Monolithic integration of an AlGaN/GaN metal–insulator field-effect transistor with an ultra-low voltage-drop diode for self-protection*

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In this paper, we present a monolithic integration of a self-protected AlGaN/GaN metal–insulator field-effect transistor (MISFET). An integrated field-controlled diode on the drain side of the AlGaN/GaN MISFET features a self-protected function for a reverse bias. This diode takes advantage of the recessed-barrier enhancement-mode technique to realize an ultra-low voltage drop and a low turn-ON voltage. In the smart monolithic integration, this integrated diode can block a reverse bias (> 70 V/μm) and suppress the leakage current ($< 5 \times 10^{-11}$ A/mm). Compared with conventional monolithic integration, the numerical results show that the MISFET integrated with a field-controlled diode leads to a good performance for smart power integration. And the power loss is lower than 50% in conduction without forward current degeneration.

Keywords: AlGaN/GaN, AlGaN/GaN heterostructures, metal–insulator field-effect transistor, field-controlled diode

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1. Introduction

The group III–V nitrides devices have recently attracted much attention due to their promising high-power electronic application because of the nature of two-dimensional electron gases (2DEGs) in the AlGaN/GaN heterojunction.[1−5] The high sheet density of the 2DEG in the AlGaN/GaN devices features a low power conversion loss for a high-frequency switching application such as a battery charging circuit, ON–OFF current ratio switching, and power amplification.[1,6] In conventional smart power chips, the AlGaN/GaN metal–insulator–semiconductor field-effect transistors (MISFETs) and high-electron-mobility transistors (HEMTs)[7,8] have been part of a recent push for integrated diodes at drain or source in order to resist a reverse surge current for self-protection.[9] This blocking diode requires a low forward voltage drop (FVD) for reducing power loss in forward conduction. However, in GaN-based devices, due to the high resistance of p-type Ohmic contact, the conventional p/n diode is replaced by a Schottky barrier diode (SBD) for process compatibility and relatively low specific-ON resistance.[10] Nevertheless, the turn-ON voltage of a conventional SBD is more than 1 V as shown in Fig. 1, which results in a relatively high voltage drop and thus leads to high power consumption in the forward biased case.[8,11] One of the most efficient solutions is a low Schottky barrier height (SBH) SBD.[7] Unfortunately, the low SBH leads to a relatively high reverse leakage current. Hence, in this paper, a field-controlled diode (FCD) with an ultra-low FVD for monolithic integration is proposed for fail-safe reasons.

An AlGaN/GaN MISFET integrated with a protection FCD at drain is demonstrated for the first time in this paper. This FCD includes a recessed-barrier drain (RBD) contact and an Ohmic contact illustrated in Fig. 1(a). Conventionally, without a Schottky contact, the AlGaN/GaN interface channel due to the

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high density 2DEG is normally-ON. In order to obtain an enhancement-mode channel, the Schottky barrier metal is connected with a thin AlGaN barrier. In this case, the electrons at the AlGaN/GaN interface in the quantum well will flow into metal to fill the surface states, and then the 2DEG density is reduced dramatically to pinch off the channel. Hence, the RBD can be used to deplete the 2DEG without changing the intrinsic polarized charge density. This property can be used to design an ultra-low turn-ON voltage (V_t) for the AlGaN/GaN channel with a certain SBH or barrier thickness. When the RBD diode is below V_t of SBD, the electron can be pumped by Ohmic contact at drain shown in Fig. 1(a). Therefore, the conduction mechanism of this diode is called a field-controlled diode. The FVD at this diode is lower than at the conventional SBD. We can also know that the proposed RBD structure can acquire a voltage blocking capability, thereby reducing the leakage current induced by a surge voltage wave either on the gate or source electrode. When the voltages on the gate and source are swept towards a high potential, the extended-drain is reverse biased and then the hold voltage drop can avoid damage to the reverse battery connection.

