Steep-Slope Gate-Connected Atomic Threshold Switching Field-Effect Transistor with MoS$_2$ Channel and Its Application to Infrared Detectable Phototransistors

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For next-generation electronics and optoelectronics, 2D-layered nanomaterial-based field effect transistors (FETs) have garnered attention as promising candidates owing to their remarkable properties. However, their subthreshold swings (SS) cannot be lower than 60 mV/decade owing to the limitation of the thermionic carrier injection mechanism, and it remains a major challenge in 2D-layered nanomaterial-based transistors. Here, a gate-connected MoS$_2$ atomic threshold switching FET using a nitrogen-doped HfO$_2$-based threshold switching (TS) device is developed. The proposed device achieves an extremely low SS of 11 mV/decade and a high on-off ratio of $\approx 10^6$ by maintaining a high on-state drive current due to the steep switching of the TS device at the gate region. In particular, the proposed device can function as an infrared detectable phototransistor with excellent optical properties. The proposed device is expected to pave the way for the development of future 2D channel-based electrical and optical transistors.

1. Introduction

2D-layered nanomaterials, such as graphene,[1–7] black phosphorus,[8–13] and transition metal dichalcogenides (TMDCs),[14–23] have received substantial attention in the fields of nanoelectronics and optoelectronics in the past few years. Recent studies on devices fabricated using 2D material for channel have revealed that they have excellent current on/off ratio, satisfactory charge carrier mobility, low subthreshold swing (SS), and interesting optical properties.[1–23] Although conventional 2D-channel-based field-effect transistors (FETs) exhibit a low SS value, the SS cannot be lower than 60 mV/decade at room temperature owing to the limitation of the thermionic carrier injection mechanism.[24–26] The SS of the transistor needs to be as low as possible to maintain the total power consumption, and a low SS leads to a high switching speed and low power consumption per device.[26,27] To overcome the SS limit, several types of steep-slope 2D-channel devices have been proposed such as tunneling FET,[13,28–30] negative capacitance FET,[24,25,31,32] and phase FET.[26,33,34] In particular, phase FETs are currently considered the most promising steep-slope device. The concept of phase FET was first implemented by Shukla et al. in 2015 using an insulator-to-metal transition (IMT) material, VO$_2$, integrated in series with the source of the conventional FET.[35] When external perturbations such as temperature, pressure, and electrical stimulus are applied to VO$_2$, phase transition is induced, which causes an abrupt change in conductivity. The phase FET using VO$_2$ shows excellent properties such as an abrupt increase in current with applied voltage, short switching time, high on-current, low fabrication temperature, and high compatibility with conventional complementary metal-oxide-semiconductor technology. Owing to these advantages, in 2017, Grisafe et al. applied the phase FET concept with VO$_2$ in the MoS$_2$-channel FET to further boost the 2D-channel device performance.[33] The suggested MoS$_2$-channel phase FET has a low operation voltage and low SS, but it involves several problems, such as a high off-state leakage current and low thermal stability, according to the limitations of the IMT materials. In 2019, HfO$_2$-based threshold switching (TS) device was suggested for MoS$_2$-channel phase FETs instead of IMT materials, because of the low off-state leakage current characteristic of $\approx 1$ pA and the superior thermal stability of $\approx 90 {^\circ}$C.[34] However, these source-connected phase FETs decrease not only the off-state leakage current but also the on-state drive current, regardless of the material used in the TS device because the TS device is located in the main current flow path. Therefore, research on realizing steep switching devices while maintaining the superior characteristics of MoS$_2$ FET needs to be conducted.
Achieving a low $SS$ value of FETs in terms of the optical concept is also important because one of the main challenges in optics is reducing the total power consumption in optoelectronics. The $SS$ corresponds to the gating efficiency, such that reducing the $SS$ makes it possible to ensure low voltage operability. In addition, the photogating effect-based phototransistor, which operates the photogenerated carriers similar to the back-gate voltage in a FET, has a close relationship with gating efficiency because the optical operating mechanism is threshold voltage shifting. Therefore, the improvement in gating efficiency by decreasing the $SS$ can enhance the optical characteristics of photogating effect-based phototransistors. However, few studies have focused on lowering the $SS$ value of phototransistors, and research on this aspect is essential for next-generation optoelectronics.

