The development of compact and fieldable mid-infrared (mid-IR) spectroscopy devices represents a critical challenge for distributed sensing with applications from gas leak detection to environmental monitoring. Recent work has focused on mid-IR photonic integrated circuit (PIC) sensing platforms and waveguide-integrated mid-IR light sources and detectors based on semiconductors such as PbTe, black phosphorus and tellurene. However, material bandgaps and reliance on SiO₂ substrates limit operation to wavelengths \( \lambda \lesssim 4 \mu \text{m} \). Here we overcome these challenges with a chalcogenide glass-on-CaF₂ PIC architecture incorporating split-gate photothermoelectric graphene photodetectors. Our design extends operation to \( \lambda = 5.2 \mu \text{m} \) with a Johnson noise-limited noise-equivalent power of 1.1 nW/Hz\(^{1/2} \), no fall-off in photoresponse up to \( f = 1 \text{MHz} \), and a predicted 3-dB bandwidth of \( f_{3\text{dB}} > 1 \text{GHz} \). This mid-IR PIC platform readily extends to longer wavelengths and opens the door to applications from distributed gas sensing and portable dual comb spectroscopy to weather-resilient free space optical communications.
Mid-IR absorption spectroscopy is a critical tool for chemical sensing and analysis, especially for inert gases that evade detection by chemical reaction-based sensors. Many such gases derive their inertness from halogenated chemistries and thus exhibit global warming potential due to carbon-halogen stretching modes resonant in the thermal IR. To facilitate sensor deployment for greenhouse gas leak detection and other chemical sensor application areas, there exists a strong need to transition from co-packaged discrete components to compact and chip-integrated sensors.

To address this challenge, mid-IR photonic integrated circuit (PIC) platforms have been investigated to reduce optical gas sensors to the size of a chip. Recent work has demonstrated integrated optical methane and volatile organic compound sensors to the size of a chip. Recent work has demonstrated integrated optical methane and volatile organic compound sensing, but required coupling to off-chip sources and detectors. However, integrating the detector on-chip is more compact and can improve sensitivity by reducing the volume of active material able to generate thermal noise. Su et al. achieved integration of a PbTe photoconductor and demonstrated methane sensing at a wavelength of $\lambda \approx 5.2 \mu m$, but their platform is limited to $\lambda \leq 4 \mu m$ due to absorption in the SiO$_2$, substrate and by PbTe’s absorption cutoff. Waveguide-integrated detectors based on narrow-gap 2D materials black phosphorus and tellurene have also been demonstrated, but they too are bandgap-limited to $\lambda \leq 4 \mu m$.

Here we exceed the wavelength limit of previous demonstrations using graphene-based detectors on an extended-transparency waveguide platform. While graphene integrated detectors have shown promise at telecom wavelengths, the material’s advantages are magnified further at longer wavelengths due to the thermal nature of the photothermoelectric (PTE) response mechanism and due to the impact of optical plasmon scattering at short wavelengths. Integrated photodetection with graphene has been demonstrated at wavelengths up to 3.8 $\mu m$ and with chalcogenide glass waveguides, but on SiO$_2$ platforms. To access longer wavelength operation and achieve good sensitivity at zero-bias, we introduce a Ge$_{28}$Sb$_{12}$Se$_{60}$ (GSSe)-on-CaF$_2$ waveguide platform supporting gated PTE-based graphene photodetectors. These key changes allow us to extend operation to a wavelength of $\lambda = 5.2 \mu m$ while achieving a Johnson noise-limited noise-equivalent power (NEP) of 1.1 nW/Hz$^{1/2}$. By comparing the gate voltage maps of our device’s resistance, transmittance, and responsivity with a photothermoelectric model, we extract material quality parameters of the graphene channel, revealing a path to further reduce the device’s NEP by shrinking the optical mode size in tandem with the graphene channel.

Results

Device design and responsivity measurement. Figure 1a, b illustrate the platform and photodetector design. The device consists of a single-mode GSSe waveguide fabricated on top of a 5.4 $\mu m$ wide by 300 $\mu m$ long, CVD-grown graphene channel, flanked on either side by source and drain contacts placed far enough away from the optical mode to avoid excess loss. Beneath the graphene channel are pair of CVD graphene back-gates, separated by a 400 nm gap and used to electrostatically induce a pn-junction along the center of the channel. We use HfO$_2$, as the gate dielectric and as an airtight capping layer. The device is fabricated on a CaF$_2$ substrate, transparent up to $\lambda = 8 \mu m$. Figure 1c depicts the resulting waveguide mode at $\lambda = 5.2 \mu m$.