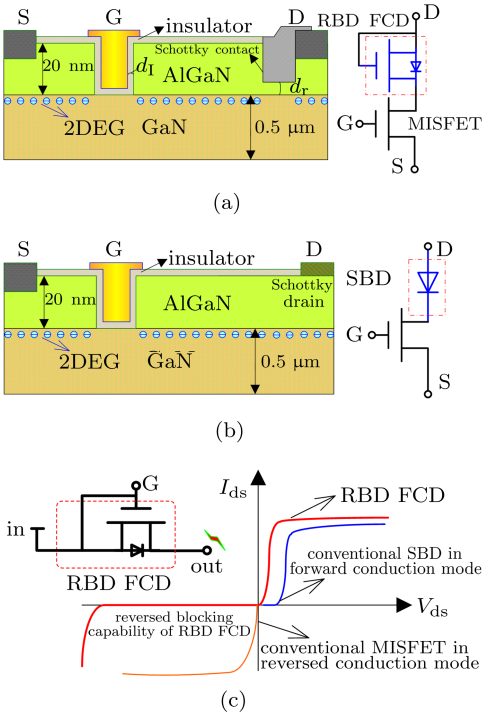


Fig. 1. Schematic cross-section view of AlGaN/GaN MISFETs and equivalent circuits: (a) RBD-MISFET, (b) SBD-MISFET, (c) the switch property diagram of integrated diodes. In the conduction mode of the FCD, the V_t can be designed to be approaching 0 V.

2. Model and device description

When the Schottky drain is biased by a small positive voltage, i.e., below the turn-ON voltage of the parasitic SBD as illustrated in Fig. 1(a), the 2DEG is generated at the AlGaN/GaN interface.[12] Meanwhile, the electron can be pumped by Ohmic contact from bypass conduction. Therefore, the FVD of FCD in forward characteristics is ultra-low as shown in Fig. 1. When the bias at the drain is beyond the V_t of the bypass SBD, the SBD is turned-ON as the integrated diode in Fig. 1(b). The total conduction current of the FCD consists of the Ohmic current and the Schottky current.

The V_t of the SBD shown in Fig. 1 is determined by the SBH, which is considerably above ~1.0 eV even using a low SBH metal (Au/Ni).[5] Additionally, the high quality AlGaN barrier layer for small gate leakage current in MISFET fabrication generates a large resistance when it is forward biased. Fortunately, the V_t of FCD at drain is determined by the generation of a 2DEG at the AlGaN/GaN interface, and it is controllable by changing the AlGaN barrier thickness. In addition, a smaller resistance can be provided by current from the Omhic contact through the 2DEG channel. The relationship between V_t and 2DEG under the recessed-barrier can be simplified into

$$V_t \approx \frac{q(d_c - d_r)n_t}{\varepsilon_b}, \tag{1}$$

where n_t is the polarization donor density at the interface, which includes spontaneous and piezoelectric polarization; the d_c is the critical thickness of the recessed-barrier for 2DEG generating conditions, which can be expressed as $d_c = (\phi_b - \Delta E_c/q + E_F/q) \cdot \varepsilon_I/n_t q$; ε_b is the dielectric constant of AlGaN; d_r is the thickness of the AlGaN barrier under the Schottky contact region; q is the charge element; E_F is the Fermi level width with respect to the GaN conduction-band-edge energy at the AlGaN/GaN interface; ΔE_c is the conduction band offset at the AlGaN/GaN interface; $q\Phi_b$ is the SBH. It is noticeable that when the barrier thickness falls below the critical thickness, the 2DEG is depleted, producing a positive V_t available for FCD design.

