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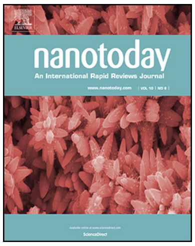

REVIEW

Building graphene p—n junctions for next-generation photodetection

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Summary The exceptional optical and electronic properties of graphene make it a promising material for photodetection, especially applications requiring fast and sensitive response to light across the spectrum ranging from the visible to the infrared down to the terahertz domain. However, the ultrashort lifetime of photocarriers caused by the fast recombination of graphene results in the weak response of light and limits its application in photodetection. To overcome the restriction of limited lifetime of photocarriers in photodetection, it is necessary to introduce graphene p—n junctions to generate photocurrent or photovoltage efficiently, and numerous efforts have been made. In this review, we first give an overview of photodetection and then evaluate physical and chemical methods available for the fabrication of graphene p—n junctions. Subsequently, we provide a detailed discussion on current research advances in enhancing the performance of graphene-based photodetectors, mainly focusing on the coupling of graphene with photonic structures and building vertical heterostructures. We believe that the potential commercialization of graphene p—n junction based photodetectors will be promoted by the development on the scalable production of graphene and its integration with highly developed silicon-based photonic and electronic platforms.

Introduction

Photodetection is the process of converting light signal to electrical signal to detect the presence or intensity of light [1—3]. Various physical principles and techniques have been developed to detect the light, from the UV to the sub-millimeter. The detection of infrared light has attracted much attention, because detections in this region are crucial for spectroscopy, biosensing, and thermal imaging. Nowadays commercial silicon-based photodetector can only operate at wavelength below 1.1 μm, restricted by the intrinsic bandgap of silicon crystal [2]. Other potential contenders, such as Ge and InGaAs, need a complex integration

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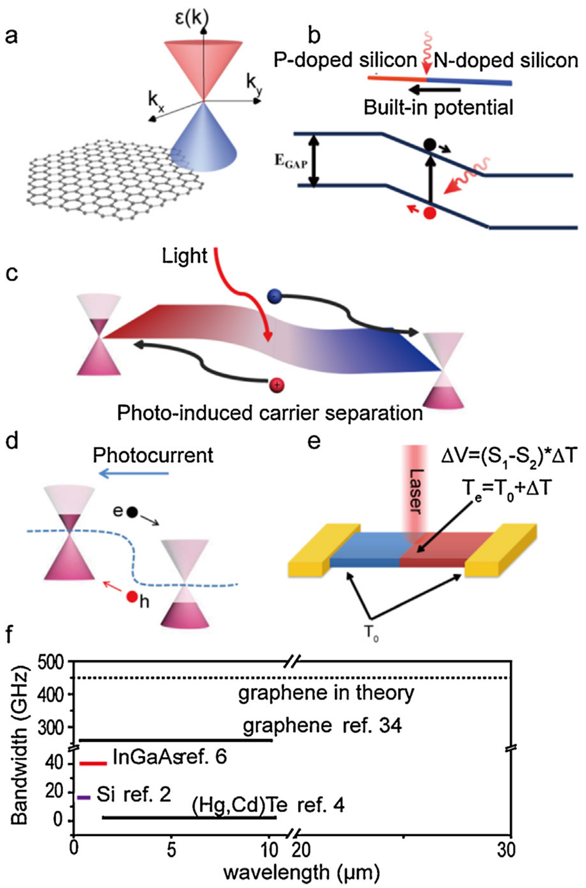

Fig. 1 (a) Hexagonal honeycomb lattice of graphene and its conical band structure in two dimensions. (b) Schematic of photo-induced extraction of e—h pairs and its separation caused by an internal electric field at traditional silicon p—n junction under illumination. E_{GAP} is the band gap of silicon. (c) Schematic of photo-induced extraction of e-h pairs and its separation at graphene p—n junction. (d and e) Schematic representation of two photocurrent generation mechanisms discussed in the main text: photovoltaic (d) and photo-thermoelectric (e). The illuminated area under the laser in (e) elevates the electron temperature with ΔT, the temperature gradient, in comparison with other area with electron temperature T_0. ΔV is photothermoelectric voltage and S_1 and S_2 are the different Seebeck coefficient of the p-doped and n-doped portions of graphene (f) The performance data (operation wavelength and bandwidth) of the common materials used in photodetection.

process or extreme operating conditions [4—7]. Thus, better materials for infrared light detection are highly required and great efforts are devoted to searching better alternatives of silicon-based photodetectors.

