IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Polarization doping technology towards high performance GaN-based heterostructure devices

To cite this article: J Wei *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **479** 012052

Polarization doping technology towards high performance GaN-based heterostructure devices

J Wei[1], D F Ouyang, S Y Deng, F Peng, C Yang and X R Luo

School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu, Sichuan, P. R. China

[1] E-mail: weijieuestc@gmail.com

Abstract. GaN-based III-V heterostructure devices are promising candidates in future power electronic, microwave and optoelectronic devices, owing to their superior material properties. The development of polarization doping technology in GaN-based material has attracted extensive interests in the recent years, because it allows the graded AlGaN layers to realize high conductivity n/p type bulk doping without introducing donor/acceptor dopants, which would significantly improve the performances of the GaN-based heterostructure devices. This lecture contains two parts: an overview of polarization doping technology and novel polarization-doped GaN-based electron devices. The review of polarization doping technology mainly focuses on its mechanism in realizing the n/p type doping in graded AlGaN layer without impurity dopants, and its unique carrier characteristics induced by polarization doping. The novel polarization-doped GaN-based power devices include the diodes and field effect transistors, which exhibit better performances than the ones with impurity-doped.

1. Introduction

Wide bandgap gallium nitride (GaN) based heterostructure devices are emerging as promising candidates for power electronic, microwave and photonic devices, owing to their superior material properties, such as high critical electric field, high carrier density and saturation velocity [1-9]. GaN-based devices have attracted lots of interests in the semiconductor community [10-20]. In the abrupt GaN-based heterostructures, the spontaneous polarization and piezoelectric polarization effect play a critical role to form the 2-D electron gas (2DEG) at the interface, owing to the polarization discontinuity. While all the 2DEG is confined in the thin and deep triangular shaped potential well [5]. Without intentional doping, the high density and high mobility 2DEG is the work foundation of GaN-based high-electron-mobility transistors (HEMTs). For GaN-based HEMTs, p-type GaN cap layer is an optional choice to realize enhance mode operation [10]. For light-emitting diodes, high injection of holes is crucial to achieve high luminous efficiency and bright optical emission [17]. However, to form high density of p-type GaN and AlGaN layers is an increasingly troublesome problem since early 1990s, because the activation energy (E_A) of the most commonly used acceptor dopant (Mg) in GaN is about ~200 meV [6-8]. Then the activation ratio of the acceptor dopants is low and the mobility of holes are inevitable deteriorated by the inherent potential barriers in heterostructures and the scattering effect induced by thermally ionized dopants [13]. In order to obtain p-/n-type bulk doped GaN-based heterostructures with high concentration and high mobility, the polarization doping technology is emerged [11-12].

2. Polarization technology

Debdeep Jena et al. firstly presented and experimental realization of the novel concept polarization doping technology, achieving bulk electron doping in graded AlGaN/GaN heterostructures [11]. Figure 1 illustrates the mechanism of polarization technology. For conventional abrupt Ga-face AlGaN/GaN heterostructure as shown in Figure 1(a), positive net polarization charge (σ) is formed at the AlGaN/GaN interface with $\sigma = P_{sp}(\text{AlGaN}) + P_{pz}(\text{AlGaN}) - P_{sp}(\text{GaN})$, wherein the two dimensional electron gas (2DEG) is formed. While positive/negative polarization charge ($N_D^{Pol}(z) = \nabla \cdot P = \partial P(z)/\partial z$) are uniformly formed in the Ga-/N-face graded AlGaN barrier as shown in Figure 1(b) and 1(c), because the polarization field is linear gradient in the graded AlGaN layer. Then three dimensional electron gas (3DEG) and hole gas (3DHG) are formed in the graded AlGaN barrier layer owing to the electric neutrality, respectively. Figure 2 illustrates the energy band diagram and charge profiles of 2DEG and 3DEG, corresponding to the heterostructures in Figure 1(a) and 1(b), respectively. The CV experimental results confirm the formation and distribution of 3DEG in graded AlGaN layer.

