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Photovoltaic high-performance broadband photodetector based on MoS_2/Si nanowire array heterojunction

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ABSTRACT

Photovoltaic MoS_2/Si nanowire array (SiNWA) heterojunction photodetectors (PDs) are constructed and investigated, which exhibit excellent photoresponse properties to light illumination at wavelengths from the deep ultraviolet to the near-infrared. Further photoresponse analysis reveals that a high responsivity of 53.5 A/W and a specific detectivity of 2.8×10^{13} Jones, as well as fast response speeds of 2.9/7.3 μs at 50 kHz are achieved in a MoS_2/SiNWA heterojunction device. The high performances could be attributed to the high-quality heterojunction between MoS_2 and the SiNWA. Such high performances of MoS_2/SiNWA PDs are much better than those of previously reported MoS_2-based PDs, suggesting that MoS_2/SiNWA heterojunction devices have great potential in optoelectronic applications.

1. Introduction

The discovery of graphene has inspired great interest in exploring the promising potential of two-dimensional (2D) layered semiconductor nanostructures for their enormous applications in electronic and optoelectronic devices based on their specific geometries and unique physical properties [1–3]. With atomically thin, stacked with van der Waals force and free of surface chemical dangling bonds, 2D layered semiconductor nanostructures provide an open platform for exploring novel physical phenomena and mechanisms [4,5]. However, the widespread applications of the pristine graphene in electronics and optoelectronics were limited by its zero band-gap. Transition metal dichalcogenides (TMDs), especially the those with atomic thickness, have been emerged as a new class of nanomaterials for fundamental studies and promising applications due to their distinct properties [6,7]. Molybdenum disulfide (MoS_2) is one of the most widely studied layered material due to its inherent and layer-dependent band-gaps [8–11]. Crystals of MoS_2 are composed of vertically stacked, weakly interacting layers through van der Waals interactions. When the layers of MoS_2 decreased to monolayer, it will transform to a direct-gap with 1.9 eV from the indirect-gap with 1.2 eV. This unique property grants the great advantages for high-performance devices with high on/off ratio and low power consumption [12–14]. Besides, few-layer MoS_2 can response light signals from ultraviolet (UV) to near infrared (NIR) because of the narrower band-gap, which is beneficial to design a variety of photodetectors (PDs) [15]. All these features revealled that MoS_2 has important potential applications in electronic and optoelectronic devices.

Compared with traditional bulk materials, 2D materials based PDs have several natural advantages, such as wide detection range, free of dangling bonds at the surfaces and strongly interact with incident light [16]. In spite of these advantages, 2D materials based PDs have their drawbacks, such as low absorptivity of incident light, large dark current and small light on/off ratio, and low detectivity. To overcome these drawbacks, diverse device structures and various enhancing methods have been developed. Constructing heterojunction is a promising way to enhanced the device performances, which can improve the separation efficiency of photoexcited electron-hole pairs [17]. Hence, an increasing interest has been attracted by heterojunction devices of 2D materials [18,19]. From previous reports, the photoconductor based PDs usually have high responsivities, with slow response speeds, whereas, the junction-based PDs always hold the advantage in fast response speeds [17]. For example, Kis et al. reported a single-layer MoS_2 photoconductor with a high responsivity of 880 A/W, but slow response speeds of 4/9 s (rise/fall time) [20]. Jie et al. reported a MoS_2/Si heterojunction PD with fast response speeds of 3/40 μs and a low responsivity of 0.3 A/W [21]. And the similar results were also reported by us and Jiang et al. [22,23]. These heterojunction devices are mainly based on planar Si with poor light harvesting capability, which may

