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Breakdown voltage over 10 kV β-Ga_2O_3 heterojunction FETs with RESURF structure

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β-Ga_2O_3 has sparked a new wave of enthusiasm in the power community because of high-voltage and high-efficiency application demands, which is attributed to its superior ultra-wide bandgap of 4.9 eV, theoretical critical electric field strength (E_C) of 8 MV/cm, and high Baliga's figure-of-merit of up to 3000. Bolstered by the large-size and low-cost substrate growth technique via the melt growth method, the development of β-Ga_2O_3-based power devices has increased rapidly. Tremendous effort has excited the power community, which is attributed to the experimental E_C of up to 5.5 MV/cm [1], breakdown voltage (BV) boosting up to 10 kV, power figure of merit (PFOM) pushing up to 900 MW/cm^2, and the achievement of vertical UMOSFET [2].

β-Ga_2O_3-based field effect transistors (FETs) have a strong capability to support the ultra-high blocking voltage; however, the experimental device performance still needs to be improved. Recent efforts focused on the optimization of techniques, such as field plate design, oxide optimization, and channel doping modulation. Nearly all edge termination techniques developed recently are in the one-dimensional direction, which limits the off-state potential of the device. The reduced surface electric field (RESURF) technique is aimed at modulating the off-state electric field extending to the two-dimensional direction, resulting in E flatness around the channel region [3]. However, the use of the RESURF method in the β-Ga_2O_3 community is difficult because of the lack of p-type β-Ga_2O_3. Recently, P-NiO_X/N-β-Ga_2O_3 heterojunction FETs (HJ-FETs) are considered to have the potential to improve the device power capability by optimizing the trade-off between the specific on-resistance and the BV [4]. Our previous study has established P-NiO_X/N-β-Ga_2O_3 HJ-FETs with an interesting PFOM of up to 0.79 GW/cm^2 [5], verifying the considered power potential of P-NiO_X/N-β-Ga_2O_3 HJ-FETs. From this view, P-NiO_X is considered to be a conceivable source to construct the RESURF structure in β-Ga_2O_3-based FETs.

In this study, we demonstrate our two-dimensional E modulation by the RESURF technique. Under the carefully designed t_{NiO}, we successfully reported RESURF P-NiO_X/N-β-Ga_2O_3 HJ-FETs with a distinguished BV of over 10 kV. To the best of our acknowledge, our HJ-FET has an advanced BV combined with an optimized E in the β-Ga_2O_3 community, verifying the strong potential for future ultra-high voltage applications.

Experiments. Fabrication begins with the photoresist patterns of S and D, followed by the multiple Si ion implantation to construct the heavily doped box-shaped Ohmic contact region. Ion activation is applied by rapid thermal annealing (RTA) at 950°C under an N_2 atmosphere for 30 min. After the evaporation of the 60/120 nm Ti/Au metal stack to serve as the S and D contact electrode, RTA at 475°C under an N_2 atmosphere for 1 min is conducted. Electrical isolation is realized by BCl_3/Cl_2-based inductively coupled plasma etching, followed by sputtering of P-NiO_X with the Ar/O_2 ratio maintained at 6 : 1 to achieve the doping concentration of 1×10^{18} cm^{-3}. Then, the patterned 50/100 nm Ni/Au is deposited to form the gate metal. In this study, we fabricate P-NiO_X/N-β-Ga_2O_3 HJ-FETs and RESURF HJ-FETs with the same t_{NiO} of 110 nm, combined with the RESURF HJ-FETs with the t_{NiO} of 70 nm. All of the HJ-FETs have $L_{\mathrm{G}}/L_{\mathrm{GD}}/L_{\mathrm{P}}$ = 2.5/74/34.5 µm.

Results and discussion. Figure 1(a) shows the device schematic of the RESURF P-NiO_X/N-β-Ga_2O_3 HJ-FETs with the doping concentration of 400 nm and the thickness of the β-Ga_2O_3 channel layer are of 3×10^{17} cm^{-3}. The cross-sectional scanning electron microscope (SEM) image of the HJ-FET is shown in Figure 1(b). As the charge density of β-Ga_2O_3 has been fixed, we explore t_{NiO} with a constant doping concentration of 1×10^{18} cm^{-3}. Three RESURF P-NiO_X/N-β-Ga_2O_3 HJ-FETs with the t_{NiO} of

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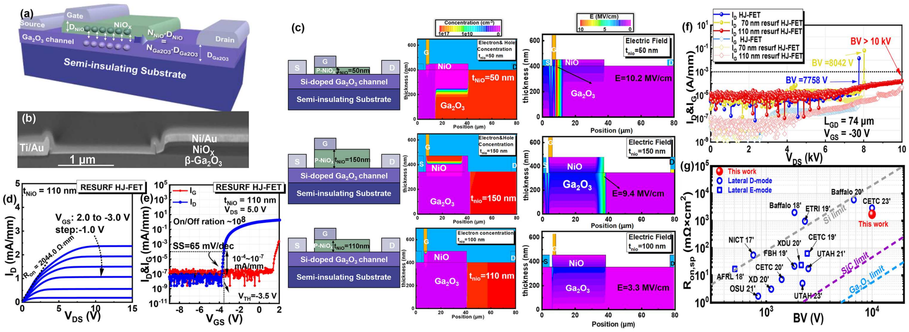

Figure 1 (Color online) (a) Cross-sectional schematic of the representative P-NiO_X/N-β-Ga_2O_3 HJ-FETs. (b) Cross-sectional SEM image of the representative P-NiO_X/N-β-Ga_2O_3 HJ-FETs. (c) Schematic cross-sectional view of the simulated carrier concentration and the simulated three-terminal off-state electric field distribution in the β-Ga_2O_3 channel at a V_{DS} of 3000 V for the RESURF β-Ga_2O_3 HJ-FETs with t_{NiO} of 50, 150, and 110 nm. (d) Output and (e) log-scale transfer characteristics of the RESURF P-NiO_X/N-β-Ga_2O_3 HJ-FETs with t_{NiO} = 110 nm. (f) Three-terminal breakdown characteristics of our devices with the L_{GD} = 74 µm. (g) Benchmark of the power performance of the recent advanced β-Ga_2O_3 transistors.