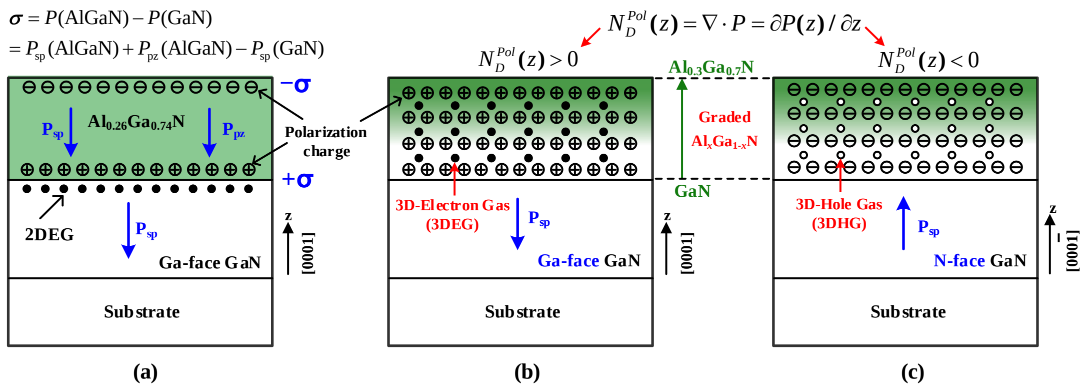


Figure 1. Schematic illustration of formation of (a) 2DEG in conventional abrupt AlGaN/GaN heterostructure, polarization-induced (b) n-type (Ga-face GaN) [11] and (c) p-type (N-face GaN) [12] doping in graded AlGaN/GaN heterostructure.

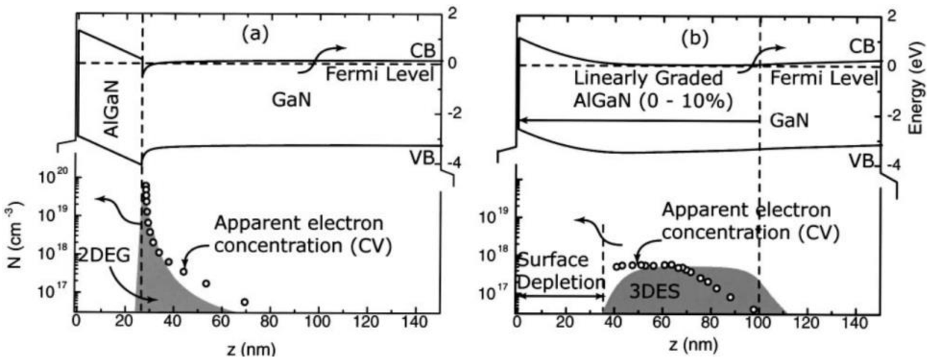


Figure 2. Energy band diagram and charge profiles of 2DEG and 3DEG in the Ga-face abrupt and graded AlGaN/GaN heterostructure [11].

Figure 3 shows the dependences of density and mobility of 2DEG and 3DEG/3DHG on temperature. Since the 2DEG, 3DEG and 3DHG are formed by the polarization effect, the sheet densities of them are almost irrelevant of temperature as shown in Figure 3(b) and 3(d). While the electron/hole density of dopant doped type are extremely lower at lower temperature, because the energy needed to activate the dopant is high and the carrier is freezeout at low temperature. In Figure 3(a) and 3(b), the mobility of 3DEG/3DEH and 2DEG are less depended on the temperature than those of donor/acceptor doped type, especially at lower temperature. Because the 3DEG/3DEH and 2DEG are formed by polarization effect and in absence of scattering of ionized dopant [13].

