10 kV GaN Power Diodes and Transistors with Performance beyond SiC Limit (Invited)

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Abstract

Medium-voltage (MV) power electronic devices are widely used in renewable energy processing, electric grids, pulse power systems, etc. Current MV devices are mainly made of Si and SiC. This paper presents our recent efforts in developing a new generation of MV devices based on the multi-channel AlGaN/GaN platform and many new device designs involving charge balance, fin, and Cascode. The specific on-resistance of our 10 kV-class GaN Schottky barrier diodes and normally-OFF transistors is ~40 mΩ·cm^2, rendering a Baliga's figure of merit exceeding the 1-D unipolar SiC limits. We show the great promise of GaN in medium and high-voltage power applications.

(Keywords: Power electronics, GaN, multi-channel, medium voltage, charge balance, cascode)

Introduction

Power semiconductor devices with low on-resistance (R_{ON}), high switching speed, and high breakdown voltage (BV) are central to improving the efficiency of electrical energy processing in many applications. Medium-voltage (MV) power devices (also referred to high-voltage in many contexts) are ubiquitously used in electricity grid, renewable energy processing, industrial motor drives, and electrified transportation. Today's MV power device market is dominated by bipolar Si IGBTs and p-n diodes up to 6.5 kV. However, they suffer from a slow switching speed due to the poor reverse recovery. A set of superior alternatives that allow fast switching is the unipolar SiC MOSFET and junction Schottky barrier (JBS) diode. These SiC devices have been recently pre-commercialized up to 10 kV by a few vendors [1] and used in R&D power applications [2].

GaN has superior power semiconductor properties over SiC and Si. Lateral GaN high-electron mobility transistors (HEMTs) have been commercialized up to 650 V [3], and industrial vertical GaN transistors have been demonstrated at the 1.2 kV class [4]. A few GaN devices have been demonstrated with BV close to 10 kV, but their specific R_{ON} are higher than SiC counterparts [5]. This has led to a common belief that GaN is only advantageous in the low voltage range.

Recently, we have developed a new generation of MV devices based on the multi-channel AlGaN/GaN platform with performance superior to the SiC and Si counterparts. The multi-channel GaN device offers combination of a high mobility in two-dimensional electron gas (2DEG) channel and a high-power handling capability enabled by the stacked channels. The multi-channel lateral device also leverages some benefits of vertical devices, e.g., spatially distributed current. To fully exploit these material properties, a series of new device designs have been proposed to enable robust termination, distributed electric field (E-field), and normally-off operation. These designs have enabled demonstration of 10 kV GaN Schottky barrier diodes (SBDs) and normally-off HEMTs with a R_{ON}~BV trade-off beyond the 1-D SiC unipolar limit.

Multi-Channel Wafer

Large-diameter multi-channel GaN wafers have become commercially available recently. The 4-inch, 5-channel, GaN-on-sapphire wafers grown by Enkris Semiconductor Inc. using the Metal-Organic Vapour-Phase Epitaxy (MOCVD) are used in this work. The wafer possesses a 2DEG density of 3.7×10^{13} cm^{-2} and a sheet resistance (R_{SH}) of 120 Ω/sq, which is 3-fold lower than the usual value of a single-channel wafer. A p-GaN cap layer can be continuously grown on the multi-channel structure in MOCVD with minimal interface charges between AlGaN and p-GaN. This p-GaN is key to enabling the E-field management structures to be detailed in the next few sections. With the p-GaN depletion, the multi-channel wafer retains a 2DEG density of 1.75×10^{13} cm^{-2}, a 2DEG mobility of 2010 cm^2/V·s, and an R_{SH} of 178 Ω/sq.

Edge Termination

The excess charges from multiple 2DEG channels often induce E-field crowding at the Schottky region or gate/drain region. Proper edge termination is thus essential. Field plate is a popular edge termination, but it contains complicated dielectrics/GaN interfaces, which may lead to device instability issues.

We proposed a distinct edge termination using the epitaxial p-GaN [6] (Fig. 1). Benefitted from the vertical depletion enabled by the p-n junction, the E-field lines spreads out, and their distribution becomes more uniform. The peak E-field is moved from the Schottky contact to p-GaN edge, thereby shielding the Schottky contact from high E-field.

