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Surge Current Capability in lateral AlGaN/GaN Hybrid Anode Diodes with p-GaN/Schottky Anode

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***Abstract*—In lateral power diodes, the conductivity modulation mechanism can pave the way to the demonstration of surge current capability. In a Hybrid Anode Diode concept with a p-GaN layer, an anode contact on p-GaN layer can be a source of hole injection that increases the electron density at AlGaN/GaN interface. The role of p-GaN layer on the surge current capability and its demonstration are investigated through TCAD simulations that explain the role of hole barrier tunneling at anode metal/p-GaN interface. These simulations show that surge current can occur in case of Ohmic p-GaN contact as the injected holes can lead to create additional electron density in the channel as well as a hole current to support the total diode current.**

Keywords—hybrid anode diodes, hole injection, surge current, tcad

I. Introduction

Gallium Nitride (GaN) became a very attractive material for high-power and high frequency device applications as a wide band gap semiconductor [1,2]. Due to its superior properties such as high critical electric field, high electron velocity, large band gap, high electron mobility and density etc., GaN based transistors and diodes are emerging as promising candidates especially for new-generation power switching. An AlGaN/GaN High Electron Mobility Transistor (HEMT) is inherently normally on device, having a negative threshold voltage (v_{th}) due to presence of the two-dimensional electron gas (2DEG) at heterostructure interface. For many power device applications, it is desirable to use normally off devices for safety reasons and system reliability. In an AlGaN/GaN heterostructure topped by a p-GaN layer, p-GaN layer raises the conduction band edge at AlGaN/GaN interface leading to a depletion of the 2DEG channel, which induces a positive V_{th} shift that is necessary for the normally-off operation [1,2]. Moreover, above a certain gate voltage in HEMTs, the p-GaN layer can allow the hole injection from the gate metal to p-GaN/AlGaN interface. Due to electrostatic equilibrium, this results in additional electron in the channel and consequently increasing of drain current. This is called conductivity modulation [1,3]. In AlGaN/GaN Schottky Barrier Diodes (SBDs) based on a HEMT structure described in Fig. 1a), a p-GaN layer can be used to obtain surge current due to the hole injection phenomena. In a study reported by Hsueh et al. [4], a p-GaN layer with a Schottky contact was inserted into SBDs in order to deplete the 2DEG and increase breakdown voltage in reverse operation. In case of Schottky contact, the depletion width in the p-GaN below anode is large and limits hole barrier tunneling at metal/p-GaN interface [5].

In this paper, investigated Hybrid Anode Diode (HAD) device consists of a Mg doped p-GaN layer on an AlGaN/GaN heterostructure on a Si substrate. The p-GaN layer is located at the anode contact side between nitride and anode. A second

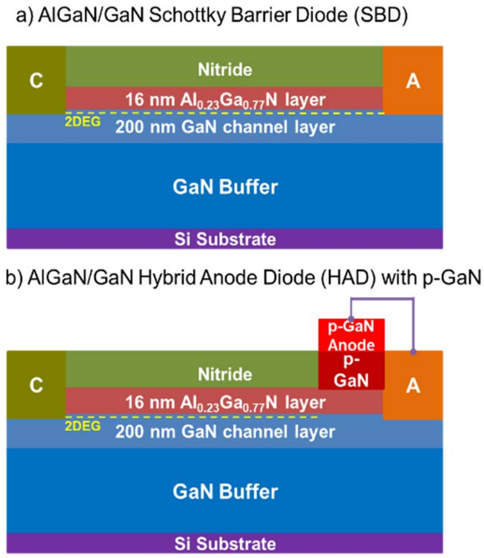

Fig. 1: Device structures used in TCAD simulations for a) a standard AlGaN/GaN Schottky Barrier Diode (SBD) without p-GaN layer and b) an Hybrid Anode Diode (HAD) with a p-GaN layer.

anode metal (p-GaN anode) is added onto p-GaN layer as shown in Fig. 1b). Total diode current is sum of anode and p-GaN anode currents. In order to demonstrate the surge current capability in HADs, we report TCAD simulations that include a tunneling model that explains the role of hole injection on the presence of additional electrons in the channel [6]. In order to achieve surge current capability in SBDs, the improvement of hole barrier tunneling and use of the hole injection can be significant.

In TCAD simulations, the electrical characteristics are simulated solving the Poisson and drift-diffusion equations. Polarization charges are calculated using a piezoelectric strain model with Vurgaftman values [7]. Hole barrier tunneling is considered at p-GaN anode metal/p-GaN interface and is simulated through Non-Local Tunneling Model [6]. In this model, the hole tunneling mass is also set to 0.3 m_0 [5].