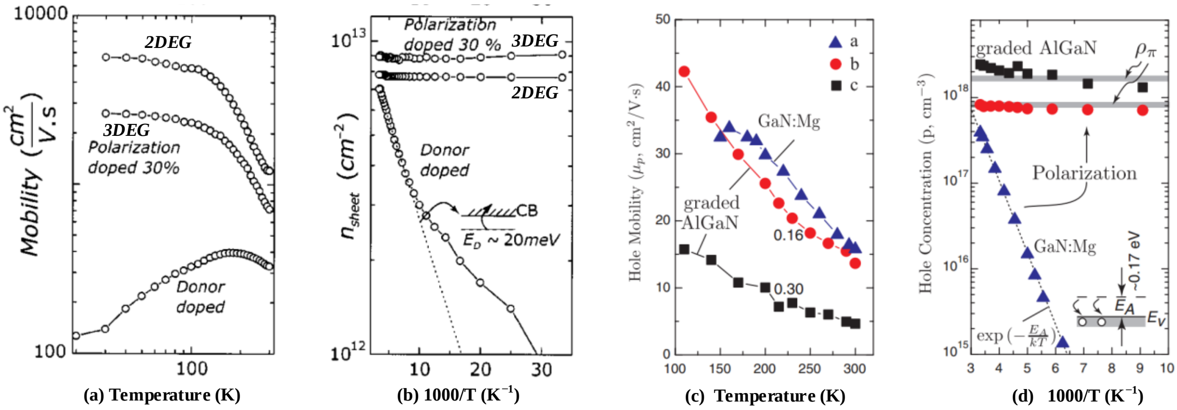


Figure 3. Influences of temperature on mobility and concentration. (a) and (b) for 2DEG and 3DEG [11], (c) and (d) for Mg-doped and 3DHG [12].

Based on the polarization doping technology, a back-to-back graded AlGaN barrier layer to form high density N-type and P-type doped region is proposed on Ga-face AlGaN/GaN heterostructure [14], as illustrated in Figure 4. The formed 3DEG and 3DHG are located in the positive and negative graded AlGaN barrier layer respectively, due to the inversion of polarization direction.

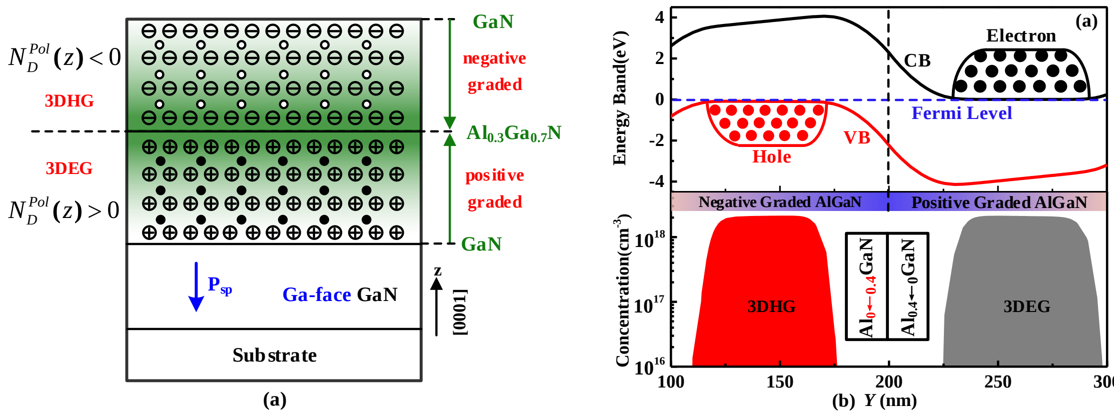


Figure 4. (a) Schematic illustration of back-to-back graded AlGaN barrier layer in Ga-face AlGaN/GaN heterostructure [14]. (b) Energy band diagram and charge distribution of the new method to form N-/P-type doped region.

Therefore, the polarization doping technology provides a new insight to realize N-/P-type doping, which widens the applications of GaN heterostructure materials.

3. Novel devices based on polarization technology

Based on the polarization doping technology, several novel device structures have been proposed for diverse applications in recent years, including microwave power applications, deep ultraviolet LEDs, GaN power transistors and so on. Owing to the polarization doping without introducing the donor or acceptor dopants, the performances of these novel devices have been significantly improved. In the following section, we will give a brief description of these typical novel devices.

