CMOS-compatible graphene photodetector covering all optical communication bands

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Optical interconnects are becoming attractive alternatives to electrical wiring in intra- and interchip communication links. Particularly, the integration with silicon complementary metal-oxide semiconductor (CMOS) technology has received considerable interest because of the ability of cost-effective integration of electronics and optics on a single chip. Although silicon enables the realization of optical waveguides and passive components, the integration of another, optically absorbing, material is required for photodetection. Traditionally, germanium or compound semiconductors are used for this purpose; however, their integration with silicon technology faces major challenges. Recently, graphene emerged as a viable alternative for optoelectronic applications, including photodetection. Here, we demonstrate an ultrawideband CMOS-compatible photodetector based on graphene. We achieved a multigigahertz operation over all fibre-optic telecommunication bands beyond the wavelength range of strained germanium photodetectors, the responsivity of which is limited by their bandgap. Our work complements the recent demonstration of a CMOS-integrated graphene electro-optical modulator, and paves the way for carbon-based optical interconnects.

Graphene’s suitability as a photodetector was first demonstrated by locally illuminating the vicinity of one of the electrical contacts of a back-gated graphene transistor. A detectable current was generated that was attributed to band bending at the metal/graphene interface. Photocurrents (PCs) have also been obtained at single/bilayer graphene interfaces and graphene p–n junctions and attributed to the thermoelectric effect. The detailed microscopic processes involved in the PC generation are still debated. Recently, graphene has emerged as a viable alternative for optoelectronic applications, including photodetection. Here, we demonstrate an ultrawideband CMOS-compatible photodetector based on graphene. We achieved a multigigahertz operation over all fibre-optic telecommunication bands beyond the wavelength range of strained germanium photodetectors, the responsivity of which is limited by their bandgap. Our work complements the recent demonstration of a CMOS-integrated graphene electro-optical modulator, and paves the way for carbon-based optical interconnects.

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length of light is reduced to 7 μm only. In addition to the fundamental TE mode, the waveguide also supports the propagation of the lowest-order quasi-transversal magnetic (TM) mode, whose damping α_{TM}, however, is significantly larger. We thus expect the photodetector to be polarization sensitive, with higher responsivity for TE polarized light. In a second step, we calculated α_{G} by setting C_{G} = 0 and integrating the tangential field component along the graphene sheet. The results for both monolayer and bilayer graphene are shown as dashed and solid lines, respectively, in Fig. 2a. For W > 100 nm (monolayer) and W > 160 nm (bilayer) the absorption of light by the metal electrode is more dominant than the absorption in graphene. To achieve high responsivity, it is thus necessary to keep the electrode width W as small as possible. However, the contact resistance increases with decreasing W, which decreases the PC and gives rise to reduced bandwidth. These requirements contradict each other, and the device parameters have to be optimized by minimizing the trade-offs.

With α_{M} and α_{G}, the fraction η of light that is absorbed in the graphene sheet (see Fig. 2b) can be calculated by:

\[ \eta(L) = \frac{\alpha_G}{\alpha_G + \alpha_M} \left( 1 - e^{-\alpha_M L} - e^{-\alpha_G L} \right) \]

The calculation results show that efficient light absorption can be achieved with short device lengths, which enables high-speed operation and dense integration capability. For example, η > 50% is obtained in a bilayer device only 22 μm long (W = 100 nm). Moreover, as can be seen from the calculated mode profile (E_{z} component) in Fig. 2a, the absorption occurs mainly near the metal/graphene interface where PC generation is most efficient. Light (~34% in the above example) is also absorbed in the graphene that covers the sidewalls of the waveguide (mainly caused by the E_{z} component (not shown)).

We now present the performance characteristics of a bilayer graphene device with L = 24 μm and W = 180 nm. For these dimensions, we estimate η ≈ 44% (see Fig. 2b). For device characterization, laser light of wavelength 1,550 nm was coupled into the silicon waveguide using a lensed single-mode fibre (~2.5 μm spot diameter). The optical power at the input port of the waveguide-integrated graphene photodetector, P_{in}, was estimated from transmission measurements of reference waveguides without a photodetector. The total losses, 15 ± 1 dB, stem mainly from coupling losses from the optical fibre to the waveguide. A similar value is obtained by calculating the overlap integral between the field profile of the incident wave and that of the guided mode. The device was connected to a transimpedance amplifier with low input impedance to measure the photocurrent I_{PC}. Figure 3a shows the power dependence of I_{PC}, which is linear across the entire measurement range. The photoresponsivity S, defined as the ratio of the measured PC to the input optical power, is S = I_{PC}/P_{in} ≈ 0.03 A W⁻¹. Our best device, made of trilayer graphene, had a responsivity of S ≈ 0.05 A W⁻¹, an order of magnitude larger than that achieved with normal-incidence graphene photodetectors. From 0.05 A W⁻¹ we estimate an internal quantum efficiency of η = (hcε)/e = 10% (h, Planck’s constant; c, speed of light; e, electron charge). Considering the values of η = 30–60% estimated from PC measurements on simple metal/graphene interfaces, we believe that there is plenty of room for improvement (for example, by applying gate11–13 or S–GND bias fields8, improving the material quality16, increasing the steepness of the potential gradient by using Ag instead of Au electrodes35, increasing η through an optimized electrode arrangement, employing graphene p–n junctions15,16 or suspending the graphene sheet in air34).

