphene	Cooling time	CW or pulsed laser	References
Zero-bias PTE	WSe ₂ –Graphene–WSe ₂ –Graphite	Exfoliated monolayer	2.3 ± 0.1 ps (screened)	CW	This work
Zero-bias PTE	WSe ₂ –Graphene–WSe ₂	Exfoliated monolayer	0.7–2.1 ps (unscreened)	CW	This work
Zero-bias PTE	hBN–Graphene–hBN	Exfoliated monolayer	1.2–1.4 ps (unscreened)	CW	This work
Zero-bias PTE	SiO ₂ –Graphene	Exfoliated monolayer	1.42 ps	CW	[17]

that only a limited number of cooling-time results obtained by CW photomixing have been reported. Nevertheless, these measurements are particularly valuable because they directly reflect the potential of the proposed stacks for practical communication devices.

Having demonstrated slower cooling and an increased photoresponse enabled by screening of carrier-carrier interactions by a nearby graphite layer, we now discuss strategies to further improve device performance by exploiting the proximity screening effect. One approach to increase the screening of carrier-carrier scattering is to place the graphite screening layer very close to the graphene channel, on the order of ~ 1 nm. Such extremely close proximity screening configurations have been studied in studies aimed at (hydrodynamic) charge transport [16, 26], however, it is not yet clear to what extent this enhanced screening would influence the carrier cooling time and the photoresponse.

To estimate this, we refer to very recent work that examined the impact of dielectric screening on cooling times in graphene [12]. For pure dielectric screening, numerical simulations of the cooling dynamics reveal that the cooling time scales approximately linearly with permittivity, $\tau \propto \epsilon$ (see supplementary note 5). In the presence of proximity screening and for small graphene-graphite distance d , the Coulomb interaction $V(q) \approx e^2 d / \epsilon$, such that the cooling time scales as $\tau \propto 1/d$.

In the limit of a monolayer WSe₂ spacer, the distance between graphene and graphite is $d \approx 1.3$ nm, determined by the monolayer WSe₂ thickness and the van der Waals spacing. This means that we could expect an additional $4.7\times$ enhancement of the cooling time beyond our measured results for which $d \approx 6.1$ nm, yielding approximately a $12\times$ enhancement of cooling time compared to the unscreened case. If we assume a photodetector operating under the photo-thermoelectric effect in graphene, where the photovoltage scales as the square root of the cooling time [5, 12, 24], this would correspond to a $3.5\times$ enhancement of the photoresponse. We note that these analyses rely on the high quality of exfoliated materials, which exhibit low surface roughness and disorder density, while the scalability of this approach to large-area materials warrants further investigation.

When considering the application of proximity screening across different classes of graphene photodetectors, its benefits are most relevant to hot-carrier-based devices, including photothermoelectric photodetectors [4, 7–9, 15], and bolometric photodetectors [27–29]. Proximity screening may also benefit devices that exploit hot-carrier excitation to modify charge transport and generate photocurrents [30]. In contrast, for photovoltaic, photoconductive, photogating, and hybrid heterostructure photodetectors [31–34], proximity screening may provide limited benefit because their photoresponse does not primarily rely on hot-carrier effects and therefore does not require an elevated electronic temperature.

Compared with previous works that focused on graphene quality and substrate optimization to reduce extrinsic cooling effects [14, 19, 20], proximity screening focuses on directly engineering graphene's intrinsic hot-carrier cooling mechanism after those optimizations have been implemented. Proximity screening also provides a unique advantage, which is its compatibility with existing photothermoelectric device architectures, particularly plasmonically enhanced graphene photodetectors, where metallic gates can serve as the screening layers simultaneously.

4. Conclusions

In this work, we demonstrate that proximity screening can prolong the cooling time of hot carriers in graphene, leading to improved internal photoresponsivity. Specifically, by introducing a graphite screening layer at a distance of 6.1 nm from graphene, the carrier cooling time is prolonged by up to a factor of four at low optical powers, resulting in a $\sim 50\%$ enhancement of the intrinsic photoresponse. Further improvement in responsivity with an extremely nearby proximity layer is expected, which is possibly enough to outcompete several competing receiver technology platforms. In addition to exploring extremely proximate screening layers, future work should address the challenge of maintaining optimal absorption in the graphene channel. The fact that our device was fabricated on a standard waveguide platform and characterized using a

CW-laser-based photomixing technique, highlights the potential for data communication and telecommunication applications.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Formal analysis (equal), Investigation (lead), Writing – original draft (lead), Writing – review & editing (lead), Methodology (lead)

Anand Nivedan

Formal analysis (equal), Investigation (lead), Methodology (lead), Writing – original draft (equal), Writing – review & editing (equal)

Florian Ludwig

Investigation (supporting), Methodology (supporting), Writing – review & editing (supporting)

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Conceptualization (supporting), Writing – review & editing (supporting)

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Conceptualization (supporting), Investigation (supporting)

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