3.1. AlGaN/GaN polarization-doped metal-semiconductor field-effect transistor (MESFET)

The polarization-doped FET (PolFET) proposed by *Siddharth Rajan et al.* is shown in Figure 5(a), while Figure 5(b) is a conventional impurity doped MESFET for comparison [15]. Both devices have the same buffer layer, which consists of 0.7 um Fe-doped GaN, followed by 50 nm AlN and 1.7 um unintentionally doped (UID) GaN. For the novel PolFET, it is followed by a 100nm channel consisting of GaN linearly graded to $Al_{0.3}Ga_{0.7}N$. In the case of the MESFET, the channel consists of 100 nm of Si doped GaN.

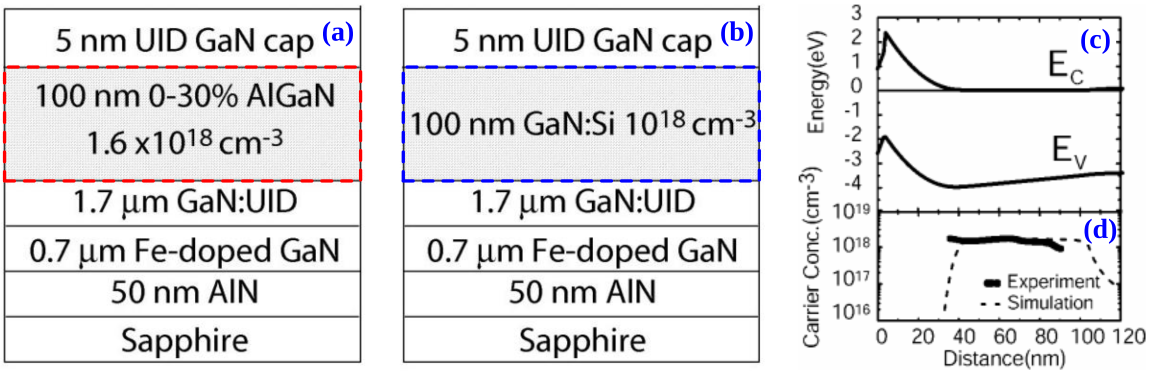


Figure 5. Epitaxial structure of the (a) novel PolFET, (b) conventional MESFET, (c) Zero bias band diagram of the PolFET and (d) Carrier concentration profiles from experiment (*CV* measurements) and simulations.

The calculated energy band diagram of the PolFET structure at zero bias is shown in Figure 5(c). The carrier profile from *CV* measurements agrees well with the simulated profile, as shown in Figure 5(d). An average charge of 1.6×10^{18} cm^{-3} was measured for a linear grade up to 30% AlGaN over 100 nm. The electron mobility for the PolFET was measured to be 826 cm^2/V s while only 284 cm^2/V s for the conventional MESFET. As expected, the mobility in the PolFET is higher than the impurity-doped MESFET, because the electron carrier is free from the ionized dopant scattering effect in the polarization doped PolFET.

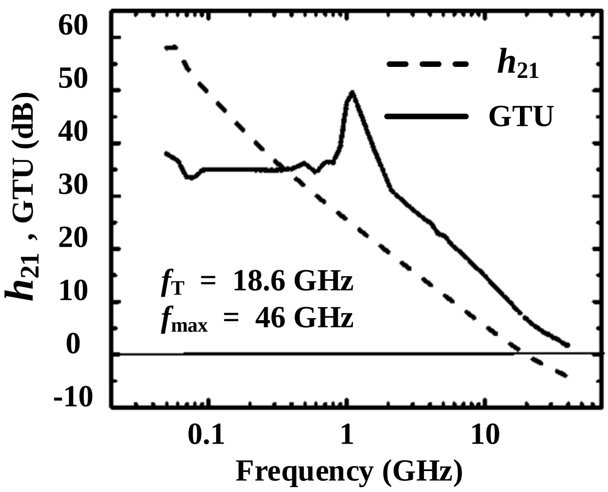


Figure 6. Unilateral power gain (GTU) and current gain (h_{21}) from small signal measurements of the PolFET. The device was biased at V_{DS} = 15 V and I_{DS} = 100mA/mm.