II. The Effect of Mg Concentration

Fig. 2 describes the conductivity modulation mechanism in a metal/p-GaN/AlGaN/GaN heterostructure. When applied voltage to p-GaN anode metal (V_A) is higher than a certain value, the hole injection begins from the p-GaN anode metal to p-GaN layer and it increases the accumulated hole density at p-GaN/AlGaN interface, where the 2-dimensional hole gas (2DHG) is formed, as V_A increases. Due to preserving electrostatic equilibrium, additional electrons are accumulated in 2DEG channel through the conductivity modulation mechanism.

Fig. 3 presents drain current as a function of anode voltage and V_{th} as a function of Mg concentration in p-GaN layer. Due to p-GaN layer, 2DEG carriers in the channel are depleted, HAD with p-GaN anode has a lower total diode current than SBD. For low Mg concentrations, increasing of Mg in p-GaN layer depletes more importantly the 2DEG, inducing a V_{th} increase. At high Mg concentrations, p-GaN layer still depletes 2DEG electrons but also allows holes to accumulate at p-GaN/AlGaN interface. V_{th} tends to decrease as Mg concentration increases above $5x10^{17}$ cm^{-3} as can be seen in Fig. 3 b). Due to electrostatic equilibrium illustrated by Fig. 2 [8], the 2DHG thus formed at p-GaN/AlGaN interface induced additional electrons in the channel responsible for V_{th} decreasing. Since low V_{th} or turn-on voltage is desirable for SBDs due to minimize power loss during operation [9, 10], use of high Mg concentration values is necessary in this device concept according to Fig. 3 b). Note that in these simulations, the hole injection from the p-GaN anode metal is limited because TiN metal induces a large depletion width. As can be seen in Fig. 2, if tunneling holes at anode metal/p-GaN interface increase, electron density in the channel can increase via conductivity modulation. To change this interface or increase the hole injection from the p-GaN anode metal, the effect of metal work-function on I-V curve can be examined.

III. The Effect of Metal Work-function

Fig 4 presents effects of p-GaN anode metal work-function considering Mg concentration is kept at $1x10^{19}$ cm^{-3} to ensure lower V_{th}. Fig. 4 a) shows total diode current for various p-GaN anode metal work-functions. Increasing work-function induces an increasing of current by the conductivity modulation. In case of Ideal Ohmic contact, after V_A= +9.0 V increase of total diode current is amplified. In cases of TiN, Ni and Pt metals, in range of V_A, total diode currents are lower than the reference device. As illustrated by Fig. 4 b), this is due to reduction of the depletion width that allows higher hole injection. One thing is interesting that in case of Pt metal, an increase of total diode current is obtained at very high V_A owing to the hole injection since relatively narrow depletion width allows the hole barrier tunneling at metal/p-GaN interface at very high V_A. On the other hand, Fig 4. a)

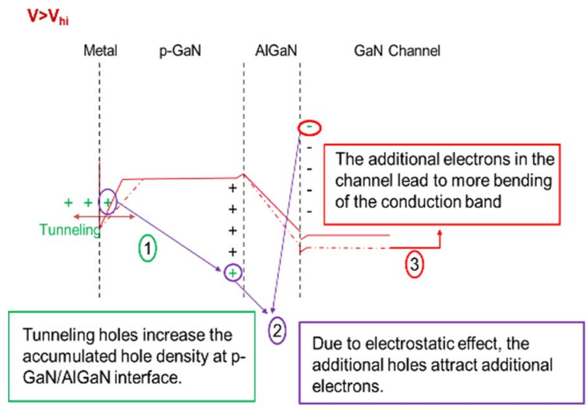

Fig. 2: The conductivity modulation mechanism in a Metal/p-GaN/AlGaN/GaN heterostructure. Hole injection begins when applied voltage to metal/p-GaN is higher than hole injection point (V_{hi}). Injected holes are accumulated at p-GaN/AlGaN interface. Due to electrostatic equilibrium, these holes cause additional electrons in the channel.