We use lock-in measurement to characterize our detectors, focusing light from a $\lambda = 5.2 \mu m$ QCL source into our chip’s input facet. Light exiting the chip is focused onto an InAsSb photodetector and amplified for transmission measurement. Supplementary Fig. 1a depicts this beam-path in more detail.

Device bandwidth and noise performance. Current modulation of our QCL source permits frequency response measurements up to its modulation bandwidth of 1 MHz. To account for the modulation response of our laser, we measure the photovoltage of Device A alongside that of a fast InAsSb photodiode. The comparison shown in Fig. 4a indicates that our device is faster than our laser’s modulation bandwidth. We thus use a COMSOL model to find the actual RC contribution to our device’s frequency response, plotted in the inset of Fig. 4a. We also plot the product of the RC-limited frequency response and the $\tau_{\text{ph}}$-limited frequency response with an assumed (1 + ($2\pi\tau_{\text{ph}}f$)$^{-0.5}$ dependence, which applies as the electron-phonon cooling length $\ell = \sqrt{\kappa x / C_{\text{el}}} \approx 230$ nm is narrower than our device channel.

Photothermoelectric device model. To confirm our understanding of device operation and elucidate the prospects for performance improvement, we apply the formalism introduced in Song et al. to calculate the electronic temperature distribution and Seebeck photovoltage in the graphene channel under illumination. Figure 3a, b compare our measured and modeled voltage responsivities using calculations described in the Methods section. The performance of our device depends on several fitting parameters, whose definitions and approximate values (derived from our measured data) we provide in Table 1. We describe our fitting process in Supplementary Note 3. Critically, all features of the modeled responsivity map in Fig. 3b up to an overall scale factor from $\tau_{\text{ph}}$ are established a priori from fitting parameters extracted from the device transmittance and resistance maps, with only $\tau_{\text{ph}}$ obtained by matching the scales of the measured and modeled responsivities. The resemblance between Fig. 3a and b thus reflects the validity of our PTE model and is not due to over-fitting. In Fig. 3c, we plot the solution to Eqn. (6), $\Delta T(x)$, as well as the source term $\mathcal{Q}(x)$. The thermal transport model predicts that 9 $\mu W$ of guided power raises the temperature of the graphene channel’s electron gas by as much as 1 K along the center of the device.
**Fig. 1 Device geometry.** a Illustration of the device cross-section perpendicular to the waveguide axis. The optical mode supported by the GSSe waveguide evanescently couples to and is absorbed by the graphene channel, which is gated by two graphene back-gates to induce a pn-junction. b Optical image of the device depicting source, drain and gate contact pads. c Depiction of the optical guided mode at $\lambda = 5.2 \, \mu m$.

**Fig. 2 Gate voltage maps.** a Measured zero-bias photovoltage produced by the device as a function of the two gate voltages. b Total device resistance as a function of the two gate voltages. c Lock-in signal reflecting power measured by an InAsSb photodetector at the focal point of our output facet collection lens, used to monitor transmission of the device as a function of the gate voltages. The star, triangle, and cross symbols on each gate voltage map represent the optimum operating points for maximum voltage responsivity, maximum current responsivity, and minimum NEP, respectively. The power-normalized transmittance is plotted in Supplementary Fig. 3b. d, e, f Plots of line sections indicated with dashed lines in panels a, b, and c, respectively.
To investigate our device’s noise performance, we modulate the QCL current at 30 kHz, amplify the photovoltage with a low-noise preamplifier and inspect using a signal analyzer. As shown in Supplementary Fig. 8, we observe in Device A no broadening of the 30 kHz photoresponse peak at offset frequencies as low as 0.1 Hz, indicating long-term responsivity stability. We then measure the un-illuminated noise spectral density and resistance versus both gate voltages. Figure 4b shows the resulting data for a

![Fig. 3 Experiment/model comparison.](image)