Meanwhile, high frequency small-signal characterization of the devices from 50 MHz to 40 GHz was carried out, and the current gain (h_{21}) and the unilateral power gain (*GTU*) were calculated from the measured *s* parameters of the device. Figure 6 shows the h_{21} and *GTU* as a function of the input signal frequency. The measured f_T and f_{max} values of the PolFET were 18.6 GHz and 46 GHz, respectively. Therefore, the PolFET is very promising for high-frequency and high power applications. Similar structure and characteristics were presented in [16].

IOP Conf. Series: Materials Science and Engineering 479 (2019) 012052 doi:10.1088/1757-899X/479/1/012052

3.2. *Polarization-induced pn diodes*

By polarization doping technology without impurity-doping, *Santino D. Carnevale et al.* developed a fundamentally new type of pn junction by grading the composition of a semiconductor nanowire resulting in alternating P and N type conducting regions [17]. By linearly grading AlGaN nanowires from 0% to 100% and back to 0% Al component, a polarization-induced pn junction was successfully formed even in the absence of any impurity doping, as illustrated in Figure 7. Since electrons and holes are injected from AlN barriers into quantum disk active regions, graded nanowires allow deep ultraviolet LEDs across the AlGaN band-gap range with electroluminescence observed from 3.4 to 5 eV. Polarization-induced p-type conductivity in nanowires is shown to be possible even without supplemental acceptor doping, demonstrating the advantage of polarization engineering in nanowires compared with planar films and providing a new strategy for improving conductivity in wide-band-gap semiconductors.

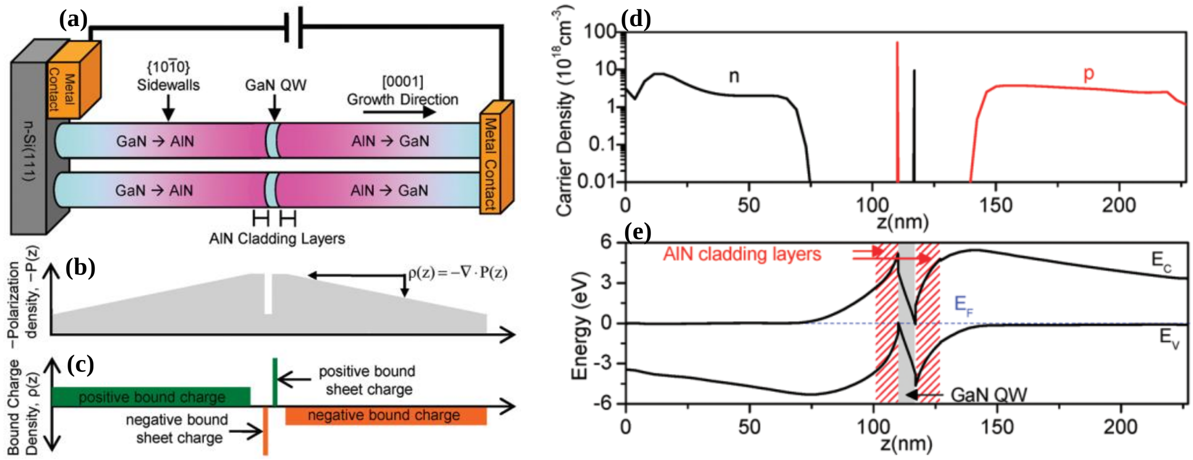
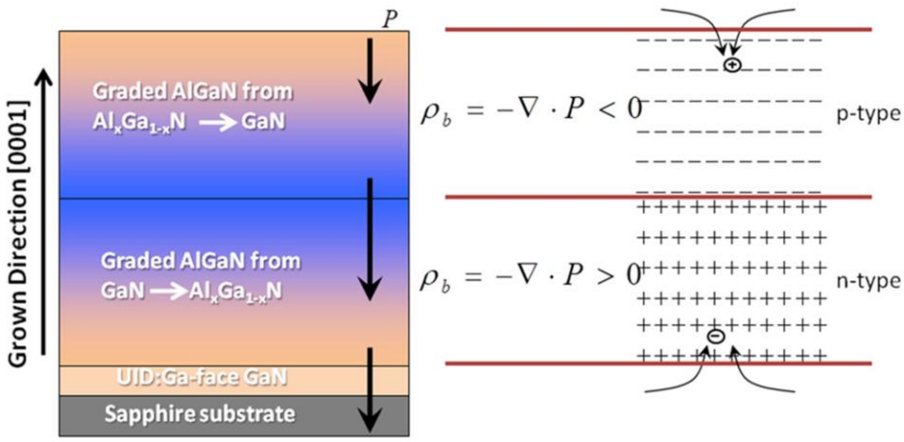