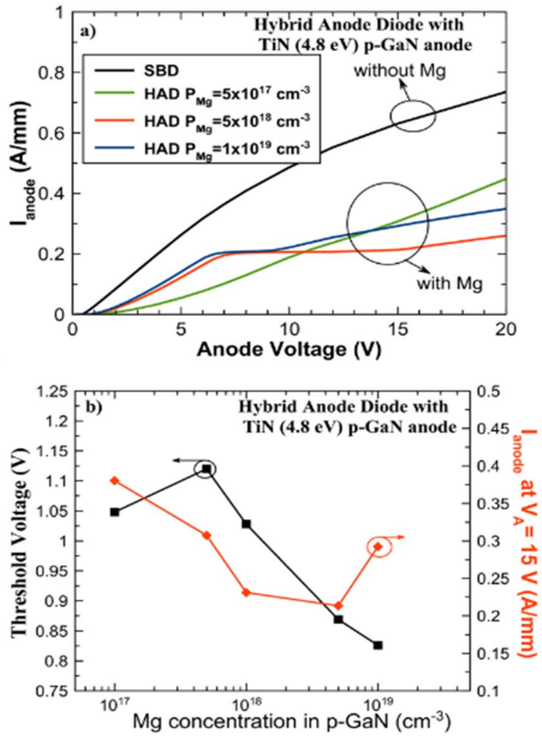

Fig. 3: a) The forward current characteristics and b) the Vth change and maximum anode current at V_A=+15.0 V for different Mg concentrations in p-GaN layer in case of HAD with Schottky p-GaN anode. The Vth is defined as V_A at I_A= 1 mA/mm.

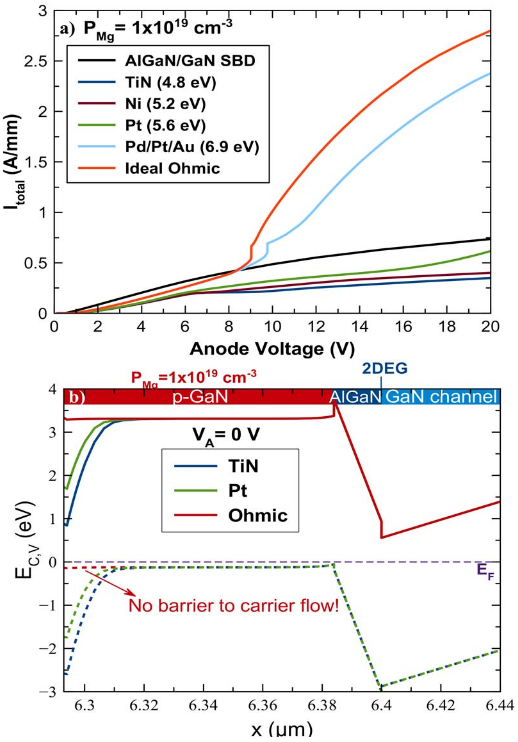

Fig. 4: a) The forward current characteristics for metal work-functions of anode metal on p-GaN and b) the conduction and valence band energy diagrams for several metal work-functions at V_A=0V.

highlights that surge current is possible in case of very high p-GaN anode metal workfunction (close to ohmic contact) owing to no barrier to carrier flow as can be seen in Fig. 4 b).

Fig. 5 a) summarizes total diode currents for investigated devices. If the anode and p-GaN anode metals are TiN, total diode current is lower than standard AlGaN/GaN SBD due to depletion of 2DEG electrons by p-GaN layer. If the anode metal is TiN and p-GaN anode metal is ideal Ohmic, this time total diode current is higher than standard AlGaN/GaN SBD. Moreover, a surge current is obtained due to injected holes that create additional electrons in the channel via the conductivity modulation mechanism described in Fig. 2. Fig.5 b) shows current components, I_{anode} (electron) and I_{pGaN} (hole) for HADs with Ohmic and TiN p-GaN anode. In case of TiN p-GaN anode, total diode current only consists of electron current. In case of Ohmic p-GaN anode, I_{anode} increases as V_A increases. After V_A= +9.0 V, a dramatic increase of I_{anode} is obtained due to the conductivity modulation mechanism. At the same voltage, a hole current (I_{pGaN}) starts to contribute to total diode current since the hole barrier tunneling is dramatically increased. On the other hand, main contribution to total diode current is still I_{anode} at high V_A and it increases as V_A increases.

When electron and hole density cartographies at V_A=15.0 V for each device are compared in Fig. 6 and 7, the conductivity modulation leads to a higher electron density in the channel in case Ohmic p-GaN anode than TiN p-GaN anode case. As V_A increases, the injected hole density from Ohmic anode metal increases and leads to more electrons in the channel due to conductivity modulation effect. On the other hand, surge current capability appears due to an increase in mostly electron current of I_{anode} via conductivity modulation effect and a hole current of I_{pGaN} contributes to the surge current.

