Progress and Perspectives of Photodetectors Based on 2D Materials

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Photodetectors based on two-dimensional (2D) materials and their heterostructures have been attracting immense research interests due to their excellent device performances, such as ultrahigh photoresponsivity, ultrafast and broadband photodetection, polarized sensitivity, flexibility, and Complementary Metal-Oxide-Semiconductor (CMOS) compatibility. Here, we firstly compare the device performance of several photodetectors based on Schottky junctions and p-n junctions, such as photoresponsivity and response time. Then, we provide an overview of the recent progress on 2D material-based photodetectors, emerging strategies to improve device performances by structure optimization and bandgap engineering as well. Finally, we discuss the challenges and perspectives on the exploration of 2D materials and their heterostructures for future application in electronics and optoelectronics.

Thousands of two dimensional (2D) van der Waals (vdWs) materials have been successfully prepared and exhibit diverse and unique properties, including metals, semiconductors, insulators, and superconductors [**1-4**]. Compared with traditional semiconductors, 2D materials have wide band gap distribution (0 ~ 6 eV), ultrahigh carrier mobility, atomically thickness, strong light-matter interaction, and thickness dependent and tunable band structure, which offered their utilization in versatile optoelectronics [**5-7**]. By stacking the 2D materials directly, we can integrate the function of different 2D materials to form complex heterostructures without considering lattice mismatch, making it possible to realize high-performance and multifunctional optoelectronic devices [**8-10**].

Recently, lots of great progress have been made in photodetectors based on 2D materials including broadband photodetection, high sensitivity, and fast photoresponse. For instance, broadband photodetectors based on a new narrow band gap 2D material black arsenic phosphorus (b-AsP) and its vdWs heterojunctions have realized the sensitive mid-wave infrared photodetection, where the detection range is broadened to 8.2 μm with a high photoresponsivity up to 30 mA W^{-1} [**11**]. Also, sensitive terahertz (THz) photodetection and imaging based on ultra-short channel black phosphorus (BP) devices were reported, where the photoresponsitivity of 297 A W^{-1} and response time about 0.8 μs have been achieved [**12**]. Besides, a hybrid graphene-quantum dot photodetector with ultrahigh photoconductive gain of $\sim 10^8$ was demonstrated, whose photoresponsivity exceeds 10^7 A W^{-1} [**13**]. In terms of fast response, a waveguide-integrated photodetector was fabricated by integrating transition metal dichalcogenides (TMDCs)/graphene heterojunction into a silicon-based optical waveguide, whose bandwidth can be up to 50 GHz [**14**]. And the theoretical bandwidth of graphene photodetector can reach 500 GHz due to the ultra-high carrier mobility [**15**]. However, there is still issue to obtain ultrafast response speed and ultrahigh responsivity, even broadband photodetection simultaneously. In addition, the high-power consumption remains unsolved. The photodetectors with high-performance, high stability, multifunctional and low power consumption need to be further studied.

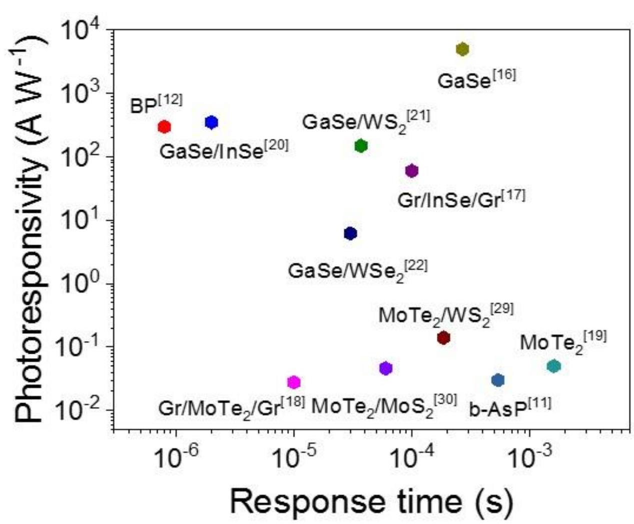

Fig. 1. The relationship between photoresponsivity and response time of photodetectors based on 2D materials as well as their heterostructures.