Figure 7. Polarization-induced pn junction formed in a semiconductor nanowire. (a) Schematic of nanowire device structure, (b) Polarization density as a function of nanowire length (*z*), (c) Positive and negative bound charge due to compositional grading, (d) Modelled carrier density and (e) Conduction and valence band edge energy along the length of nanowire.



(a) **(b)**

Figure 8. Schematic of polarization-induced n-/p-type doping in graded AlGaN pn-junction. (a) Structure of graded AlGaN pn-junction on Ga-face template, (b) polarization charge field induced by grading AlGaN on GaN.

As shown in Figure 8, without impurity-doping, *Shibin Li et al.* also proposed a novel type of pn-junction by grading the Al composition in an $Al_xGa_{1-x}N$ thin film, ultimately resulting in alternating P and N conducting regions due to polarization charges [14].

Figure 9 illustrates the current-voltage measurement for different devices. The breakdown voltage of polarization doped AlGaN pn-junction reaches 34.1V as high as that of regular doped GaN pn-junction, much higher than 4V of Schottky diode.

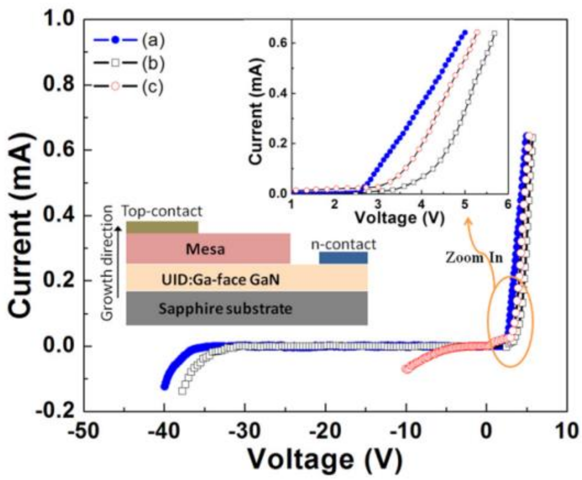


Figure 9. Current-voltage measurement for (a) regular doped GaN pn junction, (b) graded $Al_{0.1}Ga_{0.9}N$ pn junction, and (c) Schottky diode. The mesa region is Si and Mg doped GaN pn junction for device (a), graded $Al_{0.1}Ga_{0.9}N$ pn junction for device (b), and undoped GaN film for device (c).

3.3. GaN lateral polarization-doped super-junction (LPSJ) concept and corresponding enhancement-mode Heterostructure Field Effect Transistor (HFET)

In order to approach the unipolar limit of breakdown voltage and on resistance of GaN material, GaN superjunction was proposed. Due to the high activation energy of Mg in GaN, the regular Mg doping to form P type pillar in SJ still remains challenge [18]. While the natural super junction, formed by the 2-dimension electron gas (2DEG) and 2-dimension hole gas (2DHG), has a high electric field crowding problem due to the high sheet charge at the interfaces of GaN/AlGaN/GaN [19]. *Bo Song et al.* proposed a GaN lateral polarization-doped super-junction (LPSJ) as shown in Figure 10 [20]. The new structure properly avoids the problems mentioned above, because the n/p pillar regions are realized by compositionally grading AlGaN, where the electron and hole concentration are uniform and balanced in the n/p pillar regions.