Here, we demonstrate a gate-connected MoS$_2$ atomic threshold switching FET (ATS-FET) using a nitrogen-doped HfO$_x$:N-based TS device for a next-generation steep-slope 2D-channel device. The on-state drive current of a MoS$_2$ ATS-FET is maintained owing to the gate-connected structure and the SS of the device is reduced through the Ag conductive filament formed and ruptured in the HfO$_x$:N layer. In particular, the proposed device can detect the infrared range light owing to the special properties of the Ge substrate. Therefore, the proposed ATS-FET can also be used as an infrared detectable phototransistor based on the photogating effect. Compared with the conventional MoS$_2$ phototransistor, the optical characteristics of the proposed device are enhanced by the combined action of the photogating effect and the low $SS$. It was also successfully confirmed that the responsivity and detectivity for the incident infrared light were increased.

2. Results and Discussion

2.1. Device Scheme and Typical Characteristics

A schematic of the gate-connected MoS$_2$ ATS-FET is shown in Figure 1a. The proposed ATS-FET was formed by connecting the MoS$_2$ FET gate electrode in series with the HfO$_x$:N-based TS device. First, the MoS$_2$ FET was fabricated using $p$-type Ge ($p$-Ge) ($N_a = 1 \times 10^{16}$ cm$^{-3}$), which is used for the back-side gate electrode. A 50-nm-thick silicon dioxide (SiO$_2$) layer was deposited on the $p$-Ge substrate via plasma-enhanced chemical vapor deposition to form a gate oxide. Then, the MoS$_2$ flake as a channel was transferred onto the SiO$_2$/p-Ge substrate using the polydimethylsiloxane-based mechanical exfoliation method. A 40-nm-thick Ti layer was deposited as a source/drain (S/D) contact metal. The S/D contact metal was fabricated in parallel with a spacing of 10 µm, as shown in the top-view optical microscope image of Figure 1b. As shown in Figure S1, Supporting Information, two conventional peaks (E'$_{2g}$ and $A_1g$) of the MoS$_2$ were clearly revealed at 382.2 and 407.6 cm$^{-1}$ by Raman spectroscopy, indicating that the MoS$_2$ is present as a multi-layer.

The thickness of the MoS$_2$ was measured to be 11 nm by using atomic force microscopy (AFM), as shown in Figure S2, Supporting Information, which indicates that MoS$_2$ has $\approx$15 layers. Figure 1c shows the drain current–gate voltage ($I_D$–$V_G$) characteristics of the MoS$_2$ FET, which exhibited n-type transfer characteristics with a high on-state current of $\approx$10$^{-6}$ A and a high current on/off ratio of $\approx$10$^6$, similar to typical multi-layered MoS$_2$ FETs.

The HfO$_x$:N-based TS device with an Ag/HfO$_x$:N/Pt/Ti structure, which is essential for constructing the ATS-FET, was
fabricated on a 90-nm-thick SiO₂/Si substrate. Ag (100 nm), Pt (15 nm), and Ti (10 nm) metal layers were deposited via electron-beam evaporation. A 50-nm-thick HfO₂:N interlayer was deposited using radio frequency sputtering with a HfO₂ ceramic target under a N₂ gas flow of 2 sccm. Through the top-view optical microscope image and cross-sectional view transmission electron microscopy image, the TS device was confirmed that the structure of that was completed, as shown in Figure S3, Supporting Information. Figure 1d shows the typical –V characteristics and the operation mechanism of the HfO₂:N-based TS device under the direct current sweep. The TS device shows an abrupt resistance switching during forward and backward voltage sweeping, which can be explained by the formation and dissolution of the Ag filament in the HfO₂ electrolyte. When applying a forward sweep from 0 to 1 V, an Ag filament is formed between the two electrodes and the TS device changes from the off-state to the on-state. In contrast, when applying a backward sweep from 1 to 0 V, the device is turned off because the Ag filament is spontaneously ruptured to minimize the interfacial energy.

