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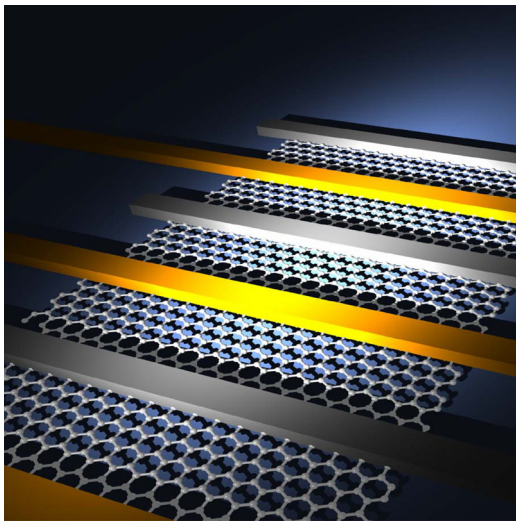

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(Invited Paper)

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Abstract: Graphene, which is a single layer of carbon atoms assembled in a honeycomb lattice, has recently attracted significant attention, primarily due to its extraordinary electronic properties. In fact, its photonic properties are not less exciting. Graphene interacts with light strongly from ultraviolet to far infrared, and such interaction is tunable by electric field. Moreover, although graphene itself is gapless, a direct, tunable bandgap can be created by breaking its intrinsic crystallographic symmetry. These unique properties make graphene a promising candidate for various light detection, manipulation, and generation applications in an ultra-wide operational wavelength range. In this paper, we first discuss a few possible photonic applications based on the exceptional photonic properties of graphene, followed by detailed presentation on graphene photodetectors. Finally, two major future directions on graphene nanophotonic research will be covered.

Index Terms: Graphene, photodetectors, optical modulators, nanophotonics.

In 2004, single-layer graphene was isolated from graphite using mechanical exfoliation, and its carrier transport properties were reported by Geim's research group [1]. Since then, it quickly became one of the hottest research topics in condensed matter physics and semiconductor electronics. Intense interests in graphene mainly arise from the unique band structure of graphene, as shown in Fig. 1(a): Graphene is a semimetal with zero band gap and linear energy dispersion around the K (K') point, i.e., the so-called Dirac point. The behaviors of the carriers in graphene can be described by the relativistic Dirac equation with zero effective mass. On the contrary, carriers in conventional semiconductors are governed by the nonrelativistic Schrödinger's equation with finite effective masses.

The unique band structure of graphene also leads to its striking photonic properties. A single graphene layer absorbs about 2.3% ($\pi\alpha$, where α is the fine structure constant) of the vertical incidence light in a wide wavelength range due to interband transitions [2], when the Fermi-level in graphene is aligned with Dirac point energy, as shown in Fig. 1(b). This makes graphene a promising candidate for photodetectors at least from near-infrared to visible wavelength range. When the Fermi-level is tuned away from Dirac point energy by ΔE_F, the graphene is expected to become close to transparent to photons with energy below $2\Delta E_F$, due to Pauli's exclusive principle, as shown in Fig. 1(b). This tunable absorption property may be utilized to construct light modulators or switches. Finally, there are a few approaches to create a direct and tunable bandgap in otherwise zero gap graphene [3]–[6], which may also lead to useful applications in infrared nanophotonics.

We first performed photocurrent imaging experiment in graphene field-effect transistors (FETs). In this experiment, light from a helium-neon laser was focused on a graphene FET and a scanning mirror was used to scan the light spot across the device. The photoinduced current in external

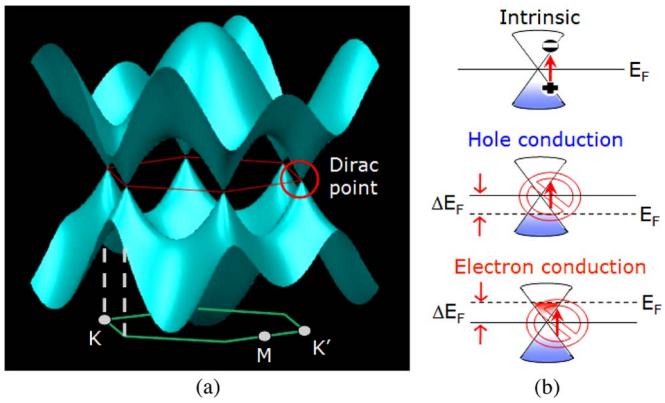

Fig. 1. (a) Band structure of the single layer graphene. (b) The alignment of the Fermi-level and Dirac point energies in intrinsic, p-doped, and n-doped graphenes (from top to bottom).