The wavelength dependence of the photoresponse, shown in Fig. 3b, was measured using three separate light sources: fixed-wavelength lasers, operating at 1,310 nm (O band) and 1,650 nm (U band), respectively, and a tunable laser, operating in the range 1,550–1,630 nm (from the C band, throughout the L band to the U band). The responsivity is flat across all optical telecommunications windows, unlike the drastic decrease of the response of Ge detectors beyond 1,550 nm (ref. 1), or strained Ge detectors beyond 1,605 nm (ref. 9). We expect the device to work at even longer wavelengths, limited only by the cut-off properties of the silicon waveguide. As InGaAs cannot be integrated monolithically with silicon CMOS, currently other materials are being investigated for photodetection in the L and U bands, with ion-implanted Si36 and GeSn37 being the most promising ones. However, implanted Si detectors suffer from low optical absorption that requires devices millimetres long to absorb the radiation, which results in device footprints 10–100 times larger than presented here. GeSn photodetectors, however, exhibit high dark currents, and waveguide integration of GeSn has, to our knowledge, not yet been demonstrated.
Figure 2 | Simulation results and device optimization. a, Comparison of the losses in the metallic electrode $S\alpha_M$ (open triangles) and the graphene absorption $\alpha_G$ (dashed line, monolayer graphene; solid line, bilayer graphene) as a function of electrode width $W$. The calculations were performed for 1,550 nm wavelength and TE polarization. For $W > 100$ nm (monolayer) and $W > 160$ nm (bilayer) the losses are more dominant than the absorption in graphene. The inset shows a mode profile ($E_y$ component) of the fundamental quasi-TE mode. The contours of the waveguide and $S$ are shown as dashed lines. b, Light absorption in the graphene sheet as a function of device length $L$ and electrode width $W$ (plotted on a double-logarithmic scale). Curves are presented for $W = 0$ nm (no electrode), $W = 100$ nm, $W = 200$ nm and $W = 350$ nm. Solid lines, bilayer graphene; dashed lines, monolayer graphene. The inset shows the same data for bilayer graphene on a linear scale. For $W = 0$ the absorption in graphene can reach 100% if the device is made sufficiently long. For $W \neq 0$ losses in the metal electrode restrict the maximum achievable absorption (and hence efficiency) of the device.

Figure 3 | Performance characteristics of a bilayer graphene photodetector. a, PC as a function of the incident optical power. The responsivity $S = I_C/P_in$ is extracted from the slope of the curve. b, Wavelength dependence of the PC. A flat response is obtained across all optical telecommunication windows.

is the FWHM pulse duration), is $\sim 18$ GHz. This is also approximately the bandwidth of our measurement system and we anticipate that the device might work at even higher frequencies. Fourier transform of the time-domain data provides the spectrum shown in the inset.

Finally, we summarize the opportunities that graphene offers as a new material for optical interconnects.

(1) Ultra-wideband operation. The gapless character of graphene enables optical interband transitions to occur over an ultra-wide wavelength range, unmatched by any other material. In this letter, we demonstrate photodetector operation from the O to the U band. However, graphene-based optoelectronic devices can operate over an even wider range of wavelengths.

(2) High-speed operation. With its extremely high carrier mobility (200,000 cm$^2$ V$^{-1}$ s$^{-1}$ at room temperature) graphene is predestined for high-speed applications, including high-speed data transmission.

(3) Low energy consumption. Besides a high data rate, low energy consumption (J bit$^{-1}$) is the most important requirement for an optical communication link. Our devices rely on built-in potentials that exist at metal/graphene interfaces and hence are operated under zero-bias conditions (that is, without dark current) and vanishing power consumption. Moreover, recently it was predicted that the energy consumption of graphene-based modulators could be at least as low as those of the best
defined using optical lithography and etched by reactive-ion etching. The wafer was spectroscopy41) was then prepared by mechanical exfoliation on a separate of suitable size and thickness (verified by optical microscopy and Raman occurred in two steps. First, a nominally 1-nm-thick Ti layer was evaporated, shape by oxygen plasma (only where necessary) and contact electrodes were taken to avoid placement of graphite chunks (which are, inevitably, also transferred in this process) on top of the optical waveguide. The graphene sheet was etched in shape by oxygen plasma (only where necessary) and contact electrodes were fabricated by electron-beam lithography and metal deposition. The metal deposition occurred in two steps. First, a nominally 1-nm-thick Ti layer was evaporated, followed by a 20-nm-thick Au layer. The Ti serves to improve the adhesion of Au to graphene and does not form a continuous layer. In a second step, a 25-nm-thick Au layer was sputtered to ensure that the waveguide sidewalls were covered with metal to achieve electrical contact between the central electrode and the bonding pad. Keeping the Ti content as low as possible is crucial, as its dissipative dielectric function leads to a strong damping of the optical mode. The sample was annealed in vacuum at 125 °C for several hours to remove polyvinylmethylacrylate residues from the surface of the graphene. Finally, the sample was cleaved using a diamond scribe to obtain a clean facet for the in-coupling of light. A schematic of the device cross-section is shown in the inset of Fig. 1a.