The leakage current reduction is another challenge facing multi-channel devices. For this, we proposed a

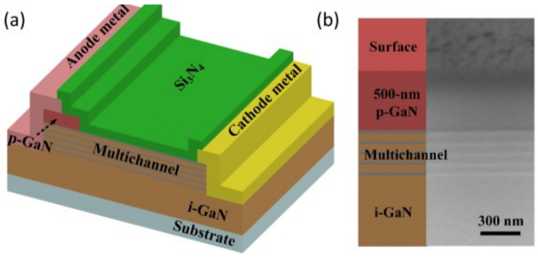

Fig. 1. (a) Schematic of multi-channel SBD with p-GaN termination. (b) Cross-sectional SEM image. [6]

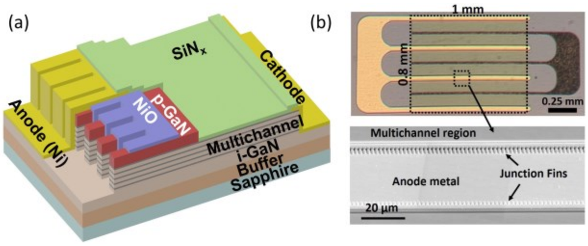

Fig. 2. (a) Schematic of multi-channel AlGaN/GaN SBD with junction-fin-anode. (b) Top-view SEM image. [7]

junction-fin-anode design, i.e., a 3-D anode structure that comprises p-n junctions wrapping around the multi-2DEG-fins (Fig. 2) [7]. Compared to the planar p-GaN termination, the 3-D wrapped p-n junctions can provide a stronger depletion of the 2DEG channel. At reverse biases, the junction-fin assists the Schottky contact for charge depletion and shields the Schottky contact from seeing high biases. Hence, the leakage current of the entire diode can be made equal to that of the sidewall SBD biased at a few volts [7].

In our prototyped 5-kV device, we realized the junction-fin structure with p-GaN on top of the fin and p-type nickel oxide at the fin sidewalls [7]. The resulting SBD shows a BV up to 5.2 kV, a specific R_{ON} of 13.5 mΩ·cm^2 and a leakage current of 1.4 µA/mm at 80% BV. Large-area 1.5 A device was also demonstrated with a BV over 4.8 kV [7].

10 kV RESURF SBD

E-field management in the lateral "drift region" is also key to upscaling BV. It was proposed that, in an unintentionally doped multi-channel, the polarization charges self-balance in each heterostructure, resulting in a zero net charge and forming a superjunction [8]. However, the net charge in our experimental multi-channel structure was found to be non-zero with net donors, which may be the origin of 2DEG in buried channels. For this multi-channel with net donors, we proposed a novel design to reduce the overall net charges (and E-field gradient), the p-GaN Reduced Surface Field (RESURF) structure (Fig. 3(a)) [9]. Compared to p-GaN termination, p-GaN RESURF layer extends to near the cathode, and its acceptor

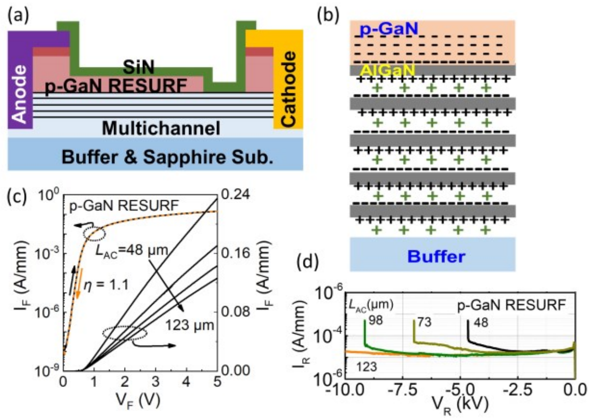

Fig. 3. Schematic of (a) multi-channel AlGaN/GaN SBD with p-GaN RESURF structure and (b) charge balance. (c) Forward and (d) reverse I-V characteristics of devices with different anode-to-cathode distances. [9]

charges balance the net donor charges in the multi-channel at high voltage (Fig. 3(b)). This charge balance can be experimentally realized by adapting the p-GaN thickness through p-GaN etch monitored by C-V measurements of a test structure [9].

