A MoTe$_2$-based light-emitting diode and photodetector for silicon photonic integrated circuits

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One of the current challenges in photonics is developing high-speed, power-efficient, chip-integrated optical communications devices to address the interconnects bottleneck in high-speed computing systems$^1$. Silicon photonics has emerged as a leading architecture, in part because of the promise that many components, such as waveguides, couplers, interferometers and modulators$^2$, could be directly integrated on silicon-based processors. However, light sources and photodetectors present ongoing challenges$^{3,4}$. Common approaches for light sources include one or few off-chip or wafer-bonded lasers based on III–V materials, but recent system architecture studies show advantages for the use of many directly modulated light sources positioned at the transmitter location$^5$. The most advanced photodetectors in the silicon photonic process are based on germanium, but this requires additional germanium growth, which increases the system cost$^6$. The emerging two-dimensional transition-metal dichalcogenides (TMDs) offer a path for optical interconnect components that can be integrated with silicon photonics and complementary metal-oxide-semiconductors (CMOS) processing by back-end-of-the-line steps$^7$$^9$. Here, we demonstrate a silicon waveguide-integrated light source and photodetector based on a p–n junction of bilayer MoTe$_2$, a TMD semiconductor with an infrared bandgap$^{10}$. This state-of-the-art fabrication technology provides new opportunities for integrated optoelectronic systems.

The power consumption of interconnects is becoming increasingly problematic in high-performance computing systems. For instance, retrieving two floating point numbers can require an order of magnitude more energy than a logic operation between them$^{11,12}$. Today, many high-performance computing applications require multiple domains to execute bandwidth-critical applications across many different parallel resources, often at intermittent but explosive data volumes. Recent theoretical studies$^8$ have shown that these rapidly shifting and intermittent communication requirements across computing domains favour multiple low-power direct-modulation light sources in place of one or few high-power lasers distributed across many transmitter modulators. The advantages of integrating light sources with electrical computing modules have increased the interest in layered two-dimensional (2D) materials, which have been demonstrated recently to possess promising properties for use in electronic and optoelectronic devices$^{13–16}$. In contrast to covalently bonded materials produced by epitaxial growth, the van der Waals interaction between the 2D layers and the silicon substrate minimizes the introduction of surface defects due to lattice mismatch$^{17–19}$. MoTe$_2$ is a 2D semiconductor with a bandgap of $\sim$1 eV at room temperature. The successful large-scale chemical vapour growth method used for MoTe$_2$ (refs 8,20) and h-BN (ref. 21) and 2D atomic thin material transfer methods$^{2,22}$ could enable practical optoelectronics applications in the near-infrared range$^{2,23,24}$. In this Letter, we demonstrate MoTe$_2$-based lateral p–n junctions with an electrostatic split-gate configuration$^{14–16}$, which allows for diverse functionalities including transistors, light-emitting diodes (LEDs) and photodetectors, integrated with a silicon photonic-crystal (PhC) waveguide.

Figure 1a illustrates the MoTe$_2$ device. The p–n junction is designed to evanescently couple to the modes of the PhC waveguide, which is based on a holey silicon membrane. The device contains a grating coupler at the far end of the waveguide to allow excitation and collection. When the p–n junction is operated as an LED (top panel of Fig. 1a), the emitted light couples to the waveguide, where it travels in-plane to the grating coupler. In the photodetector mode, incident light is coupled into the waveguide by the grating coupler and detected by the p–n junction, which transforms it into an electrical signal. As illustrated in the device cross-section in Fig. 1b, the MoTe$_2$ p–n junction relies on an exfoliated bilayer of MoTe$_2$ separated by a hexagonal boron nitride (h-BN) dielectric layer from a split-graphite gate to electrostatically induce the p- and n-type doping. The entire device is encapsulated by h-BN layers$^8$ to prevent natural oxidation of the MoTe$_2$.

Figure 1c shows the optical near-field coupling between the p–n junction and the waveguide, based on 3D finite-difference time-domain (FDTD) simulations. Emitted light from a dipole is used to represent the MoTe$_2$ emission, which is evanescently coupled into the waveguide, as expected. The final device is shown in the optical microscope image in Fig. 1d. Details of the simulation and device fabrication are described in the Methods, Supplementary Fig. 5 and Supplementary Note 4.

