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Experimental investigation on the instability for NiO/β-Ga_2O_3 heterojunction-gate FETs under negative bias stress

Zhuolin Jiang[1], Xiangnan Li[1], Xuanze Zhou[2], Yuxi Wei[1], Jie Wei[1], Guangwei Xu[2, †], Shibing Long[2], and Xiaorong Luo[1, †]

[1]State Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronic Science and Technology of China, Chengdu 610054, China

[2]School of Microelectronics, University of Science and Technology of China, Hefei 230026, China

Abstract: A NiO/β-Ga_2O_3 heterojunction-gate field effect transistor (HJ-FET) is fabricated and its instability mechanisms are experimentally investigated under different gate stress voltage ($V_{G,s}$) and stress times (t_s). Two different degradation mechanisms of the devices under negative bias stress (NBS) are identified. At low $V_{G,s}$ for a short t_s, NiO bulk traps trapping/de-trapping electrons are responsible for decrease/recovery of the leakage current, respectively. At higher $V_{G,s}$ or long t_s, the device transfer characteristic curves and threshold voltage (V_{TH}) are almost permanently negatively shifted. This is because the interface dipoles are almost permanently ionized and neutralize the ionized charges in the space charge region (SCR) across the heterojunction interface, resulting in a narrowing SCR. This provides an important theoretical guide to study the reliability of NiO/β-Ga_2O_3 heterojunction devices in power electronic applications.

Key words: NiO/β-Ga_2O_3 heterojunction; FET; NBS; instability; bulk traps; interface dipoles

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1. Introduction

β-Ga_2O_3 has attracted great attention in power electronics because of its ultra-wide bandgap (E_g) of 4.9 eV and high critical electric field of 8 MV/cm. Due to the excellent material properties, the Baliga's figure of merit (BFOM) is 3444x Si, which is much higher than other wide bandgap materials like SiC and GaN[1, 2]. In recent years, β-Ga_2O_3 power field-effect transistors (FETs) have achieved tremendous progress in high BFOM[3, 4]. However, the absence of p-type β-Ga_2O_3 makes the breakdown voltage (BV) and the BFOM far lower than its theoretical limit. To overcome this challenge and obtain the advantages of p-n junction devices, various p-type oxides have been hetero-integrated with β-Ga_2O_3[5, 6], among which NiO with E_g of 3.8-4 eV and controllable doping concentration is proved to be greatly suitable for β-Ga_2O_3 power devices[7, 8]. Moreover, great advances have been achieved in BFOM of NiO/β-Ga_2O_3 power heterojunction FETs[9, 10]. However, the abrupt NiO/β-Ga_2O_3 heterojunction may produce severe trap effects. These effects include degradation of the threshold voltage (V_{TH}) and current under the negative bias stress (NBS)[11, 12]. Few studies have focused on the critical issue of gate instability in NiO/β-Ga_2O_3 heterojunction FETs. Therefore, to promote β-Ga_2O_3 high-power applications in the future, it is important to further our investigation on the degradation mechanism of NiO/β-Ga_2O_3 heterojunction FETs.

In this work, a NiO/β-Ga_2O_3 heterojunction-gate FET (HJ-FET) was fabricated and its instability was analyzed at different gate stress voltage ($V_{G,s}$) and stress times (t_s) under negative bias stress (NBS). Two different degradation mechanisms were found: the first is a recoverable degradation owing to NiO bulk traps on the condition of a low $V_{G,s}$ and short t_s; and the second is a permanent degradation caused by the ionized interface dipoles in the NiO/β-Ga_2O_3 heterojunction with large $V_{G,s}$ or t_s values.

