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n-type GaSe thin flake for optoelectronic devices

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Summary. — Herein, we present the results obtained with a field effect transistor fabricated using a thin gallium selenide (GaSe) flake as the channel. The fabricated device exhibits n-type conduction behaviour and shows a photo response under illumination by a laser. Notably, the device exhibits memory behaviour maintaining stability for more than 4 hours with repeatable cycles and sensitivity to light stimuli. This confirms its potential as a non-volatile optoelectronic memory, offering an enhanced programming window under laser illumination. The results provide a fundamental understanding of n-type conduction of GaSe thin flake and demonstrate that the investigated material could be suitable for future optoelectronic devices.

1. – Introduction

In recent years, there has been growing scientific interest in transition monochalcogenide (TMCs) low-dimensional materials, driven by their potential for exhibiting exotic transport phenomena and their promising applications across various technological fields [1-8]. Unlike the transition metal dichalcogenides, TMCs have a direct bandgap in the bulk form, and show indirect bandgap in the monolayer form [9]. Their remarkable properties such as layer dependent bandgaps, efficient light absorption, flexibility, and exceptional electrical tunability make them highly promising candidates for future technological applications.

Additionally, the weak van der Waals forces between their layers enable easy mechanical exfoliation into ultrathin sheets. Several studies on electrical memory devices provide useful insights into the current modulation due to the charge trapping/de-trapping density [10,11]. Additionally, combining optical signals with the field effect transistor makes

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it useful for various applications such as photodetectors, optical sensors, and optoelectronic integrated circuits. The functional analysis of the device depends on variable factors, and one of them is pulse width which ensures accurate measurements and fundamental understanding of the device's behavior [12].

Herein, we have evaluated the optoelectronic behavior of the mechanically exfoliated Gallium selenide (GaSe) thin flake. The mechanically exfoliated GaSe shows promising photoconductivity upon incident laser at different powers. We combine optical and electrical features to enable optoelectronic memory with different sweeping delay times. The demonstration that an optical signal enhances the memory window of the GaSe thin flake is a step towards the exploitation of optoelectronic memory, as well as a fundamental understanding of the different pulse width times during device functioning.

2. – Experimental details

A GaSe thin flake of about 100 nm thickness was mechanically exfoliated from GaSe single crystal and transferred onto the 300 nm SiO_2/Si substrate, followed by the lithography process to fabricate the Ni/Au metal. More details on the back-gate FET fabrication can be found in our previous work [13]. Electrical characterizations were conducted using a cryogenic probe station equipped with pressure regulation down to 10^{-5} mbar and integrated with four metallic nanoprobes interfaced with a Keithley 4200 semiconductor parameter analyzer (Tektronix Inc.). The photoresponse of the system was analyzed under illumination from a supercontinuum white laser source (SuperK COMPACT by NKT Photonics), with a maximum output power of 110 mW.

3. – Results and discussion

The output characteristics (drain current *versus* bias voltage, I_d-V_{ds}) are presented in fig. 1(a), measured at ambient conditions and for different gate voltages (V_{gs}) in the range of (-30 V to $+30$ V). The output characteristics show non-ohmic behavior with an asymmetry in the current, pointing to Schottky barrier contacts [14]. The decreasing current for negative V_{gs} is typical of an n-type device. Figure 1(b) validates the modulation of current by the gate voltage at positive and negative bias applied between source and drain, V_{ds}. The reason for n-type conduction is due to the larger valence band offset compared to the conduction band offset at the interface of GaSe and Ni [13]. Figure 1(c) shows the current-voltage characteristics between source and drain under the influence of different laser power with an increase in the drain current. Figure 1(d) shows the photocurrent (I_{ph}) at the positive and negative applied bias as a function of the laser power, demonstrating that the growing light stimulus enhances the photocurrent, particularly at positive V_{ds}. Figure 2 illustrates the device's memory performance during a series of $V_{gs} \pm 50$ V pulses, with the drain current (I_d) recorded over time under ambient conditions and a fixed ($V_{ds} = 200$ mV). The device demonstrated stable memory performance for over four hours, with two distinct current levels controlled by gate pulses signifying a non-volatile characteristic, comparable to other 2D material-based memories with charge-trapping layers [15, 16]. When the gate pulse is in a high positive (negative) state, the channel current increases (decreases) sharply as charges are trapped in or released from the trap states. Subsequently, two distinct states with different current levels can be observed at ($V_{gs} = 0$ V), representing the ON and OFF states of the memory device, respectively. Further, to understand the role of trap states, we explored