The wurtzite group III nitride GaN, AlN and such mixed crystals are tetrahedrally coordinated semiconductors each with a hexagonal Bravais lattice, inducing spontaneous and piezoelectric polarizations. In this case, the parameters used in simulations are given

in Table 1. The epitaxial multilayer consists of a 20-nm $Al_{0.25}Ga_{0.75}N$ (with an Si doping concentration of 1×10^{15} cm^{-3}), and 500-nm GaN layer (with a Mg doping concentration of 1×10^{14} cm^{-3}). The relatively deep-trap-energy levels which are 1.8 eV and 2.2 eV in the middle of energy for acceptor traps in the AlGaN cap and GaN buffer were set for the concept of a "virtual gate" as proposed in Ref. [10]. Si_3N_4 is deposited on the surface of the active region to reduce the donor-like surface trap concentration,[3,13] as well as offer one insulating layer in the Metal-Insulator-Semiconductor Drain (MISD) structure. The MISD is a structure of the gate and drain shorted in AlGaN/GaN MISFET. The sketch of the RBD-FCD MISFET diagram is shown in Fig. 1(b). Simulations for the improvement of the conventional MISFET in Fig. 1(a) were carried out using the two-dimensional (2D) device simulator ISE-DESSIS. The extended drain integrated an FCD is used for unidirectional switch.

Table 1. Material constants of GaN and AlN used in simulation. The parameters of the $Al_xGa_{1-x}N$ are a linear combination of AlN and GaN, e.g. $E_g(Al_xGa_{1-x}N)=x\cdot E_g(AlN)+(1-x)\cdot E_g(GaN)$.

Parameter	Quantity	Value
$n_p/10^{12}$ cm^{-2}	polarization density	8.25
ε_{I1}	GaN dielectric constant	9.5
ε_{I2}	AlN dielectric constant	8.5
E_t/eV	acceptor trap levels	1.8/2.2
x	Al content in AlGaN	0.25
E_{g1}/eV	GaN energy band gap	3.47
E_{g2}/eV	AlN energy band gap	6.20
$\mu_{low}/(cm^2/V/s)$	electron mobility	1000

3. Results and discussion

In order to obtain a low V_t diode, a series of SBH with a fixed recess barrier thickness of $d_r = 3$ nm is investigated. The results are depicted in Fig. 2(a). From expression (1), we know that the critical thickness is attributed mainly to the surface SBH with a certain Al content in the AlGaN barrier. As the $q\Phi_b$ increases from 0.4 eV to 1.2 eV, the V_t increases to 0.5 V as shown in Fig. 2. In fact, SBH on a III–V semiconductor is limited in a small range of (0.6 eV∼1.2 eV) due to the surface pinning effect and limitation of metal type. In that sense, the d_r variation is more feasible in controlling V_t at drain as shown in Fig. 2(b). Under the equilibrium state with typical SBH (0.8 eV), $d_r = 3$ nm recessed drain depletes the 2DEG from $\sim 10^{12}$ cm^{-3} (un-modulated) to $\sim 10^9$ cm^{-3}, which guarantees a positive ultra-low V_t and power loss as well as a blocking capability able to consider a punch-through effect.

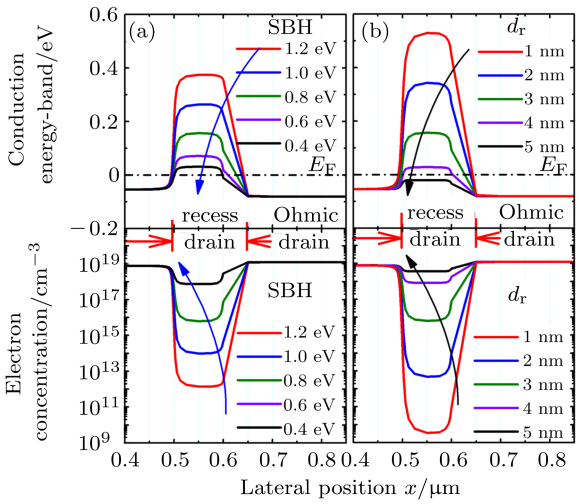


Fig. 2. Conduction energy band diagrams and electron densities of RED-MOSFET along the AlGaN/GaN interface. (a) $d_r = 3$ nm. (b) $q\Phi_b = 0.8$ eV.