Fig. 3(c) and (d) show the forward and reverse characteristics of the fabricated RESURF SBDs with an anode-to-cathode distance (L_{AC}) of 98-148 µm. A turn-on voltage was extracted to be 0.6 V. With an identical L_{AC}, the p-GaN RESURF SBD shows a BV about 1.5-fold higher than that of the SBD with p-GaN termination [9]. An average lateral E-field ($E_{AVE} = BV / L_{AC}$) of ~1 MV/cm is realized in RESURF SBDs. The SBD with a 98-µm L_{AC} shows a BV of 9.15 kV and a specific R_{ON} of 29.5 mΩ·cm^2, rendering a Baliga's figure of merit (FOM=BV^2/R_{ON}) of 2.84 GW/cm^2. The SBD with a 123-µm L_{AC} shows a BV over 10 kV and a R_{ON} of 39 mΩ·cm^2, which is 2.5-fold lower than the R_{ON} of the state-of-the-art 10-kV SiC JBS diodes. The Baliga's FOMs of our 4.6-10 kV GaN SBDs well exceed the SiC unipolar limit. Note that the junction-fin-anode can be further added to the RESURF SBD to reduce the leakage current.

10 kV Normally-OFF Multi-Channel HEMTs

The major challenge facing multi-channel HEMTs is the deep depletion-mode of a planar gate. This can be addressed by using fin-shaped tri-gates [10], and a normally-off multi-channel HEMT with 15-nm fin gates was reported [11]. However, such a demanding lithography is rarely used in power device industry (180-nm+ nodes dominantly in power industry).

We proposed a new device concept, the Multi-Channel Monolithic-Cascode HEMT (MC^2-HEMT), which monolithically integrates a low-voltage (LV),

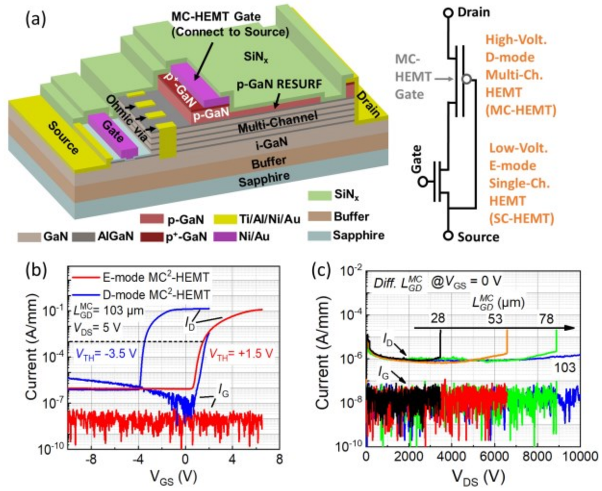

Fig. 4. Schematic of (a) MC^2-HEMT and its equivalent circuit. (b) Transfer characteristics of MC^2-HEMT with and without gate recess in the LV-HEMT. (c) OFF-state I-V characteristics of MC^2-HEMT with various L_{GD}^{MC}. [12]

normally-off HEMT based on single 2DEG channel and a high-voltage (HV), normally-on HEMT based on stacked 2DEG multi-channel [12]. As shown in Fig. 4(a), a plurality of Ohmic vias function as the effective drain for the single-channel LV-HEMT and the source for the multi-channel HV-HEMT. The HV-HEMT gate is connected to the LV-HEMT source, forming a Cascode. A gate recess is implemented in LV-HEMT to realize the normally-off operation. A RESURF structure is added to the HV-HEMT to upscale BV. This MC^2-HEMT can exploit the low sheet resistance of multi-channel, realize a normally-off gate control, and completely shield the gate region from high electric field. It also obviates the need for ~nm fin gates, relaxing the lithography requirement.

Fig. 4(b) and (c) show the forward transfer and off-state I-V characteristics of the fabricated MC^2-HEMTs, respectively. The gate recess in LV-HEMT enables a threshold voltage of over 1.5 V. BV scales with the gate-drain distance of HV-HEMT (L_{GD}^{MC}) with >10 kV achieved for L_{GD}^{MC}=103 μm. The specific R_{ON} of this device is 40 mΩ·cm^2, which is 2.5-fold smaller than that of 10 kV SiC MOSFETs and well below the 1-D SiC unipolar limit [12]. Our MC^2-HEMTs show the highest Baliga's FOMs in all 6.5-kV+ power transistors.

Conclusion

We for the first time demonstrated MV GaN power SBDs and HEMTs up to 10 kV with a R_{ON}~BV trade-off well exceeding the 1-D SiC unipolar limit. The performance of our 10 kV SBDs and HEMTs set a new record in MV devices. In contrary to common beliefs on the SiC's superiority to GaN in MV devices, our results show the tremendous promise of GaN in medium- and high-voltage power electronics, which could change the landscape of power devices.

Acknowledgments

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