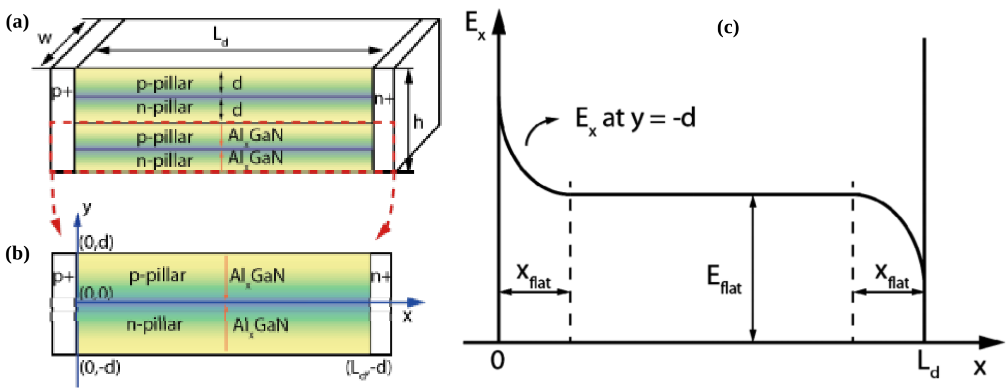


Figure 10. (a) Schematic view of the LPSJ structure, (b) the unit cell of LPSJ, (c) the electric field distribution along the x direction at $y = -d$ in a LPSJ showing the peak field E_{max} occurs at x=0.

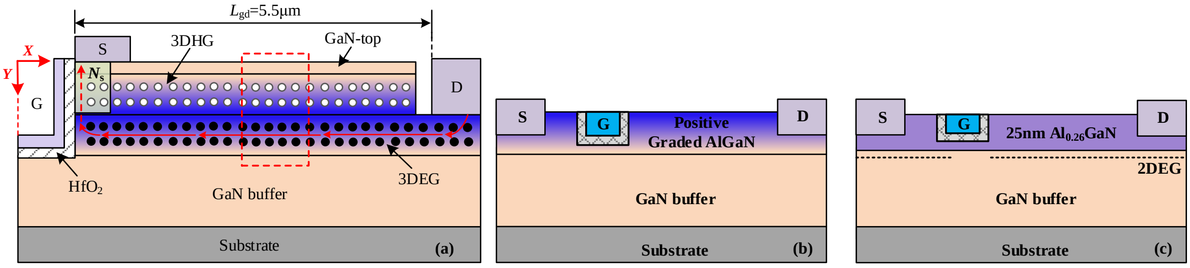


Figure 11. Schematic cross section of the (a) novel 3DHG enhancement-mode HFET with back-to-back graded AlGaN (named BGA HFET), (b) positive graded AlGaN HFET (named PolFET [16]) and (c) conventional HFET.

