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Broadband light-active optoelectronic FeFET memory for in-sensor non-volatile logic

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Machine vision has become crucial in the modern intelligence era, especially in rapidly developing applications such as autonomous vehicles and robotic visual sensors [1]. With the ever-increasing requirements of visual recognition, tremendous amounts of data are captured by sensors and must be processed and stored [2]. However, sensing, processing, and storage units are physically separated in the design of typical devices, resulting in high latency and power consumption because of massive and frequent data shuttling [3]. The recently emerging in-sensor computing strategy shows excellent promise for overcoming these issues. The aim of this approach is to allow efficient sensory data processing and eliminate data transfer and conversion at the sensor/processor interface [4].

In this study, a broadband photosensor based on ferroelectric field-effect transistors (FeFETs) for in-sensor memory and signal processing is described. Lightly doped p-type silicon (P^-Si) is applied as the gate electrode in the FeFETs and as the photosensitive region, resulting in optoelectronic and ferroelectric cooperative modulation in the FeFETs and thus photoelectric sensing and memory functions. The electrical properties of the developed device, including the memory window and endurance/retention characteristics, are also evaluated. Moreover, the nonvolatile optoelectronic properties of the device make possible optoelectronic hybrid logic operations, enabling in-sensor computing and memory.

Figure 1(a) shows a schematic diagram of the developed device. An FeFET with a multilayer MoS_2 channel was placed on top of a silicon-on-insulator (SOI). Lightly doped (10^{15} cm^{-3}) P-Si was applied as the bottom gate, resulting in a P^-G-FeFET. A high-quality ferroelectric thin film of poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) was spin-coated on the SOI substrate to form a ferroelectric dielectric layer. Two multilayer graphene strips were used as the source and drain electrodes to ensure ohmic contact. Flakes of graphene and MoS_2 were produced by mechanical exfoliation and sequentially transferred onto the ferroelectric dielectric layer via dry transfer. An optical image of the MoS_2/P(VDF-TrFE)/P^-Si-based P^-G-FeFET device is shown in Figure 1(b), where different components are marked by dashed lines.

Figure 1(c) shows a P-V hysteresis loop for a ferroelectric capacitor with a P^-Si electrode. Full polarization switching was achieved only in the presence of light. As shown in Figure 1(d), the transfer curves of the P^-G-FeFET do not indicate a change in the resistance state at zero gate voltage (V_g) in the dark. That is, the ferroelectric polarization was not fully switched. The temporary current surge at a positive gate voltage originated from the voltage-induced doping effect. The transfer curves obtained after light irradiation show typical ferroelectric switching-induced hysteresis. A nonvolatile conduction state transition with a high on-off current ratio exceeding four orders of magnitude was observed.

To elucidate the mechanism underlying the operation of the developed device, an energy band diagram of the MoS_2/P(VDF-TrFE)/P^-Si heterostructure is presented in Figure 1(e). The initial state of ferroelectric polarization points towards the P^-Si. In the dark, when a gate voltage of 16 V was applied to the P^-Si, a partial voltage drop occurred across the depletion layer capacitor ($C_{\rm Dep}$). The electric field across the ferroelectric capacitor ($C_{\rm Fe}$) was not sufficient to change the polarization. The remanent polarization depleted the electrons in the MoS_2, and thus MoS_2 remained insulating. Upon irradiation with light, the photogenerated carriers greatly increased the conductance of the Si. A full applied voltage was applied to the ferroelectric material, causing the ferroelectric polarization to switch toward MoS_2. Because of the nonvolatile ferroelectric polarization, the MoS_2 channel accumulated electrons and maintained a low resistance, even when the applied voltage was removed.

To study the photoresponse of the developed device, the transfer curve was plotted as a function of the light power, as shown in Figure 1(f). A large ferroelectric memory window was observed at an irradiation power of only 20 nW.