Correspondence to: G W Xu, xugw@ustc.edu.cn; X R Luo, xrluo@uestc.edu.cn

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2. Experimental

2.1. Device fabrication

Fig. 1(a) shows the cross-sectional view and process flow of the fabricated NiO/β-Ga_2O_3 HJ-FET. A 200 nm thick Si-doped β-Ga_2O_3 epitaxial layer with a concentration of 1×10^{18} cm^{-3} was grown on the Fe-doped semi-insulating (010) β-Ga_2O_3 substrate with Agilis R&D MOCVD system. After that, the mesa isolation was realized by an inductively coupled plasma (ICP) process. Using SiO_2 as a hard mask, the source and drain N^+ regions were selectively regrown by MOCVD with a heavy doping concentration of 1×10^{19} cm^{-3}. Then, to form source/drain ohmic contacts, Ti/Al/Ni/Au (20/160/40/80 nm) were evaporated and followed by rapid thermal annealing (RTA) at 470 °C for 60 s in nitrogen. The p-type NiO was sputtered at room temperature and followed by a lift-off process. The NiO concentration and thickness are 1×10^{19} cm^{-3} and 50 nm, respectively. Finally, the gate metal Ni/Au (20/80 nm) was fabricated using an e-beam evaporation and lift-off process. The fabricated NiO/β-Ga_2O_3 HJ-FETs have a gate length (L_G) of 2 μm, gate-source separation (L_{GS}) of 2 μm, and gate-drain separation (L_{GD}) of 3 μm.

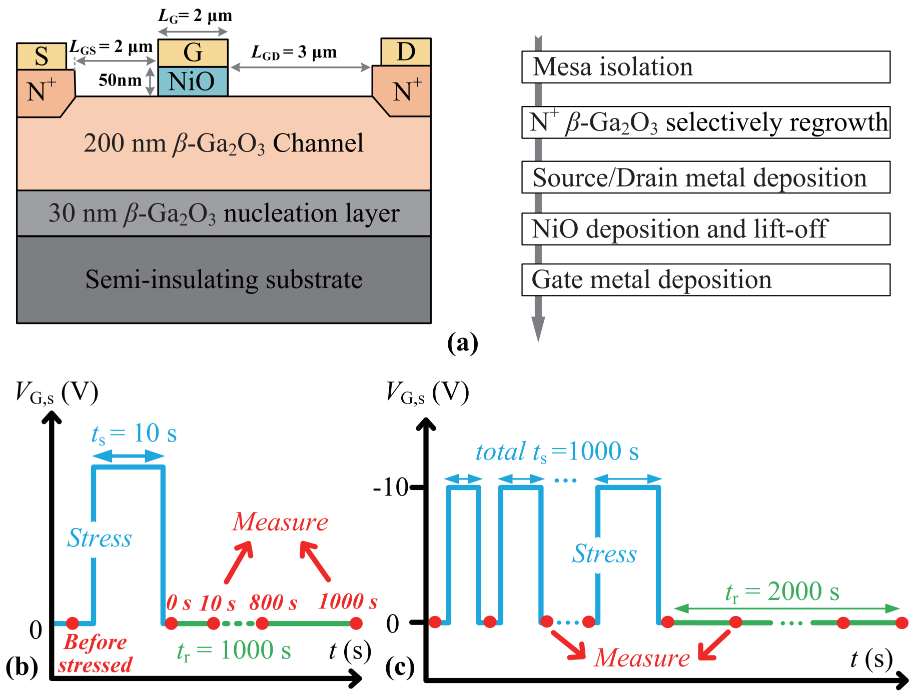

Fig. 1. (Color online) (a) Cross-sectional view of the proposed NiO/β-Ga_2O_3 HJ-FET and the main fabrication process flows. Schematic representation of the testing method for the analysis instability under NBS at (b) single pulse, and (c) multiple pulses with a prolonged t_s.

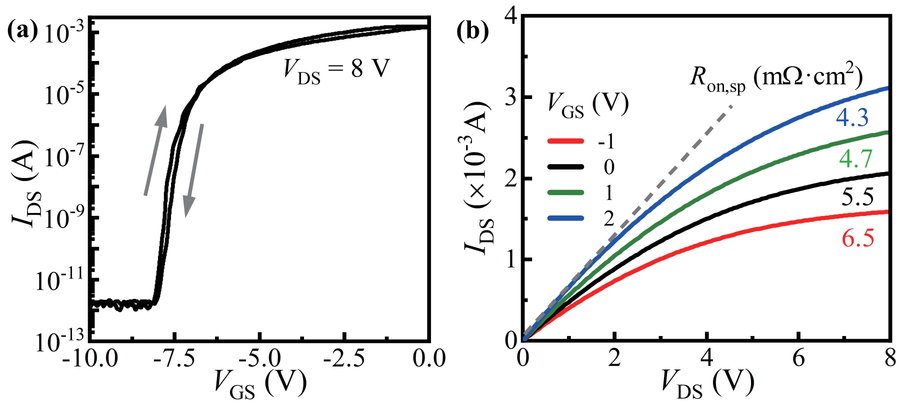

Fig. 2. (Color online) Measured DC characteristics: (a) log-scale transfer characteristics and (b) output characteristics.