**Table 1 Device parameters and approximate values.**

| Parameter          | Value            |
|--------------------|------------------|
| $\tau_{DC}$ Drude scattering time at DC | $\approx 3.5 \text{ fs}$ |
| $\tau_{IR}$ Drude scattering time at IR | 30–50 fs |
| $\sigma_n$ Standard deviation of native carrier concentration due to spatial inhomogeneity | $1.5–2.5 \times 10^{12} \text{ cm}^{-2}$ |
| $E_Fc$ Native Fermi level of graphene channel | $\approx 0.17 \text{ eV}$ |
| $E_{Fg}$ Native Fermi level of graphene gates | $0.48 \text{ eV}$ |
| $\tau_{eph}$ Electron-phonon cooling time | $50 \text{ ps}$ |
| $\alpha_e$ Excess light attenuation within device | $2-3 \text{ mm}^{-1}$ |

**Fig. 4 Bandwidth and noise properties.**

- **a** Comparison of the frequency response of our photodetector with that of the laser current modulation itself. The consistency between the two indicates that the photodetector frequency response exceeds 1 MHz. Inset: Simulated GHz-range photodetector frequency response, with and without considering the impact of the electron-phonon cooling time $\tau_{eph}$.
- **b** Measured noise spectral density versus resistance and corresponding Johnson noise spectral density of Device B, without illumination, for the 49 pairs of gate voltages $\{V_{g1}, V_{g2}\}$ where each $V_{gn}$ is varied from $-6 \text{ V}$ to $6 \text{ V}$ in steps of $2 \text{ V}$. Measurement was performed at $T = 293 \text{ K}$.
Device B of identical design to Device A, organized by resistance and compared to the expected Johnson noise spectral density. We observe excellent consistency between the measured and predicted noise, with a $2 - 4 \, \text{dB}$ discrepancy consistent with the specified noise figure of our preamplifier, corroborating our earlier claim of Johnson-noise-limited NEP.

To demonstrate our device’s utility, we analyze its predicted gas-sensing performance, summarized from Supplementary Note 6. The minimum detectable gas concentration for a given waveguide platform and photodetector is given by\(^{16}\):

$$P_{\text{gas.min}} = e^{F_{\text{base}} - \alpha_{\text{base}} N_{\text{EFP}} - \frac{\alpha_{\text{base}}}{\Gamma_{\text{E}}} I_{\text{S}}},$$

where $I_{\text{S}}$ is the source power, $\alpha_{\text{base}}$ is the waveguide attenuation coefficient in the absence of gas, $\alpha$ is the specific attenuation coefficient of the gas, $n_g$ is the guided mode group index, $\Gamma_{\text{E}}$ is the confinement factor of electric field energy within the gaseous medium, and $e = \exp(1)$. For detection of nitric oxide (NO), with an absorption peak at $\lambda = 5.24 \, \mu\text{m}$ and a specific attenuation of approximately $a = 70 \, \text{m}^{-1}\text{atm}^{-1}$ at low concentrations\(^{17}\), we arrive at $P_{\text{gas.min}} = 74 \, \text{ppm}/\sqrt{\text{Hz}}$ for a $1 \, \text{mW}$ illumination source. Assuming a measurement bandwidth of $0.1 \, \text{Hz}$ over which we have measured our photoresponse to be stable, we find $P_{\text{gas.min}} = 23 \, \text{ppm}$, roughly equal to the National Institute of Occupational Safety and Health (NIOSH) recommended exposure limit (REL) of $25 \, \text{ppm}\(^{18}\). Removing the slightly lossy HFO$_2$ dielectric underneath the gas-light interaction waveguide could decrease $P_{\text{gas.min}}$ considerably, as waveguide losses down to 0.7 dB/cm have been demonstrated at the same wavelength using a similar chalcogenide glass and liftoff process\(^{19}\).

**Discussion**

Although our demonstration is limited to $\lambda = 5.2 \, \mu\text{m}$ by light source availability, the optical conductivity of our graphene inferred from the fitting parameters in Table 1 remains relatively constant and even increases at longer wavelengths due to intraband absorption as shown in Supplementary Fig. 7. We thus expect our platform to scale to $\lambda = 10 \, \mu\text{m}$ and beyond, perhaps requiring a BaF$_2$ substrate for extended transparency, with little reduction in performance owing to the PTE effect’s thermal nature. In Table 2 we compare our device’s performance with various off-the-shelf detectors. Although its NEP is not yet on par with commercial options, its predicted bandwidth may be useful for dual-comb spectroscopy-based integrated gas analyzers\(^{20}\). Additionally, the vacuum requirement of VO$_x$ bolometers may complicate co-packaging and introduce coupling losses, and the high cost of HgCdTe may preclude use in broadly deployed sensor networks.

