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Breaking the responsivity-speed dilemma of a-GaO_x photodetector by alternating gate modulation

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The gallium oxide (Ga_2O_3) based photodetectors are usually confronted with the typical challenge of the responsivity-speed (RS) dilemma, namely high photocurrent induces a long decay time, as shown in Figure 1(a). The RS dilemma involves a trade-off issue, which is independent of photoelectric materials. Great efforts have been made to alleviate the RS dilemma in Ga_2O_3 solar-blind photodetector (SBPD) [1, 2]. However, the previous studies unilaterally improved the responsivity or response speed to alleviate or balance their dilemma, leaving a great challenge in the optoelectronics field to break the RS dilemma and improve both merits simultaneously.

In this study, a dynamic alternating gate modulation (AGM) scheme was proposed to break the RS dilemma by mode switching based on the low-cost amorphous gallium oxide (a-GaO_x) field-effect transistor (FET) photodetector. The AGM scheme injects alternating carriers to modulate the enhancement/depletion mode of the a-GaO_x FET SBPD within each detection cycle. As a result, the accumulation mode by a positive gate bias enhances the responsivity of the a-GaO_x FET SBPD, while the depletion mode under a negative gate bias eliminates the photocurrent and facilitates the decay speed. Both the enhanced responsivity and accelerated decay speed can be synchronously achieved in each detection cycle by the AGM scheme, thus breaking the typical RS dilemma in Ga_2O_3 based photodetector. In addition, this AGM strategy can be easily extended to photodetectors of other wavebands, which suffer from the typical RS dilemma. Most importantly, this general AGM scheme can promote both the contrast and frame rate of a dynamic imaging simulation.

Device fabrication and characterization. An a-GaO_x based three-terminal FET photodetector was fabricated with an intrinsic ultraviolet response, as shown in Figure 1(b). The photoresponse output curves were measured with several V_{gs} values ranging from −10 to 10 V under 242 μW/cm^2 UV illumination (see Supporting information Figure A1). The quantitative assessments of several key figure-of-merits of the phototransistor influenced by V_{gs} are extracted (see Supporting information Figure A2), including photocurrent (I_{photo}), photo-to-dark current ratio (PDCR), responsivity (R), and detectivity (D^*) [3, 4].

Based on the time-dependent I_{ds}-t curves of the a-GaO_x device under illumination with different V_{ds}, the persistent photoconductivity (PPC) effect becomes much more obvious under higher photocurrent (see Supporting information Figure A3). Similarly, with the increment of V_{gs} (−10 to 10 V) towards positive, the I_{ds}-t curves exhibit improved photocurrent (or R) along with a longer decay time (see Supporting information Figure A4). Motivated by the phenomenon that positive V_{gs} advances the photocurrent and R, while negative V_{gs} suppresses the photocurrent and promotes the decay speed, a dynamic AGM scheme was proposed to combine their advantages of $\pm V_{gs}$ control, thus optimizing the R and speed simultaneously.

Operation details of AGM scheme. It can be realized that if the V_{gs} could switch according to the requirement of detection, both the R and speed advantages may be combined. The positive pulse should be as persistent as possible to receive a long-lasting high responsivity, while the negative pulse should be cut-off when the current decreases to the initial value, as shown in Figure 1(c). The detection process under the AGM scheme with a V_{gs} of 5 V can be well divided into three stages, as shown in the inset. Namely, in stage 1 with base V_{gs} of 0 V in the dark, the device holds for the external signal; in stage 2 with $V_{gs} > 0$ V under illumination, the device boosts the responsivity for detection; and in stage 3 with $V_{gs} < 0$ V after illumination, the device recovers to the initial state. The time-dependent curve under the AGM scheme indicates a well-modulated current variation profile. Adjusted by the AGM scheme, the responsivity and speed of the device have been improved simultaneously in each detection cycle, compared to the situations of stationary V_{gs}, in which only one of the merits can be optimized. The recurrent response curves triggered by periodic light pulses with an on/off (5/5 s) switching provide evidence that the AGM scheme possesses great repeatability and stability (see Supporting information Figure A5).