Figure 2a,b presents characteristic current–voltage ($I_{ds}$–$V_{ds}$) curves for different gate voltage configurations. All the electrical measurements were performed at room temperature in vacuum (10$^{-4}$ torr) unless otherwise noted. The voltages on the two top gate electrodes ($V_{lg}$ for the left gate and $V_{rg}$ for the right gate) independently control the carrier type and density on the two sides of the junction in the bilayer MoTe$_2$. As shown in Fig. 2a, the $I_{ds}$–$V_{ds}$ curves are almost linear when both sides are p-doped (denoted PP, $V_{lg} = V_{rg} = 30$ V) or n-doped (denoted NN, $V_{lg} = V_{rg} = 30$ V). If the gates are oppositely biased, corresponding to a PN junction ($V_{lg} = 30$ V and $V_{rg} = 30$ V) or an NP junction ($V_{lg} = 30$ V and $V_{rg} = 30$ V) respectively, the curves show the expected diode behaviour.

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To explore the optical properties of bilayer MoTe₂, we measured photoluminescence (PL) and electroluminescence (EL) spectra at room and cryogenic temperatures, using a confocal microscope set-up with an infrared spectrometer and a camera (Supplementary Fig. 2). Figure 3a presents the EL spectra with \( V_{\text{lg}} = -V_{\text{ds}} = -8 \text{ V} \) at a forward bias of \( V_{\text{ds}} = 2 \text{ V} \). The current is 2.3 \( \mu \text{A} \) at room temperature and 1.5 \( \mu \text{A} \) at low temperature. The figure also shows the PL at zero gate voltage for comparison. At room temperature, the EL and PL spectra are centred at 1,175 nm with a full-width at half-maximum (FWHM) of \( \sim 70 \text{ nm} \). At 6 K, the PL emission peak is narrowed to \( \sim 70 \text{ nm} \) at 1,090 nm. A small redshifted shoulder appears at 1,110 nm, which we attribute to the trionic peak. Trions are overlaid on a false-colour optical image of the structure at room and cryogenic temperatures, using a confocal microscope set-up with an infrared spectrometer and a camera (Supplementary Fig. 2). Figure 3a presents the EL spectra with \( V_{\text{lg}} = -V_{\text{ds}} = -8 \text{ V} \) at a forward bias of \( V_{\text{ds}} = 2 \text{ V} \). The current is 2.3 \( \mu \text{A} \) at room temperature and 1.5 \( \mu \text{A} \) at low temperature. The figure also shows the PL at zero gate voltage for comparison. At room temperature, the EL and PL spectra are centred at 1,175 nm with a full-width at half-maximum (FWHM) of \( \sim 70 \text{ nm} \). At 6 K, the PL emission peak is narrowed to \( \sim 70 \text{ nm} \) at 1,090 nm. A small redshifted shoulder appears at 1,110 nm, which we attribute to the trionic peak. Trions are automatically created in the system due to intrinsic doping\(^{26}\). Both PL and EL peaks experience a blueshift with decreasing temperature (see Supplementary Figs 3a,b and 4a for details). To correlate the electrostatic doping level with the emission spectra, we configured the device as a bipolar transistor with a uniform gate voltage \( V_g = V_{\text{lg}} = V_{\text{rg}} \). Figure 3b shows the PL intensity as a function of wavelength and gate voltage \( V_g \) at 6 K, where the excitonic (\( X_0 \)) and trionic (\( X' \)) peaks can be clearly distinguished. Further spectral analysis is provided in Supplementary Notes 2 and 3.

Figure 3c shows the EL intensity with the device in LED mode, overlaid on a false-colour optical image of the structure at room temperature. The strongest emission intensity originates from the p–n junction area where carrier recombination happens. A fraction of the emission that is coupled to the waveguide is scattered at the grating couplers, which lights up in the image under forward bias. We estimate the efficiency \( \eta \) of the photonic structure—that is, the fraction of EL photons collected from the grating couplers—as \( \eta = (\gamma_{\text{couplers}}/y_{p-n} + \gamma_{\text{couplers}}) \), where \( \gamma_{\text{couplers}} \) denotes the number of photons collected from the two grating couplers (the p–n junction), respectively. Based on the EL images, we estimate...
that $\gamma \sim 5\%$, which includes the significant losses at the grating couplers and in the detection set-up. The emission at the left grating coupler is weaker because one piece of graphite was accidentally transferred onto the left side of the waveguide during the transfer process. The broadband absorption of graphene reduces the PhC mode on this arm of the device.

