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Graphene and related two-dimensional (2D) materials are currently attracting tremendous amount of attention in the research community. With its peculiar band structure and extraordinary physical properties, graphene has inspired interesting applications in nanoelectronics and many other fields. In optoelectronics, graphene has been utilized for the realization of photodetectors [1] and optical modulators [2], covering a wide range of the electromagnetic spectrum from the terahertz to the ultraviolet. Graphene also supports localized and propagating plasmons that are electrically controllable via electrostatic doping with an external electric field [3] – a property that is not available in metal-based plasmonics and that could eventually lead to ultra-small optical modulators and switches.

More recently, another family of 2D materials – transition metal dichalcogenides (TMDs), such as e.g. molybdenum disulphide (MoS_2) and tungsten diselenide (WSe_2) – have come into the focus of interest, as these offer properties that are complementary to those of graphene. Some TMDs are semiconductors with a sizable band gap, which allows the construction of logic transistors [4], light emitters [5], photovoltaic solar cells [6] and other devices. Moreover, physical properties of monolayer TMDs differ significantly from their bulk characteristics. For example, a thickness-dependent indirect-to-direct band gap transition is commonly observed in these materials [7]. In addition, the large exciton binding energies, valley circular dichroism and coherence in monolayers [8] offer exciting opportunities for novel information processing devices.

The value of graphene as an optoelectronic material is due to its wide range optical absorption, the electrical tunability of its optical properties, and the large carrier mobility. These properties allow for the realization of high-speed and broadband electro-optical modulators and photodetectors, employed in optical communication systems. Moreover, the modern trend toward the integration of different optical components side-by-side with electrical circuitry on a silicon chip, has intensified the search for CMOS-compatible photonic materials and technologies, and graphene is considered a promising candidate. Despite the absence of a band gap, graphene shows a surprisingly strong photoresponse near metal/graphene interfaces with an internal quantum efficiency of up to 30 % [1]. In RF photocurrent measurements, no photoresponse degradation was observed up to 40 GHz [9]. A metal-graphene-metal photodetector, 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 [10]. Integration of a metal-graphene-metal photodetector into an optical microcavity allowed to increase the inherently low (2.3 %) optical absorption in graphene to > 60 % [11].

Fig. 1 shows the integration of a graphene photodetector into a silicon chip [12]. The optical mode in the silicon 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, drives a photocurrent (PC) towards the ground leads. Due to the lack of an electronic band gap in graphene, the photo-generated carriers pass through the potential barriers at the ground-electrodes almost unimpeded, leading to high-speed photodetection even without bias voltage, and hence without dark-current. The photo-responsivity, defined as the ratio of the photocurrent to the input optical power, was determined to be 0.05 A/W. In an improved design [13], the responsivity has recently been pushed to 0.36 A/W, close to that of Ge photodetectors currently employed in silicon photonics. It was further found that the responsivity is approximately 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. The work on photodetectors was complemented by the development of integrated electro-optical modulators [2], paving the way for graphene-based optical interconnects.

Although graphene is suitable for light detection and modulation, the lack of a band gap hampers its use in some other areas of optoelectronics, in particular light emission and photovoltaics. In contrast, due to their direct band gaps in the visible and near infrared, TMD monolayers are perfectly suited for such applications. Most traditional optoelectronic devices are based on p-n junctions. In flatland, such junctions may be realized by lateral or vertical arrangement of atomically thin p- and n-type materials (Fig. 2).

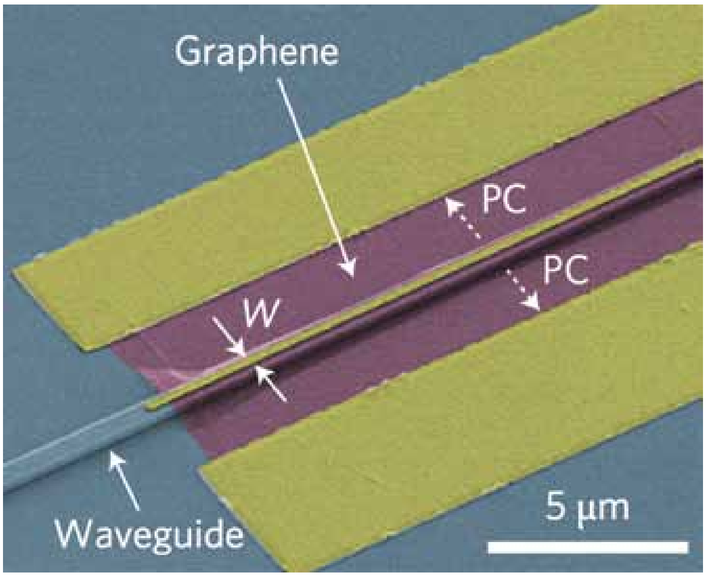

FIG. 1. Silicon chip-integrated graphene photodetector. © Nature Photonics; taken from Ref. [12].