In conclusion, we have demonstrated a PTE-based graphene photodetector, integrated in a scalable chalcogenide glass waveguide platform with an NEP of $1.1 \, \text{nW}/\sqrt{\text{Hz}}\(^{12}\) and a bandwidth exceeding $f_{\text{3dB}} = 1 \, \text{MHz}$. We have modeled the bandwidth to approach $1.3 \, \text{GHz}$ and predict similar performance at longer wavelengths for scaled-up devices enabled by the transparency of GSSe beyond $\lambda = 10 \, \mu\text{m}\(^{21}\). Finally, we have shown that our device and waveguide platform would enable NO detection at concentrations comparable to its REL. Substantial improvements are likely using metal-insulator-metal\(^{10}\) or dielectric slot waveguides to concentrate the optical mode to within a cooling length of the pn-junction, which would also increase the attenuation of the guided mode and thus decrease the device footprint needed to absorb an optical signal. Gapped bilayer graphene may also be investigated as an alternative to monolayer graphene to reduce thermal noise\(^{22}\). The PIC platform further promises to support a full toolkit of mid-IR active devices including on-chip quantum cascade light sources\(^{23}\), and may even leverage the same graphene material platform for devices such as graphene modulators\(^{14}\) and hot-electron-based\(^{24}\) or gapped bilayer graphene light sources.

The platform could also be adapted to alternative mid-IR waveguide approaches, such as suspended Ge, as necessary to reach longer wavelength ranges\(^{25}\). Chalcogenide glass could then supplement such a platform by enabling designs where the graphene channel is sandwiched between the Ge and high-index glass to increase overlap with the optical mode. This research represents the first foray into waveguide-integrated detectors operating beyond $\lambda = 4 \, \mu\text{m}$, paving the way towards 2D-material-enabled integrated mid-IR microsystems for gas sensing, spectroscopy\(^{20}\) and free-space optical communications\(^{26}\).

**Methods**

**Photodetector fabrication.** A continuous monolayer graphene film was grown on Cu foil (99.8%, Alfa Aesar, annealed, uncoated, item no. 46365) cut to a size of $15 \times 2 \, \text{cm}^2$ in a 1-inch-diameter quartz tube furnace under atmospheric pressure. The furnace was heated to 1060°C over 30 min under 500 sccm of Ar flow; afterwards, 15 sccm of H$_2$ and 10 sccm of dilute CH$_4$ (1% in Ar) were introduced as reducing gas and carbon source, respectively, and flowed for 4 h to ensure the continuity of the graphene film. Finally, the furnace was allowed to cool to 100°C without forcing the gas flow before the CVD graphene was removed from the chamber. Our devices were fabricated on a 1” diameter by 1.0 mm thick (111)-cut CaF$_2$ substrate (MTI Corporation, item CF25D100C2). We first coated our substrate with a PMMA bilayer for liftoff (495 PMMA A6 followed by 950 PMMA A2), which features a slightly re-entrant sidewall profile after developing. We then performed e-beam lithography using an Elionix FIS-125 125 keV electron beam lithography system to pattern alignment marks on our substrate, followed by room-temperature development in 3:1 isopropanol:methyl isobutyl ketone for 90 s and isopropanol rinse for 120 s (“development process”), e-beam evaporation of $5 \, \text{nm} \, \text{Ti}/100 \, \text{nm} \, \text{Au}$ (Temescal VES2550) (“metal evaporation process”), and liftoff using a 4-h room-temperature acetone soak (“liftoff process”). To transfer the first layer of graphene, we first coated one side of the CVD graphene-on-Cu sheet with PMMA and removed the graphene from the other side using 90 s of oxygen RIE (16 sccm He and 8 sccm O$_2$ at a pressure of 10 mTorr and an RF power of 100W, “oxygen RIE process”). We then etched away the Cu using a FeCl$_3$-based etchant, followed by 2 DI water rinses, a 30-min clean in 5:1 DI water:HCl 37% in water to reduce metal ion contamination, and two more DI water rinses. After letting the graphene film sit overnight in the final evaporating dish of water, we scooped it out