We firstly summarized the performance of the devices investigated recently, the corresponding photoresponsivity and response time are shown in **Fig. 1**. To understand the physical mechanism of the photodetectors, the photoresponsivity of the metal-semiconductor-metal (MSM) structure photodetectors based on layered GaSe with different electrode spacing distances were systematically investigated [**16**]. We find that the photoresponsivity of the device increases monotonously with the shrinking the spacing distance before the direct tunneling happens, and the maximum value can reach 5 000 A W^{-1}. But the response speed of the device is not high because of the back-to-back Schottky barriers [**17**]. So, we construct a vertical structure photodetector based on multi-layer $MoTe_2$ sandwiched by asymmetric graphene contacts. Adopting this structure can efficiently reduce the channel length, increase built-in electric field and break the mirror symmetry of Schottky barrier at the interface. The built-in electric field density reach to about 100 kV cm^{-1}. As a result, the response time of the device is reduced to about 10 μs compared to the 1.6 ms of the multi-layer $MoTe_2$ device and the device can also work by self-driving [**18,19**]. To further shorten the response time and widen the photoresponse spectrum, we prepared the vertical vdWs p-GaSe/n-InSe and p-GaSe/n-WS_2 heterojunctions with type II band alignment [**20,21**]. The p-n heterojunction can effectively enhance the built-in electric field in the overlapping area. And the built-in electric field can enhance the separation efficiency of photo-generated carriers, improve the transport speed of the carriers, and thus increase the photoresponsivity and reduce the response time. Interestingly, the devices exhibit a broad photoresponse from ultraviolet (UV) and visible to near-infrared (NIR) light and the response time is reduced to 2 μs. The photodetectors based on p-n heterojunctions can work at self-driven mode due the existing of the built-in electric field, which will allow the device to work without any applied voltage and thus for the development of low consumption applications. In addition, a tunable rectification inversion behavior was obtained in p-GaSe/n-WSe_2 heterojunctions by tuning the fermi-level of the bottom WSe_2 [**22**]. This finding has a great potential for gate tunable electric and optoelectronic applications. We also reported a polarized photodetector based on BP/ReS_2 heterojunctions [**23**]. The device shows a broadband polarized photodetection with high stability from visible to NIR. These findings proved that structure optimization and bandgap engineering are effective methods to realize high photoresponsivity, fast response time and broadband photodetection.

The presented works highlight the performance improvement of photodetectors based on 2D materials, but new opportunities and challenges are still remained. Firstly, most of the high-quality 2D single-layer materials are fabricated by mechanical exfoliated method, and the production efficiency is very low; the growth process of wafer-scale and high-quality 2D single-layer materials, especially for heterojunctions are still not resolved. In addition, many 2D materials are not stable enough; for example, black phosphorus will degrade quickly when exposed to air, which will greatly affect the reliability and stability of devices. Secondly, it is difficult to accurately control the band alignment of the 2D material heterojunction due to the defects, interface states, high contact resistance and fermi level pinning introduced in the manufacturing process; the controllability and repeatability of the device are not ideal. Finally, although photodetectors, light-emitters and optoelectronic memories have been demonstrated, most of the devices show single functionality. Thus, the multifunctional photodetectors integrating multiple functions into one device are still need to be explored [**24-26**]. In order to achieve high-performance and multifunctional devices for future comprehensive applications, herein, we try to propose two potential directions for further development of 2D materials-based photodetectors. Firstly, the fast, ultrabroadband photodetection from UV to THz can be achieved by combining the advantage of graphene sandwiched devices. In addition, benefit to the built-in potential of heterojunction, the low power consumption can be achieved by self-driven. Secondly, the fabrication techniques of 2D materials-based photodetectors are compatible with mature complementary metal-oxide-semiconductor (CMOS) technologies. Thus, the monolithic integration of 2D materials and heterostructures with CMOS integrated circuit can be achieved, which act as broadband image sensors (**Fig. 2**). The band alignment of the heterojunction device is the key to realize multifunctional photodetectors; for example, NIR to visible light upconversion can be achieved in a metal-insulator-semiconductor heterostructure tunneling diode by band engineering [**27**]. Moreover, integration of the photodetector and the light-emitter may be realized by using electro-optic modulators [**28**]. The further development of high-performance and multifunctional photodetectors will greatly promote future applications of 2D materials in the field of next-generation microelectronics and low power integrated optoelectronics.

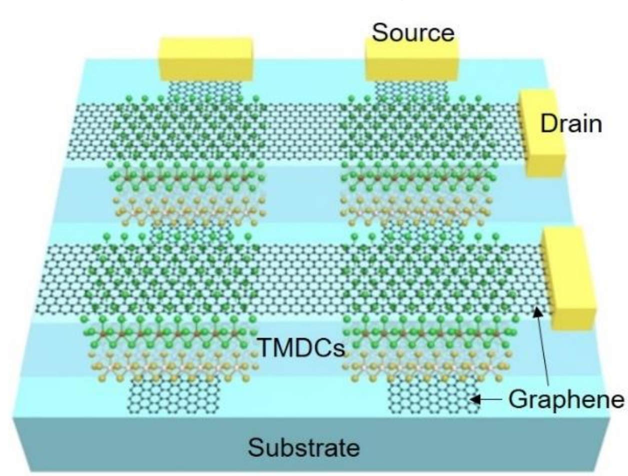

Fig. 2. The integration of 2D materials and heterostructures with CMOS integrated circuit, which act as broadband image sensors.

Keywords

Photodetector, 2D materials, heterostructures, schottky, p-n junctions.

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