2.2. Measurement method

The NBS-induced instability of NiO/β-Ga_2O_3 HJ-FET was experimentally investigated using the Agilent 4155B. The NBS with a constant stress time t_s of 10 s experiments were first performed with $V_{G,s}$ = –5 V to –20 V and V_{DS} = 0 V. After the stress was removed, the device enters the recovery process immediately with the gate/source/drain grounded, and the total recovery time (t_r) is 1000 s, as shown in Fig. 1(b). Fast measurements are performed during interrupting the recovery processes at pre-set time nodes (from 1 s to 1000 s) to record the *I*-*V* characteristics. The NBS with prolonged t_s experiments, are characterized by the stress $V_{G,s}$ = –10 V and V_{DS} = 0 V, with the t_s from 1 μs to the total t_s of 1000 s. After the stress was removed, the device repeats the recovery experiment described above with a total t_r of 2000 s, as shown in Fig. 1(c).

3. Results and discussion

Fig. 2(a) represents the transfer characteristic curves of the fabricated NiO/β-Ga_2O_3 HJ-FET, exhibiting a little hysteresis. Because the electrons in the channel are captured by the interface states in the forward sweeping (–10 V to 0 V), while these captured electrons are not released in time in the backward sweeping (0 V to –10 V). The difference in channel electron density during the forward and backward sweeping causes a little hysteresis. The max I_{DS} ON/OFF ratio of the device is about ~ 10^9 at V_{DS} = 8 V. The measured output characteristics with specific on-resistance ($R_{on,sp}$) are shown in Fig. 2(b). The instability of NBS experiment with a constant t_s was first investigated at room temperature. Fig. 3(a) shows the recovery shifts of log-scale transfer characteristic curves after NBS with $V_{G,s}$ = –5 V and t_s = 10 s. As shown in Fig. 3(a), the I_{DS} decreases after the stress is just withdrawn, and it almost returns to the value before stressed as the t_r increases to 1000 s. The same phenomenon is observed in Fig. 3(b), and the gate current decreases and recovers gradually to its initial after the stress is withdrawn. V_{TH} is extracted from the V_{GS}-I_{DS} curves at I_{DS} = 1 × 10^{-5} A and V_{DS} = 8 V[13]. Fig. 3(c) gives the extracted ΔV_{TH} (= V_{TH} – V_{TH0}, V_{TH0} is the initial V_{TH}