As stable chemical doping is currently difficult to achieve in 2D semiconductors, we used electrostatic doping to form a TMD monolayer p-n junction [5]. In our devices, split-gate electrodes couple to two regions of a mechanically exfoliated WSe_2 flake. By biasing one gate electrode with a positive voltage and the other one with a negative, electrons and holes, respectively, are drawn into the 2D semiconductor and a lateral p-n junction is realized. By driving a forward current through the monolayer diode, electroluminescence emission was obtained. The emission occurs at the same wavelength as the photoluminescence, indicating that the electroluminescence arises from excitonic transitions. The large exciton binding energy in TMDs may thus offer an opportunity for tailoring the emission wavelength by engineering of the dielectric environment. Band gap emission from free carriers was not observed. Electroluminescence efficiencies of up to 0.1 % were obtained, limited mainly by non-radiative recombination in WSe_2 and resistive losses at the contacts.

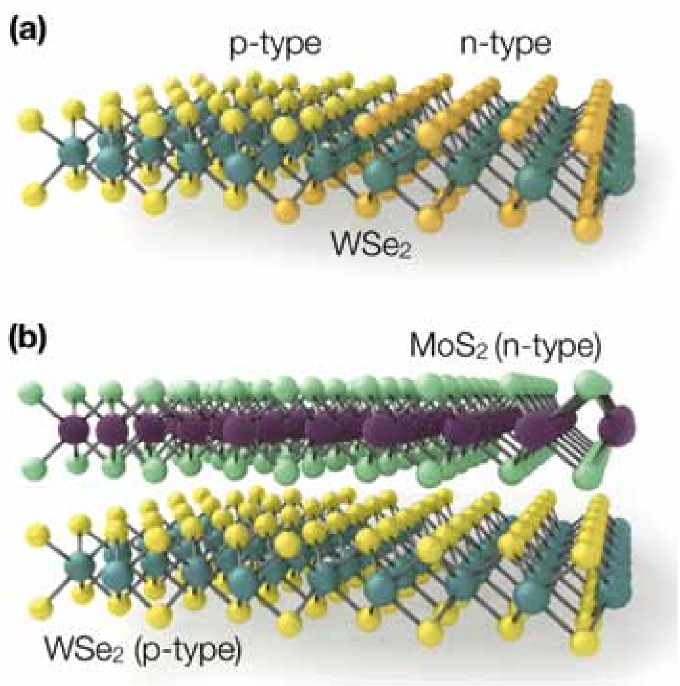

FIG. 2. P-n junctions are formed by joining p-type and n-type semiconductor materials and are at the heart of most optoelectronic devices. Such junctions may be realized by (a) lateral or (b) vertical arrangement of atomically thin p-type and n-type materials.

The lateral arrangement of the junction in above devices does not allow for easy scalability for which a vertical geometry would be desirable. We have thus developed a vertical junction device, in which MoS_2 and WSe_2 monolayers are stacked on top of each other [6]. Owing to the larger electronegativities of Mo and S as compared to W and Se, the electron affinity of MoS_2 is larger than that of WSe_2. As a result, a type-II heterojunction is formed, where the lowest-energy electron states are spatially located in the MoS_2 layer and the highest-energy hole states lie in the WSe_2. Photoluminescence studies confirmed efficient and ultrafast charge transfer between TMDs. The device current as a function of bias voltage displays diode-like rectification behavior.

Under illumination, the heterojunction exhibits a photovoltaic response. Photons are absorbed in WSe_2 and MoS_2, resulting in electron-hole pairs in both layers. Relaxation of the photogenerated carriers then occurs, driven by the type-II band offsets. As the lowest energy electron and hole states are spatially separated, charge transfer occurs across the 2D heterojunction. The relaxed carriers diffuse to the contacts, resulting in a photocurrent. Interlayer recombination occurs during diffusion, which reduces the efficiency of the solar cell. Power conversion efficiency and fill factor were estimated to be 0.2 % and 50 %, respectively. We note that these numbers need to be judged in light of the weak optical absorption of the 2D monolayers. It could be increased by stacking several junctions on top of each other or by plasmonic absorption enhancement.

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