| Table 2 Comparison of our detector with inferred room-temperature performance metrics for two HgCdTe photodiodes optimized for two different wavelengths (from ref. 31) and a VO$_x$ bolometer (from ref. 32) available off the shelf. For the photodiodes, the NEP is extrapolated from the specified detectivity for a detector scaled down to match the size of a diffraction-limited spot with $\text{NA} = 0.3$, which is the acceptance NA of these detectors. For the bolometer, we give the single $17 \times 17 \, \mu\text{m}$ bolometer pixel as calculated from the specified noise-equivalent temperature difference as described in Rogalski\(^{7}\). |
|----------------|----------------|----------------|----------------|
|                | $\lambda = 5.0 \, \mu\text{m}$ | $\lambda = 10.6 \, \mu\text{m}$ | VO$_x$ bolometer |
| NEP [pW/\sqrt{Hz}] | 1, $\lambda = 5.2 \, \mu\text{m}$ | 10, $\lambda = 5.2 \, \mu\text{m}$ | 0.9 |
|                | 0.2, $\lambda = 5.0 \, \mu\text{m}$ | 40, $\lambda = 10.6 \, \mu\text{m}$ | 1100 |
| $f_{3\text{dB}}$ [MHz] | 1.3 | 106 | 10 Hz |
| Vacuum required? | No | Yes | No |
| Waveguide-integrated? | No | Yes | Yes |
for each data point. To produce the device while biased with 1 VRMS through a 100 kΩ resistor, albeit at a higher frequency of 1.5 s, and the time of 1.5 s, and the filter of our lock-in was set to 100 ms with a 120 kΩ lock-in. To measure the averaged noise spectral density between 22 and 32 kHz where we find no electromagnetic interference-related spectral peaks in our lab environment. At the same time as the noise measurement, we also use a lock-in amplifier to measure the device resistance by recording the voltage across the device while biased with 1 VRMS through a 100 kΩ resistor, albeit at a higher frequency so as to not produce a signal in the noise measurement range. So use our signal waveguide arrangement feature to measure the noise spectral density for each data point. To produce the final plot, we manually record the resistance and noise spectral density for all gate voltage pairs from −6 V to 6 V in steps of 2 V.

Device modeling. We use the Kubo formula reproduced here from Hanson27 to model graphene’s conductivity at DC and infrared frequencies (albeit with different values of the Drude scattering time τ for the different frequency ranges):

where e is the elementary charge, \( f_d(ε) = (\exp(ε - E_F/k_BT) + 1)^{-1} \) is the Fermi-Dirac distribution and \( k_B \) is Boltzmann’s constant. As I will show below, grapheme’s low-frequency conductivity \( \sigma_0 \) and infrared conductivity \( \sigma_\infty \) have various intermediate model parameters; \( \sigma_0 \) and \( \sigma_\infty \) themselves depend strongly on \( E_F \), which features spatial variation due to the back-gates. For the graphene channel, we assume a constant \( N_S = N_{SCH} - e^{-1}C_V \) in the region above each gate, where \( N_S \) is the carrier concentration in the channel (positive for \( E_F \) negative for \( E_F \)). \( N_{SCH} \) is the native carrier concentration at zero gate voltage, \( C_V \) is the capacitance per area of the gate dielectric, and \( V_g \) is the voltage applied to the gate in question (using a set of test devices, we measure \( C_V \) = 34. fF/μm on our chip, corresponding to a back-gate dielectric constant of \( K = 12 \); this is described in more detail in Supplementary Note 4). In the part of the graphene channel above the gap between the two gates, we assume a linear slope between \( N_S \) and \( N_{SCH} \) for the gates, \( N_S = N_{SCH} - e^{-1}C_V \) with \( N_{SCH} \) defined similarly to \( N_S \) and \( N_{SCH} \). In general, the graphene’s Fermi level and carrier concentration are related by \( E_F = h\nu/√(\pi)[N] \) sign(\( \nu \)), where \( \nu \) is graphene’s Fermi velocity. To incorporate the blurring of the graphene’s Fermi level-dependent properties due to spatial carrier concentration variations, we convolve the Kubo formula with a Gaussian as follows:

\[
\sigma_{DC}(N) = \frac{1}{\sigma_0 \sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\frac{1}{2}(\frac{\varepsilon - \varepsilon_0}{\sigma_0})^2} \cdot \delta(\varepsilon) \cdot (E_F(N), \tau_{DC}, T_g) \, d\varepsilon
\]  