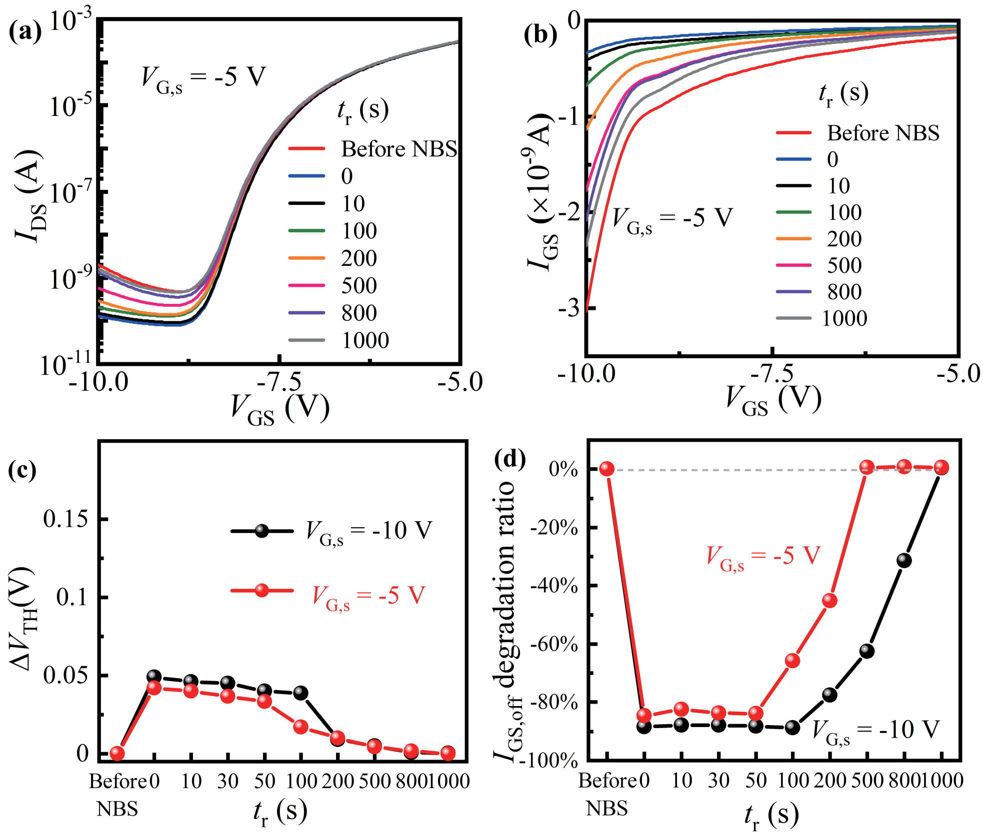

Fig. 3. (Color online) Measured (a) V_{GS}-I_{DS} and (b) V_{GS}-I_{GS} curves after NBS as a function of t_r. Extracted (c) ΔV_{TH} and (d) $I_{GS,\,off}$ degradation ratio.

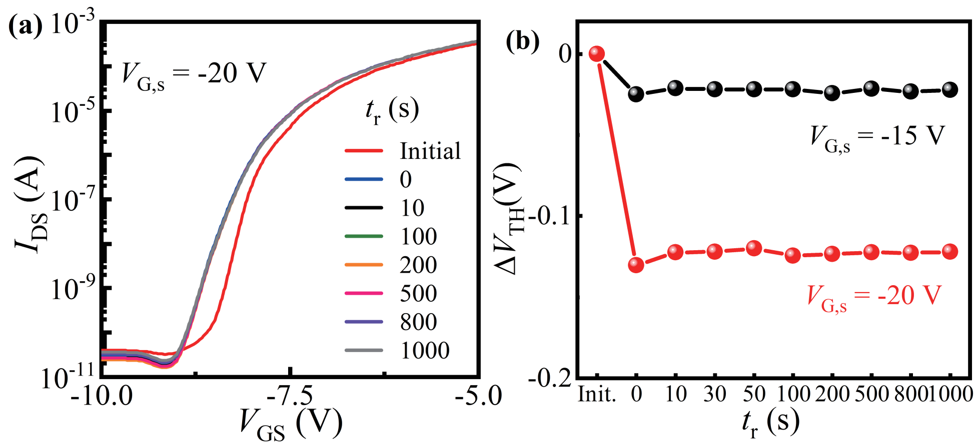

Fig. 4. (Color online) Measured (a) V_{GS}-I_{DS} and (b) V_{GS}-I_{GS} curves after NBS as a function of t_r. Extracted (c) ΔV_{TH} and (d) $I_{GS,\,off}$ degradation ratio.

without gate bias stress) with a slight positive shift, and V_{TH} almost returns to its initial value after the stress is withdrawn for 1000 s. $V_{G,s}$ = −10 V leads to a larger V_{TH} shift than $V_{G,s}$ = −5 V. The gate off-state current ($I_{GS,off}$) is defined as the gate current at V_{GS} = −10 V from the V_{GS}-I_{GS} curves. The $I_{GS,off}$ degradation ratio is given as ($I_{GS,off(t)}$ − $I_{GS,off(0)}$)/$I_{GS,off(0)}$. Fig. 3(d) shows that $I_{GS,off}$ decreases by 84% for $V_{G,s}$ = −5 V and then gradually recovers to its initial value. Also, $V_{G,s}$ = −10 V causes a larger decrease in $I_{GS,off}$ of about 87%.