50, 150, and 110 nm are simulated simultaneously under the V_{DS} of 3000 V at the off-state. The device diagram, carrier concentration, and electric field distribution of the three RESURF P-NiO_X/N-β-Ga_2O_3 HJ-FETs are displayed in Figure 1(c). For the device with t_{NiO} = 50 nm, the hole in P-NiO_X has been fully depleted whereas the electron in β-Ga_2O_3 has been partly depleted, resulting in the sharp E crowded under the gate edge and E decreasing rapidly along the lateral channel. For the device with t_{NiO} = 150 nm, the surface P-NiO_X cannot reach the depletion state, which plays a role in extending the gate length so that the electric field distribution of this device is similar to that of HJ-FET devices with gate length the same as that of P-NiO_X. For the device with t_{NiO} = 110 nm, the electron in β-Ga_2O_3 and the hole in P-NiO_X have both been nearly depleted, resulting in the entire channel layer beyond the P-NiO_X being able to support the reverse voltage. Notably E in the channel layer distributes flatly, leading to an increased capability to sustain an ultra-high off-state voltage. Because of the continuity of the displacement field at the heterojunction interface, we can derive the equation $\varepsilon_{(Ga_2O_3)} \cdot N_{(Ga_2O_3)} \cdot V_{(Ga_2O_3)} = \varepsilon_{(NiO_X)} \cdot N_{(NiO_X)} \cdot V_{(NiO_X)}$, where ε, N, and V are the dielectric constant, doping concentration, and voltage drop, respectively. Combined with the Poisson equation $V = q \cdot N \cdot D^2/2\varepsilon$, we can derive $N_{(Ga_2O_3)} \cdot D_{(Ga_2O_3)} = N_{(NiO_X)} \cdot D_{(NiO_X)}$, where D is the depletion depth at each side. As discussed previously, we want P-NiO_X and N-β-Ga_2O_3 to fully deplete at the same time so that the layer thickness should be the same as D. The $N_{(Ga_2O_3)}$, $D_{(Ga_2O_3)}$, and $N_{(NiO_X)}$ values applied in this study are 3×10^{17} cm^{-3}, 400 nm, and 1×10^{18} cm^{-3}, respectively, leading to an optimized P-NiO_X thickness of 120 nm. However, the optimized P-NiO_X thickness is approximately 110 nm according to the simulation, which is ascribed to the trapped charge at the interface.

Figure 1(d) depicts the I_D-V_{DS} output characteristics for the RESURF HJ-FETs with t_{NiO} = 110 nm. The maximum I_D is 2.4 mA/mm at a V_{GS} of 2.0 V, and the on-resistance (R_{on}) is exacted to be 2044.0 Ω·mm from the linear region. Then, the $R_{on,sp}$ value is calculated to be 1594.32 mΩ·cm^2 by multiplying R_{on} and L_{SD}. The log-scale transfer characteristics at a V_{DS} of 5 V are plotted in Figure 1(e). The on/off ratio, subthreshold swing, and threshold voltage are 10^8, 65 mV/dec (at the I_D ranging from 10^{-4} mA/mm to 10^{-7} mA/mm), and −3.5 V (at the I_D of 10^{-4} mA/mm), respectively. The I_G surge after PN HJ conducting, which affects the power consumption and limits the gate voltage swing. Figure 1(f) depicts the three-terminal breakdown characteristics of our devices, which are submerged in the Fluorinert liquid to alleviate premature air breakdown. The BV for HJ-FETs with t_{NiO} = 110 nm is 7758 V, and the BV for RESURF HJ-FETs with t_{NiO} = 70 nm is 8042 V.

With optimized E modulation by controlling t_{NiO} at 110 nm, the BV for RESURF HJ-FETs is over 10 kV, which is the upper limit of the test equipment. The benchmark of power performance with the recent advanced lateral β-Ga_2O_3 transistors is summarized in Figure 1(g). The P-FOM, expressed as $BV^2/R_{on,sp}$, is calculated to be more than 63 MW/cm^2 for RESURF HJ-FETs with t_{NiO} = 110 nm. This study aims to achieve ultra-high BV via the two-dimensional E modulation technique, illustrating the considerable power potential of the RESURF β-Ga_2O_3-based power devices.

Conclusion. In summary, we have demonstrated the RESURF technique in β-Ga_2O_3 transistors, which benefits the E flatness and BV tolerance. The carefully designed charge density can ensure that the P-NiO_X and N-β-Ga_2O_3 sides are fully depleted simultaneously. The RESURF P-NiO_X/N-β-Ga_2O_3 HJ-FETs with t_{NiO} = 110 nm achieve a BV of more than 10 kV and a PFOM of 63 MW/cm^2. These results show the considerable power potential of β-Ga_2O_3 in the high-power and high-voltage communities.

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