Figure 3 shows that the 2DEG concentration at the AlGaN/GaN interface is controlled by the applied voltage. As shown in Fig. 3(a), the threshold voltage of the MISFET is achieved to be 0.4 V. When the gate is biased at 0.6 V, the gated electron gas concentration rises to the level of un-gated 2DEG, indicating the potential largest saturation current. The conventional SBD several times the size of MISFET can match the MISFET in forward current conducting. Unlike SBD, the recess drain region acts as a "gate" driven by a drain voltage larger than 0.6 V when it is forward biased mostly, thus the lowering magnitude of the potential barrier height at the recessed drain for transversely flowing electrons exceeds that of gate potential barrier. It means that the FCD and MISFET of the same width can match well when they are forward biased.

When the barrier is as thin as d_c in expression (1), the turn-ON voltage of the FCD approaches 0 V. The FVD is low enough to realize ultra-low power loss. From Fig. 4, we can obtain the critical thickness $d_c = d_r = 3$ nm, which is around 3 nm at $q\Phi_b = 0.8$ eV. In this condition, the power loss of the FCD is due mainly to the Ohmic contact resistance. As the SBH $q\Phi_b$ changes from 0.4 eV to 1.2 eV, the V_t in expression (1) of the FCD increases to 0.5 V. In comparison with the monolithic integration

of MISFET and MISD FCD, the RBD-MISFET shows good DC characteristics. Its performance shown in Fig. 6(a), achieves 991 mA/mm. Figure 5 shows the representative DC I–V characterization performed on individual sites. The static power loss of MISD MISFET is half higher than the RBD MISFET at output current $I_{ds} = 1$ A/mm.

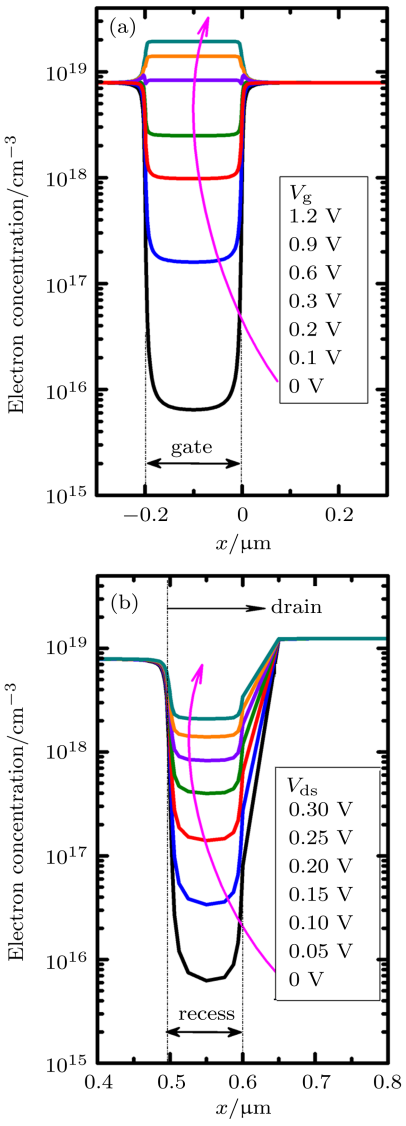


Fig. 3. The field-controlled electron density characteristics of the enhancement channel ($d_I = 10$ nm, $q\Phi_b = 0.8$ eV, $d_r = 3$ nm): (a) gate bias, (b) drain bias. The channel is a triple one which contains a depleted channel at the drift region, a MIS channel in the gate region and a field controlled channel at the recessed extended-drain.

The RBD FCD with Ohmic contact can be used to design an ultra-low FVD diode. The family of I–V curves is shown in Fig. 5, with the gate-source voltage increasing from 0.0 to 3.0 V in steps of +0.5 V, and the drain–source voltage is swept to 6.0 V. The knee voltage at $V_{gs} = 1$ V is 0.65 V, which is lower than 1.3 V in Fig. 5(b). Figure 5 exhibits good ON-state FCD properties.