NiO bulk traps could explain the $I_{GS,off}$ variations. When NBS is applied, electrons injected from the gate are trapped by the acceptor-type bulk traps in NiO, causing the bulk traps to be negatively charged[14]. After the stress is removed, the negatively charged bulk traps block the gate leakage, resulting in a decrease in $I_{GS,off}$. In terms of transfer characteristics, it will lead to a decrease in I_{DS} and a slight positive shift in V_{TH}. During the recovery phase, these negatively charged bulk traps gradually release the trapped electrons and return to the initial neutral state[15].

The mechanism will change for a high $V_{G,s}$, as shown in Fig. 4. The NBS experiment in Fig. 4(a) shows an increase in the current of the linear region with the increasing t_r at $V_{G,s}$ = −20 V, while the current in the off-region is reduced. The current did not recover significantly in the recovery process nevertheless. The extracted ΔV_{TH} shows that a high $V_{G,s}$ causes a near-permanent negative shift in V_{TH} and a higher $V_{G,s}$ cause a larger shift, as given in Fig. 4(b).

To investigate the instability of NiO/β-Ga_2O_3 HJ-FET under a prolonged t_s, the prolonged t_s NBS experiments were performed on another fresh device with the same structure.

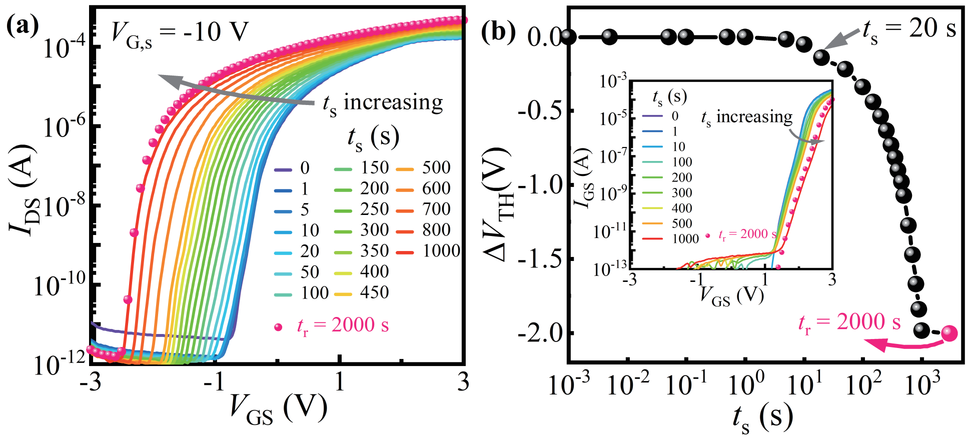

Fig. 5. (Color online) (a) Measured V_{GS}-I_{DS} curves during NBS at $V_{G,s}$ = -20 V. (b) Extracted ΔV_{TH}.

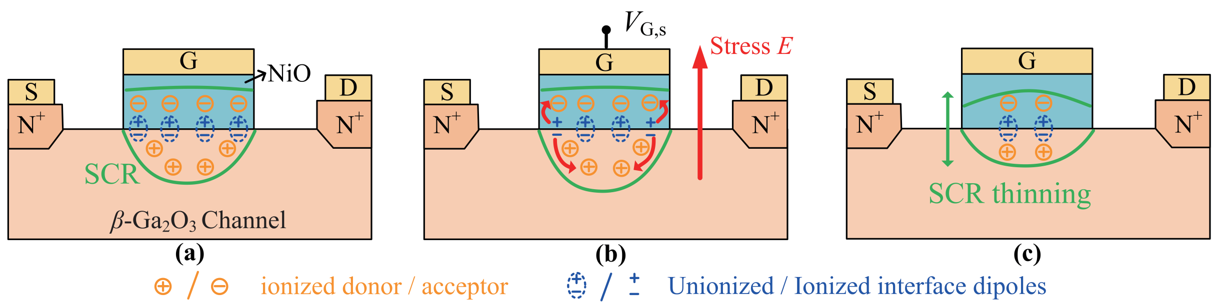

Fig. 6. (Color online) Schematic cross-sections of NiO/β-Ga_2O_3 HJ-FET (a) at initial, (b) under NBS, and (c) after NBS, respectively.