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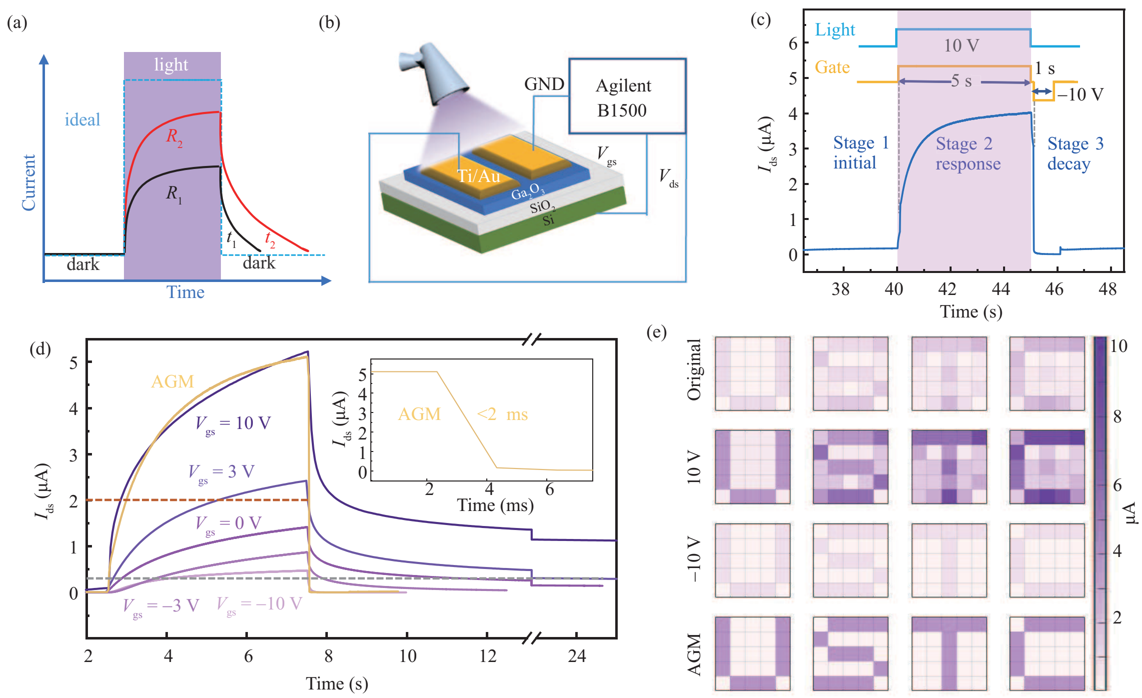

Figure 1 (Color online) AGM scheme to break the RS dilemma. (a) Schematic diagram of the ideal response and RS dilemma in photodetectors. (b) Structure diagram of the a-GaO$_x$ FET SBPD and the measurement platform. (c) Time-dependent photoresponse curve of the AGM scheme under different stages. The inset shows the detailed gate switching sequences. (d) Performance comparison of various gate parameters and the AGM scheme. The inset shows the enlarged decay edge of the AGM scheme. (e) Comparison of the AGM scheme and stationary V_{gs} conditions on dynamic UV imaging simulation.

To further verify the universality of the method, the AGM has also been demonstrated to be effective to break the RS dilemma on the 2D WSe_2 film photodetector, which is capable of wide-spectrum photodetection [5] (see Supporting information Figure A6).

Performance and application demo. For a comprehensive comparison of the modulation results, we revealed the time-dependent photoresponse curves under various operating schemes and ensured a long enough decay process, as shown in Figure 1(d). Except for the AGM scheme, the other operating conditions are all carried out with a stationary V_{gs} (−10, −3, 0, 3, 10) V. 2 μA was set as the response threshold (labeled as the brown dashed line) of the photodetector, and 0.3 μA was set as the recovery threshold (dashed line in grey), respectively. Obviously, V_{gs} at 0/−3/−10 V suppresses the photocurrent below the response threshold. Thus, only under the situation of V_{gs} = 3 V, V_{gs} = 10 V, and the AGM schemes, the response threshold could be reached. When the illumination is removed, different control schemes present distinctive speeds. Among them, the AGM scheme performs the quickest reaction by reaching the decay threshold in 2 ms, as shown in the enlargement of the decay process (inset), which is two thousand times smaller than the decay time (4.32 s) of V_{gs} = 0 V scheme. The R values of V_{gs} = 0 V and AGM scheme are calculated to be 586.8 and 2115.1 A/W, respectively.

Optimizations of dynamic imaging (UV light) by various schemes (AGM and V_{gs} = −10, 0, 10 V) are mimicked by a 5×5 a-GaO$_x$ phototransistor array, as shown in Figure 1(e). The images (5×5 pixels) with letters "U", "S", "T", and "C" are projected onto the array in sequence per 5 s. AGM scheme enables the highest contrast and frame rate owing to the simultaneously enhanced R and decay speed.

This AGM scheme breaks the RS dilemma in photodetectors by the alternating carrier injection. It provides chances for PDs fabricated by low-cost processes or low-quality materials to advance towards high-performance devices, which are more favorable in terms of practicality and commercialization prospect.

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Supporting information Appendixes A and B. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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