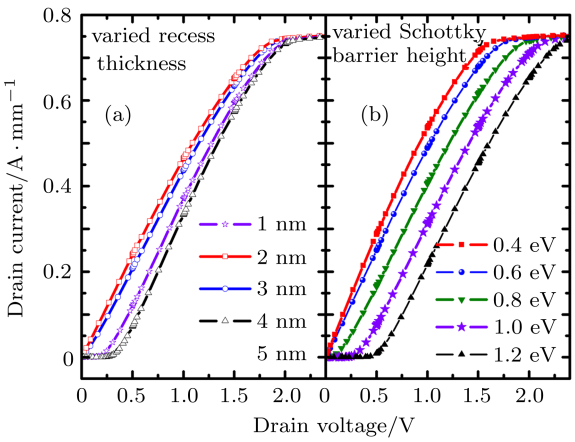


Fig. 4. The forward I–V characteristic curves of RBD-MISFET with different RBD parameters. The SBH of the recessed drain contact and the recessed AlGaN barrier thickness affect the V_t of the RED-MISFET with a fixed gate bias ($V_{gs} = 1.2$ V) that is larger than its threshold voltage. (a) $q\Phi_b = 0.8$ eV and (b) $d_r = 3$ nm.

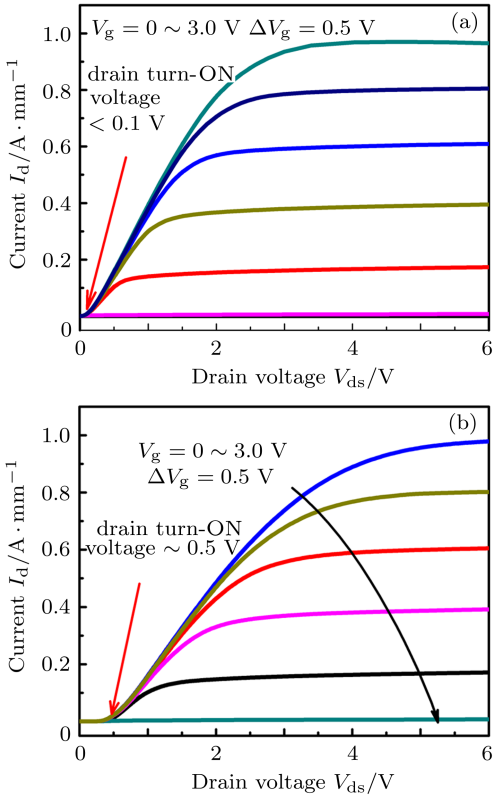


Fig. 5. The I_d–V_d characteristic curves of MISFETs (a) RBD-MISFET ($d_I = 10$ nm, $q\Phi_b = 0.8$ eV, $d_r = 3$ nm), and (b) MISD-MISFET ($d_I = 10$ nm).

The reverse blocking capability for the ON state of the Schottky-drain is obtained. As shown in

diode-protected mode in Fig. 6(a), the electrons in the surroundings of the Schottky drain electrode are strongly depleted, thus preventing a reverse current and thereby protecting the transistor. The equipotential contours are accumulated at the recessed-drain edge in Fig. 6(a) and lumped at the gate edge in Fig. 6(b). Hence, both of the edges are breakdown points with an electric field peak. As a lateral voltage withstanding device, FCD and MISFET share the same drift region. From the data in Fig. 7, we know that the leakage current (10^{-12} A/mm) of RBD-MISFET is lower than that of the conventional SBD and larger than that of MISD. The main reversed current of RBD is a tunneling current, which is determined by SBH. The RBD as a breakthrough of the trade-off between the forward turn-ON voltage and the reverse current, by comparison with the conventional SBD (SBH = 0.5 eV, $I_{\rm d} \sim 10^{-3}$ A/mm), is realized to be an ultra-low FVD shown in Fig. 7. Since the leakage current of the MISD FCD is mainly from the substrate, the whole leakage current can be reduced but at a relatively high $V_{\rm t}$.

