Ultra-wideband graphene photodetectors for photonic integrated circuits

Andreas Pospischil[1], Markus Humer[2], Marco M. Furchi[1], Romain Guider[2], Thomas Fromherz[2],
and Thomas Mueller[1]

[1]Vienna University of Technology, Institute of Photonics, Gußhausstraße 27-29, 1040 Vienna, Austria
[2]Johannes Kepler University Linz, Institut für Halbleiter und Festkörperphysik, Altenbergerstraße 69,
4040 Linz, Austria
thomas.mueller@tuwien.ac.at

Abstract

Graphene is a two-dimensional electron system comprised of a single atomic layer of carbon. It has unique physical properties, such as linear electronic dispersion, zero effective mass, and extraordinary high carrier mobility. Despite the absence of an electronic band gap, graphene also holds great promise for applications in photonics and optoelectronics. Photocurrent experiments have demonstrated a strong response near metal/graphene interfaces with an internal quantum efficiency of up to 30 %. The high photocurrent generation efficiency is related to the high carrier velocity, which leads to an ultrafast separation of the photo-generated carriers near local potential variations, such as they exist near metal/graphene interfaces. In ultrafast photocurrent measurements [1, 2], no photo-response degradation was observed up to 40 GHz, demonstrating the feasibility and unique benefits of using graphene in high-bandwidth optical communication systems. A metal-graphene-metal photodetector [3], consisting of a large number of inter-digitated finger electrodes, was used for the faithful detection of an optical bit stream at a data rate of 10 Gb/s. Integration of a metal-graphene-metal photodetector into an optical microcavity [4] allowed to increase the inherently low (2.3 %) optical absorption in single-layer graphene to >60%.

Here, we demonstrate the first monolithic integration of a graphene-based photodetector with a silicon-on-insulator waveguide [5]. Ultra-wideband operation across all optical telecommunication windows, from O- to U-band, is achieved. Such a broad operation range cannot be achieved with materials that are traditionally used in silicon photonics, such as strained germanium, whose responsivity range is limited by its band gap. Our work complements the recent demonstration of a CMOS-integrated graphene electro-optical modulator [6], paving the way for carbon-based optical interconnects.

A schematic illustration of the device structure is shown in Figure 1 (a). The devices were fabricated on a silicon-on-insulator (SOI) wafer with 270 nm thick Si device layer and 3 µm buried oxide. A 600 nm wide waveguide was defined using lithography and etched by reactive-ion etching. The wafer was then covered with a 7 nm thick layer of SiO2 and a sheet of graphene (≈25×25 µm2 in size) was transferred to the desired location on the waveguide. Contact electrodes were fabricated by electron-beam lithography and Ti/Au sputtering. Finally, the sample was cleaved in order to obtain a clean facet for the in-coupling of light. The optical mode in the waveguide is absorbed as the light propagates along the graphene sheet. The potential gradient, originating from different dopings in the metal-covered and uncovered parts of graphene [1,3], drives a photocurrent (PC) towards the ground leads, as illustrated in Figure 1 (b). Due to the lack of an electronic band gap in graphene, the photo-generated carriers pass through the potential barriers at the GND-electrodes almost unimpeded, leading to high-bandwidth photodetection even without S-GND bias, and hence without dark-current. A careful design of the device geometry was performed in order to evaluate the tradeoff in photo-responsivity due to the optical absorption in the signal electrode. For achieving optimum performance, it is necessary to keep the signal electrode width as small as possible. On the other hand, the contact resistance increases with decreasing electrode width, giving rise to reduced photocurrent and reduced RC-bandwidth.

The performance characteristics of a 24 µm long bilayer graphene device with 180 nm wide signal electrode was determined by coupling laser light (1.55 µm wavelength) into the silicon waveguide using a lensed single-mode fiber (2.5 µm spot diameter). The optical power at the input port of the waveguide-integrated photodetector was estimated from transmission measurements of reference waveguides without photodetector. The photo-responsivity, defined as the ratio of the measured photocurrent to the input optical power, was determined to be 0.05 A/W – an order of magnitude higher than that achieved with normal-incidence photodetectors [3]. The wavelength-dependence of the photo-response was measured using two separate light sources: a laser operating at a fixed wavelength of 1310 nm (O-band), and a second laser, tunable in the range 1550–1630 nm (from the C-band, across all over the L-band, into the U-band). It was found that the responsivity is entirely flat across all telecommunication bands, unlike the drastic decrease of the response of Ge photodetectors beyond 1550 nm, or strained

Ge detectors beyond 1605 nm. We expect the device to work at even longer wavelengths; limited only by the cut-off properties of the silicon waveguide.

Because InGaAs cannot be monolithically integrated with silicon CMOS, other materials are currently being investigated for photodetection in the L- and U-bands. Among them, ion-implanted Si and GeSn are considered the most promising ones. Our graphene photodetectors outperform devices based on these materials in several respects. Implanted Si detectors suffer from low optical absorption, resulting in device footprints that are 10–100 times larger than what we achieve with graphene. GeSn photodetectors, on the other hand, exhibit high dark currents, whereas our devices can be operated without bias (and hence without dark current).

References

[1] F. Xia, T. Mueller, Y. Lin, A. Valdes-Garcia, and Ph. Avouris, Nature Nanotechnol. **4** (2009) 839.
[2] A. Urich, K. Unterrainer, and T. Mueller, Nano Lett. **11** (2011) 2804.
[3] T. Mueller, F. Xia, and Ph. Avouris, Nature Photon. **4** (2010) 297.
[4] M. Furchi, Nano Lett. **12** (2012) 2773.
[5] A. Pospischil, M. Humer, R. Guider, T. Fromherz, and T. Mueller, to be published.
[6] M. Liu, X. Yin, E. Ulin-Avila, B. Geng, T. Zentgraf, L. Ju, F. Wang, and X. Zhang, Nature **474** (2011) 64.

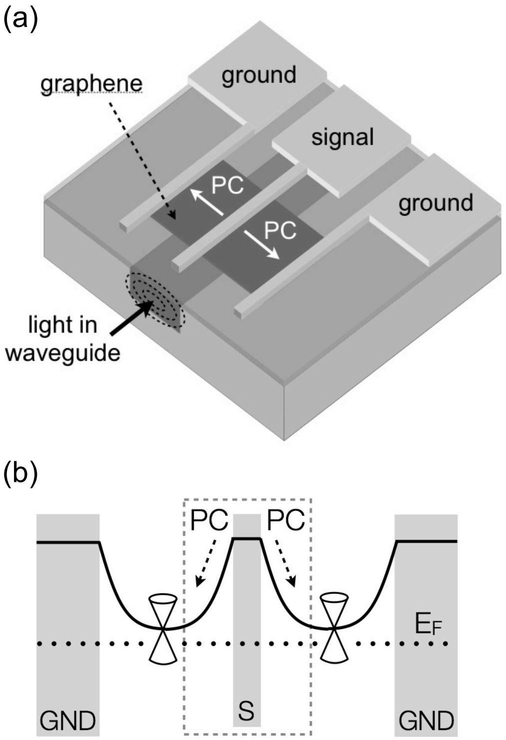

Figure 1: (a) Schematic drawing of a silicon waveguide integrated graphene photodetector. (b) Potential profile in the graphene sheet. The GND-S-GND configuration allows doubling of the photocurrent.