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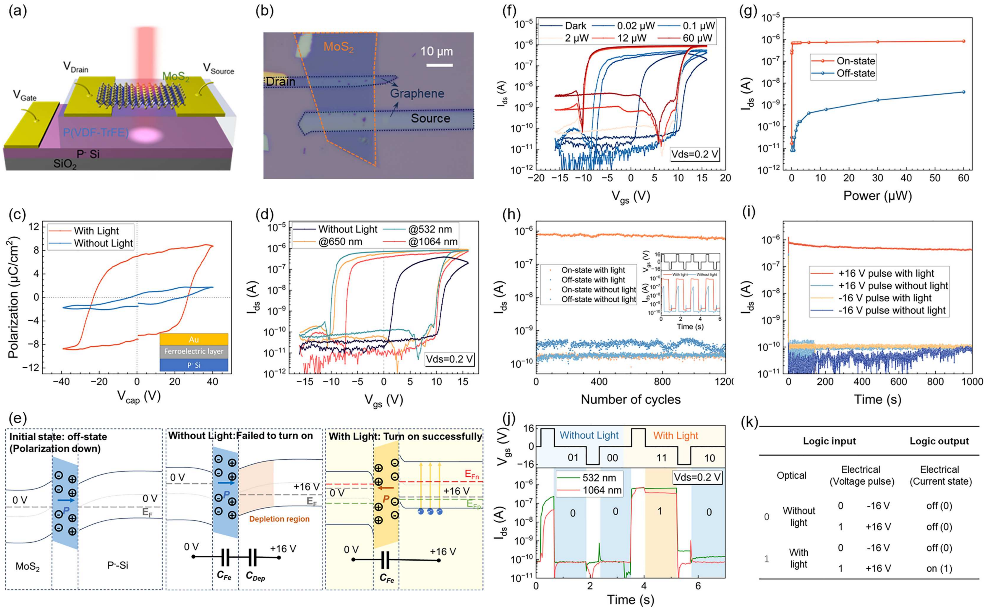

Figure 1 (Color online) (a) Schematic configuration of a P$^-$G-FeFET with a MoS_2 channel. (b) Optical image of the P$^-$G-FeFET. Dashed lines indicate different 2D flakes. (c) Ferroelectric hysteresis loop of an Au/P(VDF-TrFE)/P$^-$Si capacitor. (d) Transfer curves of the MoS_2 P$^-$G-FeFET at three light wavelengths. (e) Mechanism of the device operation. Energy band diagrams of MoS_2/P(VDF-TrFE)/P$^-$Si. (f) Transfer curves of the P$^-$G-FeFET upon irradiation with 532 nm light at different powers. (g) The I_{ds} corresponding to the different optical powers in the on and off states. (h) Endurance properties of the device. The inset shows the cyclic operation during the endurance test. (i) Distinct current levels as a function of time in four states. (j) Optoelectronic nonvolatile logic gates. Realization of AND logic functions with a designed voltage pulse and light scheme. (k) Truth table for optoelectronic hybrid logic.

The on-state current under light irradiation was 10^4 times greater than that in the dark, demonstrating the excellent photosensitivity of this device. The on/off state current was defined as the channel current (I_{ds}) after reducing the positive/negative V_g to 0. As shown in Figure 1(g), when the optical power increased, the on-state current was closely related to the light-controlled ferroelectric switching and saturated quickly.

In addition to its excellent photosensitivity, the P$^-$G-FET device exhibited robust endurance and retention properties. As shown in Figure 1(h), the device was repeatedly switched between on and off states by applying alternating 16 and −16 V voltage pulses with a pulse width of 250 ms. No considerable changes were observed during the endurance tests, confirming the stability of the performance of this device. Furthermore, the retention tests showed an almost negligible loss within 1000 s (Figure 1(i)), indicating a superior nonvolatile memory capability. The data presented in Figures 1(f)–(i) were all obtained upon irradiation with 532 nm light.

Finally, the optoelectronic hybrid logic operation of the developed device was investigated by executing Boolean logic functions in terms of the obtained optical signals, enabling in-sensor digital computing. The light and gate voltage pulses were defined as the logic inputs, and the channel current was regarded as the logic output. As shown in Figure 1(j), a high-channel-current state (output “1”) occurred only when there was a positive voltage pulse in the presence of light (input “1, 1”). An optoelectronic hybrid “AND” logic gate was implemented. This logic output state was stable over time, indicating nonvolatile logic. This characteristic enabled the logic-in-memory computation of the recorded sensory data. The truth table of the proposed optoelectronic hybrid logic is presented in Figure 1(k), demonstrating the capability of this device for in-sensor nonvolatile logic.

Conclusion. A MoS_2 channel FeFET with a P$^-$Si gate was developed for use as a photosensor with a memory function. A current ratio of 10^4 was achieved at an irradiation power of 20 nW. The reliability of the device was evaluated by means of endurance tests, and a retention time of more than 1000 s was observed. Furthermore, in-sensor digital computing was verified by applying an optoelectronic hybrid logic AND gate. This novel optical sensing principle enables the development of new approaches for optoelectronic hybrid integration.

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