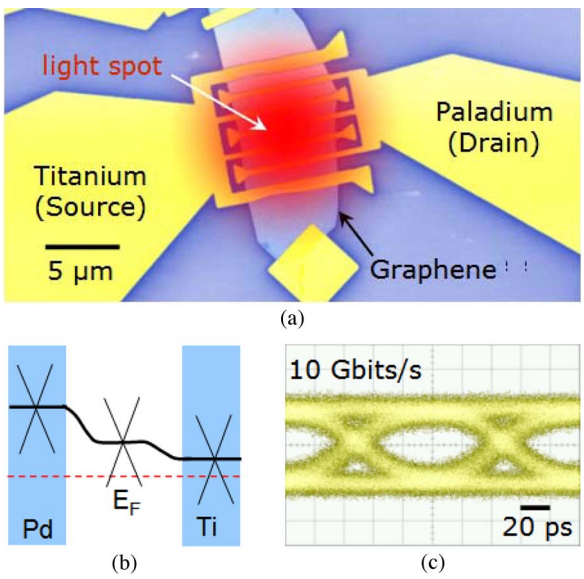

Fig. 2. (a) A scanning electron micrograph of a graphene photodetector with interdigitated metallic finger (in false color). Titanium (Ti) and Palladium (Pd) are used as source and drain electrodes, respectively. (b) The schematic band profile of such the graphene FET with Ti and Pd as source and drain electrodes. Pd introduces heavy p-doping, while the doping introduced by Ti is much lighter. The red dashed line represents the Fermi-level, and the thick solid black line denotes potential profile. (c) The 10-Gbits/s eye-diagram obtained using the graphene photodetector shown in (a) in an optical communication link (adopted from [10]).

circuit was then recorded as a function of the light illumination position. Strong photocurrents are usually observed when the light is focused at the metal–graphene interface, due to the strong built-in electric field at the interface caused by the charge transfer between the metal and graphene. Such a built-in field separates the electron–hole pairs generated by photons and leads to photocurrent [7], [8]. We also measured the high-frequency photoresponse of such graphene FET-based photodetectors and found no significant photoresponse degradation, even at a light intensity modulation frequency of 40 GHz [9]. This is due to the high carrier mobility and large carrier velocity in graphene, leading to a very large operational bandwidth. However, the external photoresponsivity in such photodetectors is much smaller than that of a conventional III–V based high bandwidth photodetector for the following two reasons. First, absorption of vertical incidence light in single- and

few-layer graphene is rather limited. Second, the effective light detection area is much smaller than the light spot size, because the high built-in electric field only exists at the metal–graphene interface.

In 2010, we showed that the external photoresponsivity of such graphene photodetectors can be improved greatly via a structure consisting of multiple interdigitated metallic fingers, as shown in Fig. 2(a) [10]. In this device, a strong internal field exists on all the metal–graphene interfaces, and the total effective light detection area is hence significantly enhanced. However, due to the symmetric nature of the internal field, photocurrents generated at the source and drain electrodes cancel each other out, and the net photocurrent in external circuit will be zero regardless of the gate bias, if source and drain electrodes are made from the same metal [10]. Therefore, we utilized different source (Titanium) and drain (Palladium) metals to resolve this problem. Different doping levels are introduced in graphene under source and drain electrodes, as shown in Fig. 2(b) [10]. By adjusting the back gate bias, the internal E-field at both source and drain electrodes can be aligned to the same direction, leading to greatly enhanced light-detection efficiency. Moreover, by applying a small bias between the source and drain, the detection efficiency can be further improved. A device shown in Fig. 2(a) exhibits a maximum external photoresponsivity of around 6.1 mA/W at 1.55 μm light excitation, which is 15 times more efficient than the graphene photodetector reported in [9]. Such a photodetector was deployed in a 10-Gbits/s optical communication link, and error-free recovery of optical PRBS was realized, as shown by the complete open eye-diagram in Fig. 2(c).

Future research on graphene nanophotonics will most likely focuses on the following two major directions. The first is development of integrated graphene optoelectronic devices for near-infrared optical communication and interconnects applications. High-performance, high-bandwidth photodetectors and optical modulators are within reach through the monolithic integration of large-scale single or few-layer graphene with submicron silicon photonic waveguides [11]. The second direction is the application of graphene in infrared and terahertz regimes [12]. For example, creation of a moderate direct bandgap in biased bilayer graphene may allow for widely tunable, mid-infrared light emission [3]–[5]. Terahertz imaging can also be another promising direction due to the strong absorption of far-infrared and terahertz light in graphene resulting from intraband transitions [13].

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