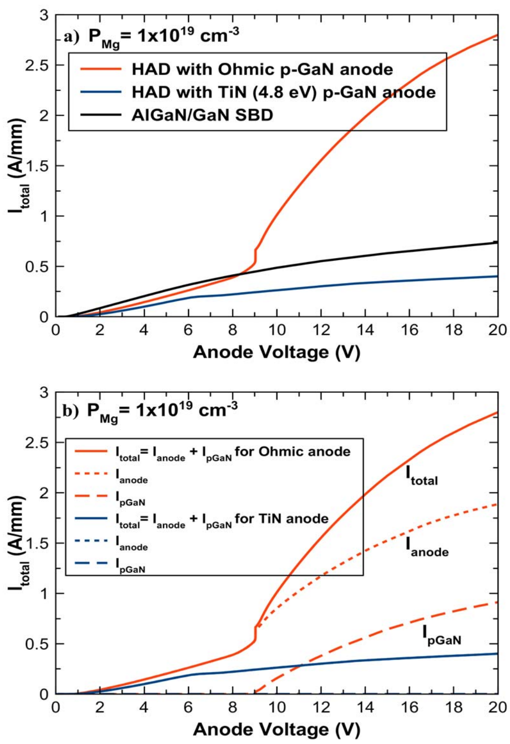

Fig. 5: a) The forward current characteristics for three different type devices and b) a demonstration of current components of HAD with Ohmic and TiN p-GaN anode device.

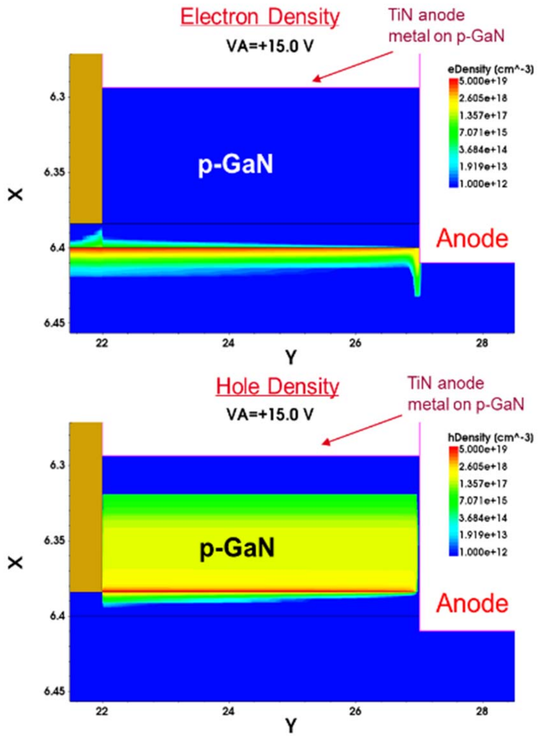

Fig. 6: Electron density and hole density distributions at V_A=15.0 V for HAD with TiN p-GaN anode.

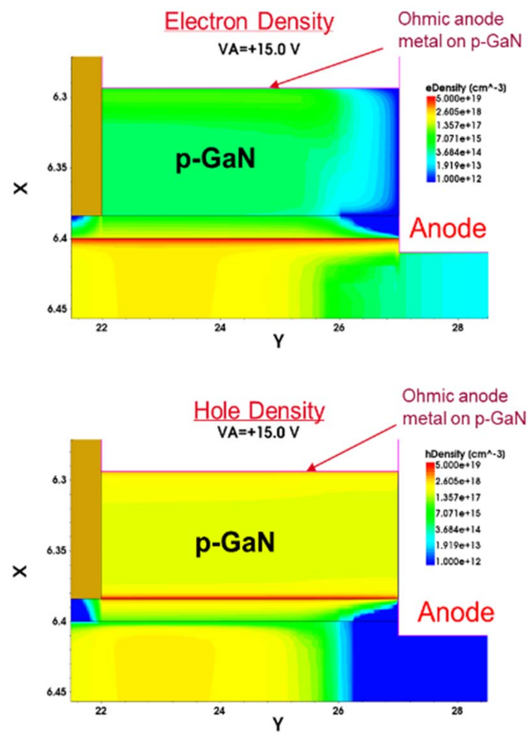

Fig. 7: Electron density and hole density distributions at V_A=15.0 V for HAD with Ohmic p-GaN anode.

IV. Conclusion

In this paper, the forward characteristics of AlGaN/GaN SBDs and HADs with Ohmic and Schottky p-GaN contacts were studied via TCAD simulations in order to demonstrate the surge current capability in lateral power diodes. It was shown that use of high Mg concentrations in p-GaN layer for HADs provides lower turn-on voltage owing to the conductivity modulation which was described for HEMTs. The surge current can occur in case of Ohmic p-GaN contact as the injected holes from anode can lead to create additional electron density in the channel and even holes can create a hole current to support the total diode current. Recently, several studies [11,12] show possible Ohmic contact formation on p-GaN. The findings obtained in our work can pave the way to the use of conductivity modulation to obtain surge current capability in lateral power diodes.

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