The selective detection offered by the confocal microscopy allows a comparison of the emission spectra from the different areas of the device. In Fig. 3d, the blue line plots the normalized EL emission spectrum collected from the grating coupler, showing a narrow peak (FWHM of $\sim 10$ nm) centred at 1,160 nm on top of a broader peak that matches the free-space emission of the bilayer MoTe$_2$ centred at 1,175 nm. For comparison, the transmission spectra of the silicon waveguide are also plotted before (orange line) and after (green line) MoTe$_2$ stack transfer. Here, the transmission spectra were measured by sending broadband white light onto one grating coupler and collecting from the other coupler within the same field of view of the collection objective. The pre-transfer PhC transmission shows a peak at 1,160 nm, which matches well with the guided EL emission. After the MoTe$_2$ transfer, the peak transmission at 1,160 nm drops, as shown by the green line in Fig. 3d, mainly because of the MoTe$_2$ absorption that disturbs the PhC modes. However, as the p–n junction works as an LED, the MoTe$_2$ absorption is reduced because the excited states have been filled by electrically excited carriers and the waveguided light is not reabsorbed by the MoTe$_2$. Therefore, the peak at 1,160 nm due to the PhC mode recovers and is detected from the grating coupler in the EL emission spectrum (blue line). In addition to the narrow peak at 1,160 nm, the broader peak centred at 1,175 nm is the product of the LED
2.5% of the incident laser power is guided to the p–n junction. Similarly, the external quantum efficiency (EQE) can be calculated as 

\[ \text{EQE} = \frac{I_{\text{sc}}}{P_{\text{laser}}} \left( \frac{hc\epsilon}{e} \right) \]

where \( I_{\text{sc}} \) is the short-circuit current, \( P_{\text{laser}} \) is the laser power, \( h \) is Planck’s constant, \( c \) is the speed of light and electron charge, respectively. A detailed analysis of the responsivity is provided in Supplementary Note 7.

Unlike the reported photogating and photoco nductive-type detectors based on few-layer MoTe2 transistors\(^{26,30}\), the bilayer MoTe2 p–n junction shows a far higher response speed, as shown in Fig. 4c. Using the time-domain method, the photocurrent response bandwidth of the p–n junction is measured up to 200 MHz, limited only by the response speed of our current amplifier in the experimental set-up. From the consideration of built-in electrical field and drift velocity, we estimate that the p–n junction can achieve gigahertz bandwidth. More details are provided in Supplementary Note 6 and Supplementary Fig. 9.

Figure 4d plots the wavelength-dependent photocurrent, which shows that the photocurrent response originates from the guided, and not the scattered, light. The response peak is near 1,160 nm where the waveguide transmission is largest. Above 1,200 nm and below 1,110 nm, the photoresponse drops because of the reduced absorption of the bilayer MoTe2 and the waveguide transmission cutoff. The MoTe2 p–n junction can potentially be used to detect the emission from the MoTe2 in an emitter–receiver configuration.

Our results demonstrate the integration of light-emitting diodes and photodetectors based on bilayer MoTe2 p–n junctions with silicon PhC waveguide technologies. The integration of TMD LEDs into silicon photonics enables point-to-point optical links. Furthermore, narrowband lasers may be realized in a similar way, by integrating the electrically pumped TMD gain materials with PhC nanocavities, which can be coupled to waveguides with near-
unity efficiency\(^3\), which could further increase the optical coupling efficiency and allow for on-chip waveguide division multiplexing. Given the rapid advancements of devices based on 2D van der Waals materials, novel functionalities and better performance can be expected\(^3\). For example, the interlayer exciton emission and electrostatic gating effect provides extra tuning capabilities for the emission wavelength, while the use of heterostructures that allow exciton emission in the near-infrared (NIR) range could provide more efficient active layers for light emission, and higher-speed data communications can be expected by integrating with large-bandwidth graphene modulators\(^4\). Moreover, this work shows that all active optical components for point-to-point interconnects are possible with 2D TMD devices transferred onto otherwise passive photonic integrated circuits. We emphasize that a silicon waveguiding layer is not the only choice; our approach is compatible with passive waveguide layers, such as silicon nitride, which are available as top layers in most CMOS processes. This ease of integration on a wide range of electrical processors and memory has the potential to greatly simplify the design of high-speed interconnects in advanced computing and sensor systems.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions


Additional information

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Competing financial interests

The authors declare no competing financial interests.
Methods

Fabrication of encapsulated MoTe$_2$ p–n junctions. Device fabrication began with exfoliation on SiO$_2$/Si substrates of bulk MoTe$_2$ (from 2D semiconductors, HQ graphene or grown in-house using a chemical vapour transport technique), h-BN and natural graphite crystals. The graphite layer was then prepatterned to match the split-gate geometry. Monolayer and bilayer MoTe$_2$ were identified by optical contrast and PL. The target thin flakes were picked up by the transfer slide, composed of a stack of glass, a polydimethylsiloxane (PDMS) film and a polycarbonate (PC) film, as described in ref. 33. We picked up the flakes for stacking in the following order: graphite gate layer, top h-BN layer, bilayer MoTe$_2$, two pieces of thin graphite for electrodes and the bottom h-BN layer. The resulting stack was then placed on top of the PhC waveguide with the help of a transfer set-up that allowed a precision of 500 nm under an optical microscope. The alignment of the split graphite gate with the waveguide channel was subsequently verified by atomic force microscopy (AFM; for AFM images see Supplementary Fig. 1). The split gates were separated by a 400 nm gap, patterned using electron-beam lithography and reactive ion etching with oxygen plasma. The graphite thicknesses for both split gates and source drain electrodes were ∼3–5 nm. The top h-BN worked as a dielectric layer with a dielectric constant $\varepsilon_r$ of 3.9. In the device measured in Fig. 3a,b and Supplementary Figs 3 and 4, 35-nm-thick h-BN was used as the dielectric layer, but for the other bilayer devices, the thickness of the dielectric h-BN layer was 80 nm. The thickness of the bottom h-BN, which separates the MoTe$_2$ layer and the waveguide, was 10 nm.

Waveguide design. The PhC waveguide was designed to support a transverse-electric-like (TE-like) mode at wavelengths within the MoTe$_2$ emission range. Simulations were carried out using commercially available FDTD software (Lumerical). This software includes a frequency-dependent complex refractive index for the silicon layers. In the simulations, we included the bottom silicon substrate, the SiO$_2$ layer (3 μm), the silicon PhC membrane (220 nm) and a top h-BN layer of 100 nm thickness. The coupling of light emitted from the p–n junction into the waveguide was modelled using a dipole source (directed perpendicular to the x–z plane) located 10 nm above the silicon PhC membrane at the centre of the waveguide.

Fabrication of the PhC waveguide. Fabrication of the PhC device was carried out on a silicon on insulator chip with a 220 nm silicon device layer. Because the top silicon film is conductive, several trenches were etched to separate the electrodes and avoid short circuits. The PhC waveguide was 140 μm long and was designed with lattice constant $a$ ranging from 271 to 298 nm and an air hole radius of $r = 0.25a$. The PhC patterns were defined by electron-beam lithography (JEOL JBX-6300FS, 100 keV) on a 150-nm-thick ZEP520A resist layer. Cold development with hexyl acetate was used to improve the pattern contrast. Patterns were then transferred from the electron-beam resist layer to the Si device layer using plasma etching with an SF$_6$ and O$_2$ gas mixture (SF$_6$:O$_2$ = 40:18) at cryogenic temperature (Oxford Instruments Plasmalab 100). A scanning electron micrograph (SEM) of the resultant device is shown in Supplementary Fig. 5a, and the lattice-constant-dependent waveguide transmission spectra are shown in Supplementary Fig. 5b.

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

References