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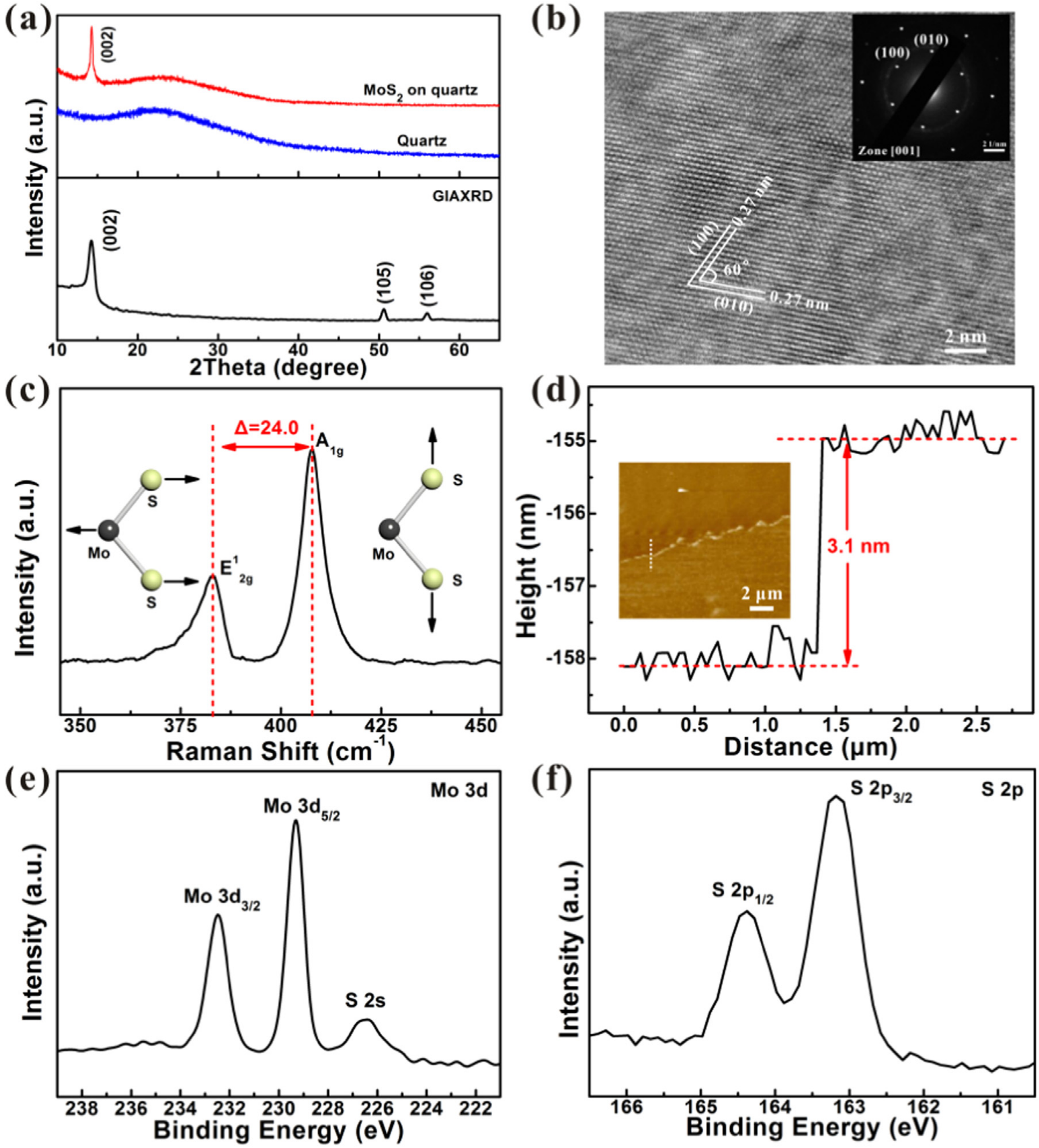

Fig. 1. (a) XRD and GIAXRD patterns of MoS_2 thin film. (b) HRTEM and corresponding SAED pattern of MoS_2 thin film. (c) Raman spectrum, and (d) height profiles of a MoS_2 thin film. The XPS spectra show the binding energies of (e) Mo and (f) S of the MoS_2 thin film.

lead to the low responsivity. Achieving a high responsivity and a fast response speed simultaneously in a single MoS_2-based PD is an urgently desired for practical optoelectronic applications in the future.

Silicon (Si), one of the most important optoelectronic materials in the semiconductor industry, is widely used in commercial PDs, PV devices and semiconductor chips due to their high performance as well as the mature large-scale production and integration technologies [24–26]. Si nanostructures, and in particular, Si nanowire arrays (SiNWA) have received increasing attention in recent years due to their unique properties in terms of enhanced light absorption and excellent electron transport characteristic. In addition, enhanced device performances have been demonstrated in PV devices and PDs by using SiNWAs as light harvesting candidates [27–30]. Inspired by these progresses, it is anticipated that combing MoS_2 with SiNWAs may lead to heterojunction PDs with both high responsivities and fast response speeds.

Herein, the photovoltaic MoS_2/SiNWA heterojunction PD was constructed, and its optoelectronic properties were systematically investigated. This PD has exhibited excellent rectifying characteristics and photoresponse properties with pronounced photovoltaic effect. Therefore, it can serve as a self-powered PD, which can operate at voltage bias of 0 V. The photoresponse properties of the MoS_2/SiNWA heterojunction PD were studied, displaying excellent repeatability and stability with high current on/off ratio, high responsivity, specific detectivity, as well as fast response speeds. The method presented in this work is an efficient way to improve the performances of 2D materials based PDs.