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All group IV photodetector (graphene/oxide/GeSn film)

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## Final Report

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### **Abstract:**

Photodetectors are key devices in optoelectronic systems used in our daily life. Recently, hybrid PDs made using graphene on semiconductor outperformed their graphene and semiconductor PD counterparts, making them a potential candidate for high-performance optoelectronic systems. In this project, two new findings are demonstrated with characteristics of both amplified and attenuated photocurrent (which measures the characteristic of responsivity). This is achieved by operating the PD with back-gated bias using a newly designed structure. These results provide a direct impact to the all group IV photonic as well as paving the way to the monolithic integration of optic and electronic devices in a single chip.

Hybrid photodetectors (PDs) possess several characteristics that enable them to outperform their graphene and semiconductor PD counterparts. For instance, hybrid PDs exhibit a responsivity level as high as  $10^7$  A/W, which is seven orders of magnitude larger than that of commercial Si PDs (peak responsivity of 1 A/W), the mechanism of which is associated with the photogating effect. Research on the potential usage of hybrid PDs in high performance optoelectronic systems is being actively pursued. Herein, we report two new findings based on a novel design that significantly broadens both our understanding of the mechanism of photoresponse and device performance.

The proposed design comprises graphene and Si layers sandwiching a thin oxide, shown schematically in Fig 1(a). Here, an oxide thickness at MOS device level is fabricated and TEM characterization on the thin oxide layer is depicted in Fig 1(b). The device is operated with a back-gated bias and the working principle is briefly described here. It can be understood through the energy profile of the heterostructure depicted in Fig 1(c). Under illumination, most light transmission occurs through graphene and SiO<sub>2</sub> reaching the Si wafer, generating

an electron-hole pair. These carriers are spatially redistributed owing to a build-in electric field where electrons move toward the Si bulk while holes move in opposite direction toward SiO<sub>2</sub>/Si interface trapped at the low energy potential. Under the other operation conditions, positive bias ( $V_{BG}$ ) is applied at the back of the device, which drives electrons toward the Si bulk, leaving positive ions accumulated at SiO<sub>2</sub>/Si interface. For both operation types, positive charges are presented at the interface. This functions as an electrical gate to the graphene channel that induces electron generation in the channel, altering both electrical properties and the photoresponse of the channel. The charge distribution at the interface is illustrated schematically in Fig 1(c).