(3)

and similarly for \( \sigma_{\infty}(N) \) using \( \nu = 2m\nu/\alpha \) instead of 0 and \( \alpha_0 / \nu \) instead of \( \alpha_0 / \nu \). Finally, we have \( R = \sigma_{DC, \infty} = \pi \rho_{\infty} k_B T_g \sigma_{DC, \infty} / 2e^2 \) via the Wiedemann-Franz law, and \( S = -\langle -\log(\sigma_{DC, \infty}) / E_F \rangle \). \( U_{\infty} \) is obtained by convolving the heat capacity of pristine graphene with a Gaussian of standard deviation \( \sigma_0 \) as in Eqn. (3), where the pristine heat capacity is given by 28.

We use a waveguide eigenmode solver to find the mode profile of our waveguide at \( \lambda = 5.2 \) μm, using refractive indices of 1.4, 2.6, and 1.88 for the CaF2, GSes, and HIO3, respectively. The resulting mode profile enters into our expression for \( \Omega_0 \) as follow29:

\[
\Omega_0 = \int_{\Omega_{IR}} \int_{\Omega_{IR}} P(\Omega_{IR}, \Omega_{IR}) \, d\Omega_{IR} \, d\Omega_{IR}
\]  

(5)

Here, \( y \) is the y-coordinate of the graphene channel, and \( y_g \) would be the y-coordinate of the graphene gates. We may then write \( \alpha_0 = P^{-1}(y, y_g) \cdot Q_{\Omega_0}(\omega) \). Similar expressions hold for \( \alpha_\infty(\omega) \) as well, usually except for the integration in electronic temperature per guided power \( \Delta T_{\phi}(\omega) \) for electronic temperature per guided power  \( T_{\phi}(\omega) = \int (\Omega_0 \cdot \Omega_{IR}) \, d\Omega_{IR} \, d\Omega_{IR} \) the electron-phonon scattering 12, this is described in more detail in Supplementary Note 4).

Here, the average of the Fermi level and carrier concentration are related by \( E_F = h\nu/√(\pi)[N] \) sign(\( \nu \)), where \( \nu \) is graphene’s Fermi velocity. To incorporate the blurring of the graphene’s Fermi level-dependent properties due to spatial carrier concentration variations, we convolve the Kubo formula with a Gaussian as follows:

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\]  

(3)

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\]  

(5)
resistivities (dimensions of $\Omega \cdot m$), respectively. Averaging over $z$ along the length of the waveguide we obtain:

$$V = \frac{\mathcal{R}_c}{L \alpha_{tot}} (1 - e^{-\alpha_z L}) P_{tot} - (R_L + R_T + R_m) I,$$

where $I$ is the current produced by the photodetector, thus describing a Thévenin equivalent source. Here, $\alpha_{tot} = \alpha_c + \alpha_{g} + \alpha_e$ is the total guided power attenuation coefficient within the detector, including contributions not only from the graphene channel but also from the graphene gates ($\alpha_g$), as well as a gate-independent excess loss $\alpha_e$ associated with scattering and absorption from organic or metallic impurities attached to or trapped underneath the graphene sheets. Thus, the total device resistance is equal to $R = R_L + R_T + R_m$, and the voltage responsibility is given by:

$$R_v = \frac{\mathcal{R}_c}{L \alpha_{tot}} (1 - e^{-\alpha_z L}),$$

which we plot versus both gate voltages in Fig. 3b for the best-fit device parameters given in Table 1 obtained as described in Supplementary Note 3. All calculations are carried out in Mathematica.

Data availability
The datasets generated during and/or analysed during the current study are available in the FigShare repository at https://doi.org/10.6084/m9.figshare.c.5514759.v1.

Code availability
The Mathematica document used to simulate photodetector performance metrics is available in the FigShare repository at https://doi.org/10.6084/m9.figshare.c.5514759.v1.

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Author contributions
J.M., D.E., and J.G. conceived the experiments. J.G. designed, fabricated, and measured the devices, with the exception of chalcogenide glass deposition, performed by H.L. and A.-Y.L. under the supervision of J.H., and graphene growth, performed by M.H. and A.-Y.L. under the supervision of J.K. and T.P. K.R. provided the chalcogenide glass source for thermal deposition. J.G. and D.E. wrote the manuscript. All work was supervised by D.E.

Competing interests
The authors declare no competing interests.

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