2.2. Electrical Properties of Gate-Connected MoS₂ ATS-FET

Figure 2 shows the electrical properties of gate-connected MoS₂ ATS-FET, which was formed by connecting the MoS₂ FET gate electrode in series with the HfO₂:N-based TS device. Figure 2a shows the I₀–VG characteristics of the MoS₂ FETs with and without the TS device in the gate region at VD from 0.5 to –3.5 V with a step of 0.05 V with constant VD = 0.5 V. The threshold voltage (VTH) of the gate-connected MoS₂ ATS-FET is shifted toward the left side as compared with the MoS₂ FET from –2.19 to –2.60 V (the VTH was defined for VD when I₀ = 10⁻¹¹ A). The higher |VTH| of the gate-connected MoS₂ ATS-FET indicates that the applied gate voltage is not used entirely to turn off the transistor. In the case of drain current for both devices, the on- and off-state currents are 10⁻⁶ and 10⁻¹² A, respectively, and the on/off switching ratio is 10⁸. The reason for the same on- and off-state currents in both devices is that the TS device is connected to the gate rather than the channel through which current flows directly, and therefore it does not interfere with the flow of the drive current. In addition, a sharp rise in the drain current is observed while maintaining the on- and off-state current values. This change in drain current results in a dramatic decrease in the minimum SS value, as shown in Figure 2b. The SSs of the two devices are obtained from the transfer characteristics at VD = 0.5 V, where SS = 𝑑I/D 𝑑V G. While the MoS₂ FET had a minimum SS of 73.8 mV/decade, the gate-connected MoS₂ ATS-FET achieved a significantly low minimum SS (SSmin) of 11.1 mV/decade with a range of abrupt current transition close to 10⁴. Besides, Figure 2c shows the distribution of SSmin in 10 devices to confirm the device-to-device variation. As a result, the value and variation of SSmin of ATS-FET tend to decrease compared to that of MoS₂ FET and it shows that our proposed device has good reliability. The I₀–VG characteristics and SSmin values for various VG steps are shown in Figure S4, Supporting Information. It was confirmed that as the VG step became finer, more data points appeared on the SS slope, and the SSmin values are maintained at a very low value compared to the conventional MoS₂ FET. Furthermore, as a result of the I₀–VD measurement (Figure S5, Supporting Information), it was confirmed that a large gap was formed between the drain current values according to the gate step due to the low SS of the ATS-FET.

To explain the modulation of the electrical properties of the gate-connected MoS₂ ATS-FET, the schematic I₀–VG curves and circuits are illustrated in Figure 3. Figure 3a shows a schematic illustration of the transfer I₀–VG curve with and without the TS device at the gate region. As shown in Figure 3a, the gate-connected MoS₂ ATS-FET shows a left shift of VTH and a decrease of SS compared to the MoS₂ FET, when sweep VG is in the negative direction. These modulations can be explained by the equivalent circuit and voltage distribution for the device, as shown in Figure 3b. When low VG is applied, most of the voltage drops occur on the TS device owing to the high resistance, as shown on the left side of Figure 3b. Therefore, the applied gate voltage of the MoS₂ FET (VG,FET) remains low and the MoS₂ channel remains in the on-state. For this reason, VTH of the gate-connected MoS₂ ATS-FET was shifted toward the left side. As VG increases in the negative direction, the voltage applied to the TS device (VG,TS) increases, eventually forming an Ag filament between the two electrodes to turn on the TS device, as shown on the right side of Figure 3b. Then, the TS device changes to a low resistance state, which is makes the extremely low VG,TS drops, and VG,FET changes steeply to a value approaching VG. As a result of the sudden change in
Figure 3. Mechanism of steep-switching in gate-connected MoS₂ ATS-FET. a) Schematic of transfer curves of the MoS₂ FET and gate-connected MoS₂ ATS-FET showing changes of $V_{TH}$ and $SS$. b) Circuit illustrations of gate-connected MoS₂ ATS-FET at small and large $V_G$.