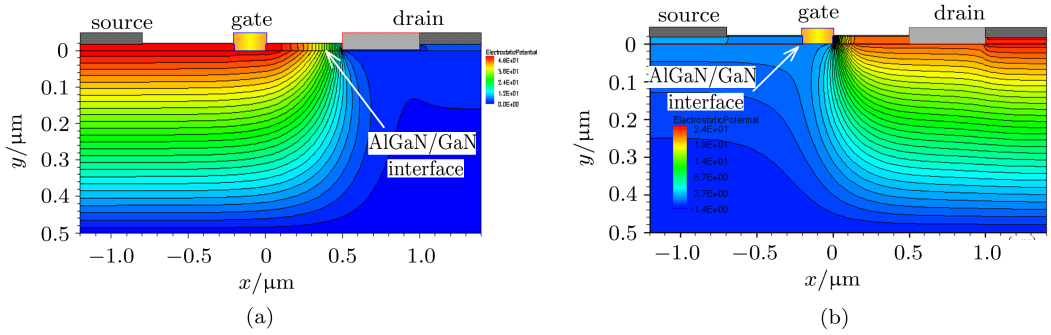


Fig. 6. Potential distributions of RBD-MISFET ($\Phi_{\rm b}$ = 0.8 eV, $d_{\rm r}$ = 3 nm) (a) at the $V_{\rm sd} = V_{\rm gd}$ = 49 V and (b) at $V_{\rm gs}$ = 0 V and $V_{\rm ds}$ = 29 V. The solid lines are equipotential ($L_{\rm s} = L_{\rm rd} = L_{\rm d}$ = 0.5 μm, $L_{\rm g}$ = 100 nm, $d_{\rm I}$ = 10 nm, and $d_{\rm r}$ = 3 nm).

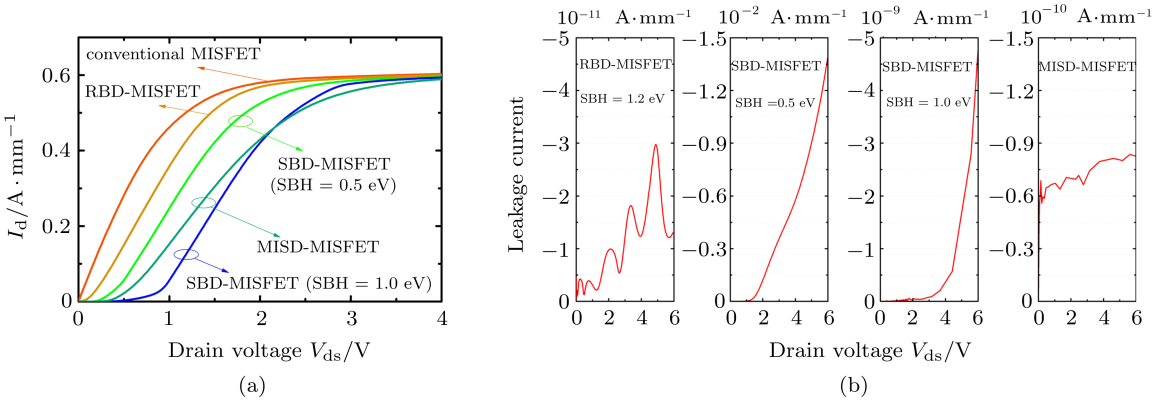


Fig. 7. (a) The I–V characteristic curves in forward-bias condition, and (b) the leakage current at OFF state. ($L_{\rm s} = L_{\rm rd} = L_{\rm d}$ = 0.5 μm, $L_{\rm g}$ = 100 nm, $d_{\rm I}$ = 10 nm, $d_{\rm r}$ = 3 nm).

4. Conclusion

In this paper, we demonstrated an ultra-low FVD diode for a self-protection function compared with a SBD and a MISD. This diode with a low FVD is realized by the recessed-barrier enhancement technique. This field-controlled channel can not only reduce the ON-state resistance at drain, but also suppress the switching loss of the monolithic integration. The reversed leakage current of the monolithic integration is below 5×10^{-11} A/mm. The improvement of the monolithic device leads to an optimal choice for a modern smart chip.

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