Graphene, which is considered as a promising material for the next generation electronics, exhibits great potential in fundamental study and applications in electronics and optoelectronics [8—12], since its first successful synthesis by exfoliation method in 2004 [8,13—16]. As shown in Fig. 1a, graphene is consisting of the sp^2 carbon atoms, which are arranged in a honeycomb lattice and covalently bonded by σ bonds and localized π bonds. Each atom provides a π and a π^* orbital to from the valence band (VB) and the conduction band (CB), respectively. In its first Brillouin zone, the two conical symmetric bands touch each other at six high symmetry points (K and K', named as Dirac points) with linear energy-monument dispersion near Femi level [17], resulting in the semimetal and gapless characteristic of graphene. As described by the relativistic Dirac equation, electrons in graphene behave as massless two-dimensional (2D) particles, leading to an exceptional wavelength-independent absorption of incident light (below 3 eV). In a broad spectrum, graphene shows a constant absorption (2.3%) of incident light, which is advantageous over silicon and other semiconductor materials [9,10,14]. In addition, these massless 2D particles exhibit Fermi velocities up to 10^6 m/s (1/300 that of light), endowing graphene with an ultrahigh carrier mobility (200,000 $cm^2\,V^{-1}\,s^{-1}$) [18,19], which is the key attraction of graphene in the quest for next-generation electronics and photonics [9,20—22]. However, photo-generated carriers in graphene-based photodetector usually undergo a fast recombination, resulting in difficulty in ultrafast photoconversion [23]. Thus, graphene p—n junction is usually introduced to separate photo-generated carriers before their recombination. This separation is realized by built-in potential [24,25] or temperature gradient [26] according to different photoconversion mechanisms. Consequently, to date, great efforts are devoted to building graphene-based p—n junction both by the chemical methods [27—29] and physical methods [30—32].

Recent years have witnessed fast progress of graphene-based photodetection especially concerning broad operation spectrum and fast photo-response [25,33—35]. In the near-infrared and mid-infrared region, photodetection based on graphene p—n junction showed an efficient internal quantum efficiency at wavelength up to 10.6 μm [34]. In terms of response speed, the graphene-based photodetector exhibiting 262 GHz [35] bandwidth was demonstrated, and as predicated, intrinsic bandwidth of graphene would exceed 500 GHz [25,36]. On the other hand, the light absorption of graphene-based photodetector was highly restricted by the intrinsic low absorption of graphene and limited photosensing area of lateral junction [11,14]. Therefore, several strategies were applied to resolve this limitation, focusing on integrating graphene with photonic structures and vertical combination of graphene with other photosensing 2D materials. For example, cavities, silicon waveguides and plasmonic structures were widely introduced to enhance the graphene—light interaction [37—42]. And by vertically stacking graphene with planar materials such as 2D MoS_2, the efficiency of photoconversion was highly improved due to the existence of a new vertical junction and enlargement of photo active area [43,44].

In this review, we would begin with an overview of the photo-conversion process at p—n junction, especially graphene p—n junction, its mechanism and recent progresses. Subsequently, we highlight recent methods to build the graphene p—n junction for photodetection, both chemically and physically. Finally, we discuss the design of materials and novel device geometries aimed at enhancing the sensitivity of graphene-based photodetectors. Due to the limited scope of this review, we are only able to focus on some of major contributions in photodetection based on building graphene p—n junction. Fortunately, there are