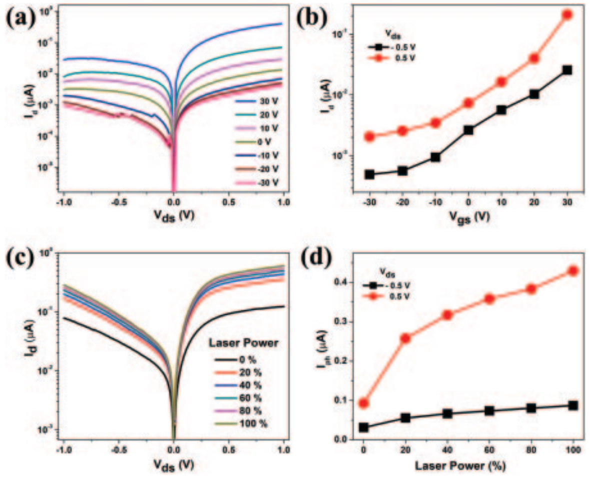

Fig. 1. – (a) I_d-V_ds output characteristics, (b) I_d *vs.* V_gs at different V_ds, (c) I_d-V_ds output characteristics under illumination, and (d) I_ph *vs.* laser (percentage) power.

the device performance with different pulse width during the memory behavior combined with the laser illumination.

Figure 3(a)–(c) shows the single program-rase cycle with maximum laser power at the pulse width of 50 s, 70 s and 90 s, respectively. The key findings of this work, which represent a significant contribution, were anticipated, as laser light illumination leads to the generation of electron-hole pairs and the excitation of trapped charges. These processes enhance the carrier concentration in the GaSe channel, altering the local charge distribution and reducing the Schottky barrier height, resulting in an exponential increase in current. Additionally, charges released from the trap states contribute to the observed increase in photocurrent. Further, it was observed that the increased pulse width does not significantly affect the memory window, *i.e.*, the difference in the drain current, both in dark and under laser illumination, as shown in fig. 3(d). Interfacial traps have been reported to have less contribution due to fast time constants [13]. Thus, we ascribe the slow trap states to the GaSe and SiO_2 trap states. Particularly, slow border traps in SiO_2 have been attributed to trivalent silicon dangling bonds or hydrogenic defects.

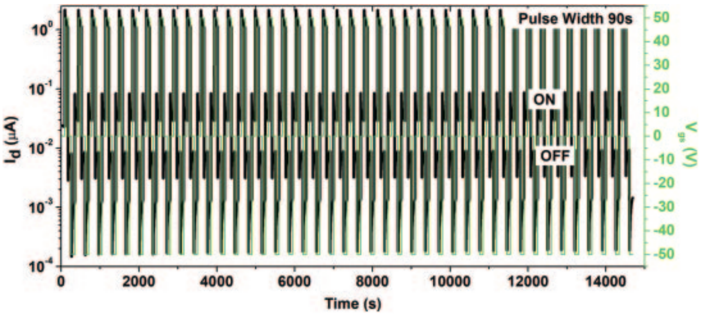

Fig. 2. – Channel current (black line) recorded under gate pulses (green line) at ± 50 V showing repeated cycles at pulse width of 90 s.

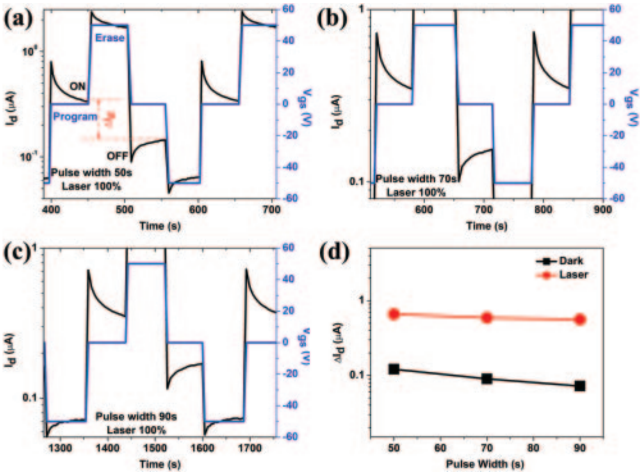

Fig. 3. – Single program-read–erase-read cycle with maximum laser power at (a) pulse width of 50 s, (b) pulse width of 70 s, (c) pulse width of 90 s, and (d) memory window *vs.* pulse width in dark and maximum laser power.

4. – Conclusion

We demonstrated a field-effect transistor using a mechanically exfoliated GaSe flake, which exhibited n-type conduction behavior. The GaSe flake displayed significant photoconductive properties that varied with laser power intensity. Additionally, the fabricated device showed non-volatile memory behavior, maintaining stability for over four hours with repeatable cycles and sensitivity to light stimuli with an enhanced memory window. Notably, the memory window is not significantly affected by the pulse width time period, both in dark and under laser illumination conditions.

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