Fig. 5(a) shows the shifts of log-scale V_{GS}-I_{DS} curves during NBS for different t_s. As t_s increases, the curves steadily shift negatively, and the saturation current significantly increases. The extracted ΔV_{TH} indicates that the device characteristics are relatively stable at t_s < 20 s, but when $t_s \geqslant$ 20 s, V_{TH} starts to be negatively shifted and eventually decreases by about 2 V, as shown in Fig. 5(b). However, during the recovery process, both the characteristic curves and ΔV_{TH} are not recovered at t_r = 2000 s, as shown in Figs. 5(a) and 5(b). This non-recoverable degradation is also illustrated by the equivalent heterojunction diode current V_{GS}-I_{GS} shown in the inset of Fig. 5(b). The V_{GS}-I_{GS} curves shift toward the opposite direction compared to the V_{GS}-I_{DS} curves in Fig. 5(a). As the t_s increases, I_{GS} decreases and does not recover at t_r = 2000 s. The interface recombination current in the NiO/β-Ga_2O_3 diode acts as the dominant current transport mode. The decrease in I_{GS} is attributed to a decrease in the recombination centers.

Fig. 6 describes the mechanism of the almost permanent degradation under NBS. Due to the energy band discontinuity at the NiO/β-Ga_2O_3 heterojunction interface, the presence of interface dipoles offsets the internal electric field generated by the ionized impurities in the space charge region (SCR)[16], as shown in Fig. 6(a). These interface dipoles may be considered as charged interface states from two sides of the heterojunction[17]. The larger $V_{G,s}$ generates an extremely large electric field at the interface, which causes some interface dipoles ionize into electrons and holes, as given in Fig. 6(b). Under the stress electric field, electrons and holes move towards β-Ga_2O_3 and NiO respectively and recombine with the ionized charges in the SCR, resulting in the thinning of the SCR and the decrease in the on-resistance, as shown in Fig. 6(c). This leads to an increase in current and a negative shift in V_{TH}. The almost non-recovery of V_{TH} indicates that this ionization is irreversible. The large potential barrier in the SCR prevents the combined electrons and holes from reorganizing into interface dipoles after the stress is withdrawn. The NiO/β-Ga_2O_3 heterojunction current (I_{GS} in the inset of Fig. 5(b)) transport is dominated by the interface recombination current[18], and a reduction in interface dipoles lead to the reduction in the recombination centers, which eventually causes the leakage current in the off-region to decrease. We have also shown that interface dipoles are also ionized for prolonged experiments at relatively small $V_{G,s}$.

4. Conclusion

In summary, the impact of NBS on the electrical characteristics of NiO/β-Ga_2O_3 HJ-FETs has been studied at different stress voltages and stress times. With low $V_{G,s}$ and t_s values, the NiO bulk traps capture electrons to reduce the gate-injected electrons, resulting in a decrease in leakage current. Fortunately, it will fully recover after a long t_r. With the increasing stress voltage or stress time, the ionization of the interface dipoles expands the current conduction path leading to an increase in the current and a negative shift in V_{TH}. This is a near-permanent degradation for NiO/β-Ga_2O_3 heterojunctions and should be considered in engineering.

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Zhuolin Jiang received the M.S. degree from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2017. He was a senior researcher with the BOE Technology Group Co., Ltd in 2020. He is currently pursuing the Ph.D. degree in microelectronics with the University of Electronic Science and Technology of China, Chengdu, China.

Guangwei Xu received his Ph.D. degree at IMECAS in 2017. Then, he joined the University of California, Los Angeles as a postdoc. He joined the University of Science and Technology of China as an associate research fellow in Shibing Long Group in 2019. His research focuses on wide bandgap semiconductor power device fabrication, device defect state measurement and device modeling.

Xiaorong Luo received the Ph.D. degree in microelectronics from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2007. She is currently the Vice Director of the Department of Microelectronics Science and Engineering with UESTC.