Figure 4. Optical characterization and operating mechanism of gate-connected MoS₂ ATS-FET. a) Schematic of the gate-connected MoS₂ ATS-FET under incident light ($\lambda = 1550$ nm). b) $I_D-V_G$ characteristics of the gate-connected MoS₂ ATS-FET with and without 1550 nm infrared light. The inset shows threshold voltages with and without the incident light. c) Energy band diagram of the MoS₂ FET in the vertical direction under infrared light using a Ge gate. d) Cross-section illustration of the gate-connected MoS₂ ATS-FET under incident light, indicating a reduction in migration of Ag⁺ ions.

$V_{G,FET}$, the $SS$ of the gate-connected MoS₂ ATS-FET decreases significantly as compared with that of the MoS₂ FET. According to the above-mentioned, the main factor determining $V_{TH}$ and $SS$ of the gate-connected MoS₂ ATS-FET is the formation and dissolution of the filament of the TS device in the gate region.

2.3. Optical Properties of Gate-Connected MoS₂ ATS-FET

In general, MoS₂ FETs have been widely studied as optoelectronic devices.[16,18,20,40,45] Similarly, the proposed gate-connected MoS₂ ATS-FET is also capable of photodetection. To assess the photodetection performance, the infrared light ($\lambda = 1550$ nm) was incident perpendicularly and uniformly onto the channel region of the device shown in Figure 4a. The $I_D-V_G$ characteristics of the gate-connected MoS₂ ATS-FET with and without irradiation of 1550 nm infrared light are presented in Figure 4b. With irradiation, the ATS-FET exhibited a negative $V_{TH}$ shift from −2.60 to −2.95 V (inset in Figure 4b) while maintaining a low $SS$ of 11.1 mV/decade. In addition, rise time of 51.1 ms and decay time of 27.3 ms were measured as shown in Figure S6, Supporting Information, and the rise and decay time values were extracted between 10% and 90% of the increasing and decreasing drain current. The principle of threshold shift under incident infrared light can be explained using a band diagram and a schematic of

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the proposed device as shown in Figure 4c,d. Figure 4c shows a band diagram of the channel/gate oxide/gate electrode of the MoS2 FET. Under thermal equilibrium conditions, initial band bending is caused by the difference in work functions between MoS2 (\(\phi_{\text{MoS2}} = 4.2\) eV) and Ge (\(\phi_{\text{Ge}} = 4.516\) eV) as shown in the band diagram. When infrared light is incident onto the device, the MoS2 and SiO2 layers hardly absorb the light and act as transparent windows owing to their wide bandgaps. Therefore, the incident light can reach Ge and is absorbed owing to the narrow bandgap of Ge (\(E_g = 0.66\) eV). The absorbed light creates electron–hole pairs in the Ge region, and the generated electrons accumulate at the SiO2/Ge interface because of the initial band bending. The accumulated electrons can cause two phenomena. One is decrease of the n-type doping in the MoS2 channel, and the other is prohibition of the Ag+ ion migration in the HfO2:N layer, as shown in Figure 4d. Decrease of the n-type doping in the MoS2 channel causes right shifting of the transfer curve, and inhibition of the Ag+ ion migration causes left shifting of the transfer curve. In the case of the gate-connected MoS2 ATS-FET, the switch operation is determined by the turn on and off of the TS device. Therefore, the transfer curve is shifted to the left side, as shown in Figure 4b. This phenomenon, in which the threshold voltage is shifted through the charge generated by incident light, is called the photogating effect.\(^{38,46-47}\)