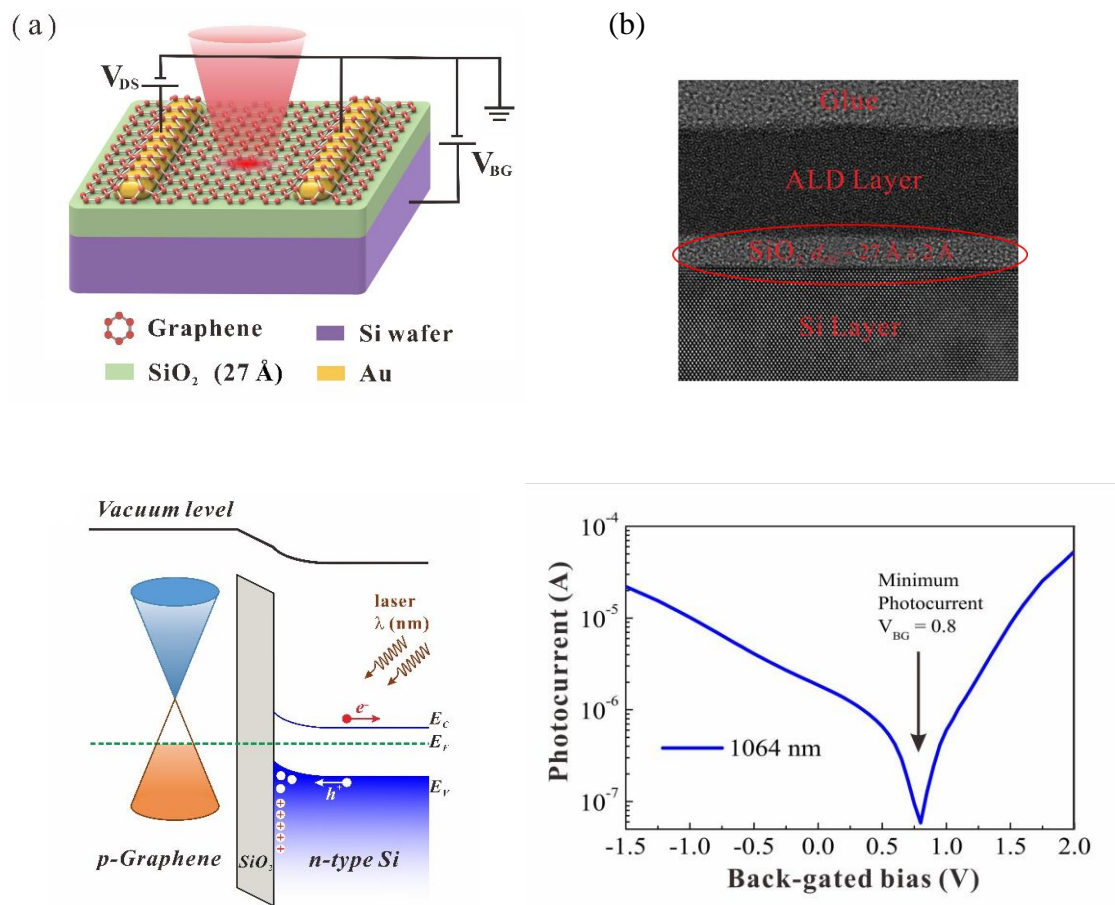


Figure 1. (a) Schematic of the device layer structure and electrical measurement set-up for the I-V measurement. (b) TEM image of the thin oxide layer,  $d_{OX} = 27 \text{ \AA} \pm 2 \text{ \AA}$ . (c) Schematic energy band profile of p-type graphene/SiO<sub>2</sub>/n-Si, photoexcited carrier transport under illumination, and positive ion locations under positive back-gated bias. Solid (dashed) arrow line represents the direction of motion of a photoexcited electron (hole). These electrons (holes) are represented by ● (○) symbol. Back-gated bias induces positive ions, which are represented by ⊕. (d) Photocurrent

plots as a function of gate bias

Two findings of p-type electrical characteristic and photocurrent tunability in the graphene channel are demonstrated. The two new results are briefly described below. Contrary to the conventional thinking, which considers graphene as neutral (without free carriers), similar to its free standing film, our results show that the graphene layer is not electrically neutral but exhibits a p-type characteristic after fabrication. This 'intrinsic carrier' introduces a key photocurrent factor that has not yet been discussed in any related research in this or other journals. Moreover, it dominates the photoresponse instead of the current induced by the conventional photogating effect. This factor provides a possible explanation for the wide range of responsivity reported in the literature (from A/W to  $\sim 10^7$  A/W), as the devices were fabricated via different processes with different doping concentrations in the graphene channel (see the manuscript for details). A quantitative model for both types of photocurrent is newly developed on the basis of a simple model that has been used for the MOS device and is required for practical usage.

The second finding is regarding the performance, namely, the photocurrent tunability when operating under a low back-gated bias (up to 2 V, in contrast to previous studies, which used 20 V). Both amplification and attenuation on photocurrent is found shown in Fig 1(d). In addition to amplification of the photocurrent, which has been the focus of existing research, a reduction of the photocurrent that has not previously been discussed is presented. This gate amplification on the photocurrent is larger than the current generated by the photogating effect, reflecting the effectiveness of the operation. The ability to reduce the photocurrent provides a functionality regarding the integration with a read-out circuit in optoelectronic systems. It allows the adjustment of the detector output so that the saturation effect in a read-out circuit under intense illumination can be effectively avoided. The photocurrent tuning mechanism is proposed to quantify the gate-dependent currents based on the model proposed in this study.