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Methods
Our devices were fabricated on a commercial silicon-on-insulator wafer with a 270-nm-thick Si device layer and 3 μm buried oxide. A 600-nm-wide waveguide was defined using optical lithography and etched by reactive-ion etching. The wafer was then covered by plasma-enhanced CVD with a 7-nm-thick layer of SiO2, to prevent electrical contact between the graphene and the silicon waveguide. A graphene sheet of suitable size and thickness (verified by optical microscopy and Raman spectroscopy18) was then prepared by mechanical exfoliation on a separate 300-nm-thick oxide-coated Si wafer, lifted off from this wafer and transferred with micrometre precision onto the desired location on the waveguide sample. Care was taken to avoid placement of graphene chunks (which are, inevitably, also transferred in this process) on top of the optical waveguide. The graphene sheet was etched in shape by oxygen plasma (only where necessary) and contact electrodes were fabricated by electron-beam lithography and metal deposition. The metal deposition occurred in two steps. First, a nominally 1-nm-thick Ti layer was evaporated, followed by a 20-nm-thick Au layer. The Ti serves to improve the adhesion of Au to graphene and does not form a continuous layer. In a second step, a 25-nm-thick Au layer was sputtered to ensure that the waveguide sidewalls were covered with metal to achieve electrical contact between the central electrode and the bonding pad. Keeping the Ti content as low as possible is crucial, as its dissipative dielectric function leads to a strong damping of the optical mode. The sample was annealed in vacuum at 125 °C for several hours to remove polyvinylmethylacrylate residues from the surface of the graphene. Finally, the sample was cleaved using a diamond scribe to obtain a clean facet for the in-coupling of light. A schematic of the device cross-section is shown in the inset of Fig. 1a.

Figure 4 | High-speed photosresponse of a bilayer graphene photodetector. Impulse response of the device recorded with a 20 GHz sampling oscilloscope. The FWHM pulse duration is Δt ≈ 25 ps, which translates into a bandwidth of Δf = 0.44/Δt ≈ 18 GHz. The inset shows the frequency response obtained by Fourier transform of the time-domain data. a.u., arbitrary units.

modulators fabricated using Si and SiGe technology38 (<0.5 fF bit−1). Hence, graphene could provide substantial advantages for use in energy-efficient optical interconnects.

(4) Small device footprint. The strong optical absorption in graphene (absorption coefficient at infrared wavelengths more than 100 times higher than that of Ge) allows for a high level of integration of optoelectronic devices on a single chip. With device footprints down to 50 μm2 (without contact pads), about 20,000 of our photodetectors could be integrated on a 1 × 1 cm2 die. A similar integration density is predicted for graphene-based modulators10.

(5) Compatibility with CMOS and other technologies. Graphene’s two-dimensional character makes it compatible with standard semiconductor technology and allows for monolithic integration with silicon and other materials. Our devices operate under the voltage and current requirements of CMOS and their fabrication does not involve any high-temperature processes or contamination issues that could harm silicon circuitry. The recent developments in high-quality chemical vapour deposition (CVD) graphene synthesis39 will allow for wafer-scale integration of such devices into optical interconnects. The mechanical flexibility of graphene also enables integration with bendable substrates. In particular, we envision that graphene could play a role in realizing various active components in polymer-based optical circuits40.

(6) Simplicity and low cost. The versatility and broadband capability of graphene allows for intriguingly simple device layouts and offers low development and fabrication costs by eliminating the need for multiple detector and modulator designs. All these aspects lead us to consider graphene a promising new material for integrated photonics.

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Author contributions
T.M. conceived and designed the experiments. A.P. and M.H. fabricated the samples. A.P. carried out the measurements. T.M. and M.H. performed the simulations. M.M.F. and D.B. contributed to the development of the measurement set-ups. R.G. and T.F. contributed to the sample fabrication. A.P. and T.M. analysed the data. T.M. wrote the paper. All authors discussed the results and commented on the manuscript.

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Competing financial interests
The authors declare no competing financial interests.