To further evaluate the performance of the phototransistor, we extract the light to dark current ratio, photocurrent, responsivity, external quantum efficiency (EQE), and detectivity from the \(I_{\text{th}}-V_{\text{G}}\) curves. As shown in Figure 5a, an ultrahigh light-to-dark current ratio can be obtained in the threshold shift region because of the steep SS and the significantly steady SS operate simultaneously in the proposed device, and the maximum value of the factor is \(4.7 \times 10^4\) at \(V_{\text{G}} = -2.9\) V and \(V_{\text{D}} = 0.5\) V. The photocurrent \(I_{\text{photo}} = I_{\text{light}} - I_{\text{dark}}\) shows a rapid change based on threshold voltage due to the threshold shift according to the incident light, and maximum values as high as \(3.58 \times 10^{-7}\) A are achieved as shown in Figure 5b. Because the responsivity (R) and the EQE, as shown in Figure S7a and S7b, Supporting Information, are parameters related to \(I_{\text{photo}}\), they exhibit the same trend of change as \(I_{\text{photo}}\). R indicates the ratio of the generated photocurrent and effective incident optical power \((R = I_{\text{photo}}/P_{\text{eff}})\), and \(P_{\text{eff}}\) is calculated as \(P_{\text{eff}} = P(A_{\text{device}}/A_{\text{phot}})\), where \(P\) is the actual output laser power and \(A\) is the area of the device and laser spot, and the value of \(P_{\text{eff}}\) is \(1.69 \times 10^{-2}\) W. EQE is the ratio of the number of photoexcited charge carriers to the number of incident photons on the device from the outside; it can be expressed as \(\text{EQE} = I_{\text{photo}}/h\nu/\lambda\), where \(h\) is Planck constant, \(c\) is the speed of light, \(\lambda\) is the wavelength of incident light, and \(e\) is the electron charge. \(R\) and EQE increased steeply at the subthreshold region and reached the highest values of 2.1 AW\(^{-1}\) and 169.0%, respectively. Detectivity \(D^* = R(A_{\text{device}}/2eI_{\text{dark}})^{0.5}\), one of the most important parameters for photodetectors, is defined as the signal-to-noise ratio of the photodetector normalized by the device area. Because of the ultrahigh light-to-dark current ratio in the threshold shift region, \(D^*\) was measured to have a considerably high value of \(2.7 \times 10^{12}\) cmHz\(^{0.5}\)W\(^{-1}\) as shown in Figure 5c. All parameters mentioned above have incomparable selectivity for the applied gate voltage owing to the extremely low SS and threshold shift. The optical performance of the gate-connected MoS2 ATS-FET is dramatically enhanced, as compared with that of the conventional MoS2 FET (Figure S8, Supporting Information), which is without the TS device. A comparison of the critical optical performance indicators is presented in Table S1, Supporting Information. These optical characteristics prove that the ultra-low SS of the gate-connected MoS2 ATS-FET can be beneficial when a gate-connected MoS2 ATS-FET is used as a photodetector. Compared to recently reported advanced phototransistors, as shown in Table 1, the gate-connected MoS2 ATS-FET can not only operate in the infrared region, but also exhibit a significantly high photo-to-dark current ratio, responsivity, and detectivity. These excellent optical performance characteristics of the gate-connected MoS2 ATS-FETs indicate that the proposed device has significant potential for application in optoelectronics.

3. Conclusion

We developed a gate-connected MoS2 ATS-FET using a HfO2:N-based TS device to overcome the SS limit in 2D channel-based transistors. The proposed ATS-FET has an extremely low SS of 11.1 eV/decade with a range of abrupt current transitions close to \(10^4\). The operation mechanism was successfully investigated based on electrical characteristics and circuits, and the main factor determining \(V_{\text{TH}}\) and SS is the formation and dissolution of the Ag filament in the TS device. In addition, because the TS device used to obtain a low SS is connected to the gate and does not lower the drive current, the ATS-FET has a high on-state drive current of \(\approx 10^{-6}\) A and a high on-off ratio of \(\approx 10^6\). Moreover,
Table 1. Performance comparison of gate-connected MoS$_2$ ATS-FET and recently reported advanced photodetectors.

| Device                           | Wavelength [nm] | $I_{\text{photo}}/I_{\text{dark}}$ | Responsivity [A W$^{-1}$] | Detectivity [cm Hz$^{0.5}$ W$^{-1}$] | Ref |
|----------------------------------|-----------------|-----------------------------------|---------------------------|-------------------------------------|-----|
| Gate-connected                   |                 |                                   |                           |                                     |     |
| MoS$_2$ ATS-FET                  | 1550            | $2 \times 10^5$                   | 2.11                      | $2.7 \times 10^{15}$                | This work |
| Multilayer MoS$_2$               | 405             | $10^3$                            | 3.7                       |                                     | [45]|
| Au-MoS$_2$                       | 466             | $10^5$                            | 20                        | $6 \times 10^{10}$                  | [48]|
| Ta$_2$Pd$_3$                     | 633             | $1.4 \times 10^6$                 | 7.1$	imes 10^{10}$       |                                     | [49]|
| Hybrid-layered OPT               | 365             | $2.9 \times 10^4$                 | $8.6 \times 10^4$         | $3.4 \times 10^{14}$                | [50]|
| Pb–Sn perovskites/InGaZnO        | 473–2712        | $4.7 \times 10^2$                 | $1.2 \times 10^{12}$      |                                     | [52]|
| Amorphous MoS$_2$                | 473–2712        | $4.7 \times 10^2$                 | $1.2 \times 10^{12}$      |                                     | [53]|
| MoS$_{2.15}$                     | 445–9536        | $2.2 \times 10^2$                 |                           |                                     | [54]|
| CdTe-MoS$_2$                     | 200–1700        | $3 \times 10^4$                   | $3.7 \times 10^2$         | $6.1 \times 10^{10}$                | [55]|
| HgTe quantum dot PT              | $\approx$1500–2500 | 10                    | > 1                       |                                     | [56]|
| Si nanomembrane                  | 1550            | $10^2$                            | $7 \times 10^3$           |                                     | [57]|
| GeSn/Ge                          | 1550            | $2.3 \times 10^2$                 | 99                        | $3 \times 10^{11}$                  | [58]|
| GeSn heterojunction              | 1550            | $6.8 \times 10^{11}$              |                           |                                     |     |

the gate-connected MoS$_2$ ATS-FET can be used as an infrared detectable phototransistor owing to the detection of infrared light through a Ge gate electrode, which has a narrow bandgap. When the infrared light is incident onto the device, the threshold voltage is shifted from $-2.6$ to $-2.95$ V, while maintaining a low SS. Owing to the shifting of the threshold voltage and the maintained low SS, the proposed device achieves significantly high performance as an optical device, featuring characteristics such as an ultrahigh light-to-dark current ratio ($4.7 \times 10^4$) and high-selective detectivity ($2.7 \times 10^{12}$ cm Hz$^{0.5}$ W$^{-1}$). Owing to these advantages, gate-connected MoS$_2$ ATS-FETs are considered promising candidates for next-generation 2D channel-based electrical and optical devices that require high switching speed and low power consumption.

4. Experimental Section

Characterization of MoS$_2$ Flakes: To confirm the existence and measure the thickness of MoS$_2$ flakes, Raman Fourier transform infrared spectroscopy (LabRam ARAMIS IR2, Horiba Jobin Yvon) and AFM (XE-100, Park systems) were performed. The Raman spectroscopy was performed with an excitation wavelength of 532 nm and a spatial resolution of 1 µm. AFM was performed with lateral and vertical resolutions of 2–3 and 0.1 Å, respectively.

Measurement of Electrical and Optical Characteristics: The electrical properties of the fabricated devices were measured using a Keithley 4200-SCS with laser irradiation at 1550 nm wavelength and without laser irradiation.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

atomic threshold switching field-effect transistors, high detectivity, infrared detectable phototransistors, low subthreshold swing, 2D channel

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