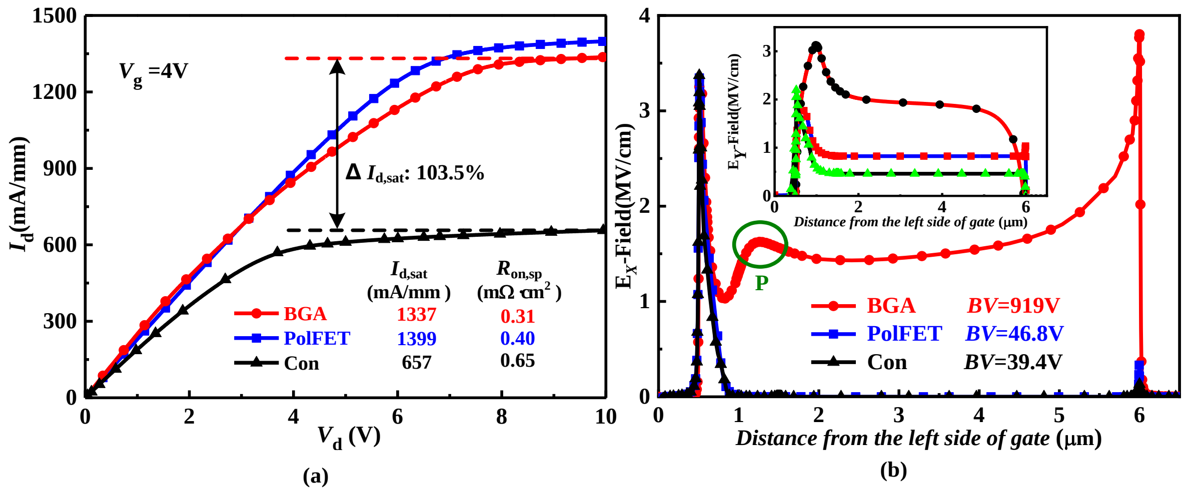


Figure 12. (a) *I-V* characteristics curves at V_g=4V, (b) E_X and E_Y distributions of the three devices at breakdown.

Based on GaN LPSJ concept, *Fu Peng et al.* proposed a novel 3DHG enhancement-mode HFET with back-to-back graded AlGaN, as shown in Figure 11 [21]. First, the on-state current of the new device is significantly improved owing to the high-density 3DEG in the positive-graded AlGaN and the absent scattering effect of ionized impurity dopant, as shown in Figure 12(a). Next, the vertical conductive channel between the source and 3DEG is blocked by the 3DHG, thereby realizing the enhancement-mode operation. Meanwhile, owing to the use of super-junction concept, a much higher breakdown voltage of 919 V is obtained compared to the breakdown voltage of 39 V for the conventional HFET with the same gate to drain spacing. The corresponding electric field distribution is given in Figure 12(b).

4. Conclusions

In this paper, we give an overview of the polarization doping technology and several novel polarization-doped GaN-based devices. In addition, we briefly present the design and characteristics of the novel devices based on graded AlGaN/GaN heterostructures. Without introducing the donor or acceptor dopants, the polarization doping technology improves the performances of these novel devices significantly, which make it promising in the applications for deep ultraviolet LEDs, microwave power applications, GaN power transistors and so on.

References

[1] U K Mishra, P Parikh and Y-F Wu 2002 *Proc. IEEE* **90** pp. 1022
[2] S Nakamura, T Mukai and M Senoh 1991 *Jpn. J. Appl. Phys.* **30** pp. L1998
[3] T Zimmermann *et al*. 2006 *IEEE Electron Device Lett.* **27** pp. 309

[4] O Ambacher *et al.* 1999 *J. Appl. Phys.* **85** pp. 3222–3233
[5] A S Augustine Fletcher, D Nirmal 2017 *Superlattices and Microstructures* **109** pp. 519
[6] P Kozodoy *et al.* 2000 *J. Appl. Phys.* **87** pp. 1832
[7] W Götz, N M Johnson, J Walker, D P Bour, R A Street 1996 *Appl. Phys. Lett.* **68** pp. 667
[8] C J Eiting, P A Grudowski, R D Dupuis 1997 *Electron. Lett*. **33** pp. 1987
[9] Y Taniyasu, M Kasu, T Makimoto 2006 *Nature* **441** pp. 325
[10] O Hilt, A Kanuer, F Brunner *et al.* 2010 in *Proc. ISPSD* pp. 347
[11] D Jena, S Heikman, D Green, D Buttari, R Coffie, H Xing, S Keller, S DenBaars, J Speck, U K. Mishra and I P Smorchkova 2002 *Appl. Phys. Lett.* **81** pp. 4395
[12] J Simon, V Protasenko, C Lian, H Xing and D Jena 2010 *Science* **327** pp. 60
[13] J Simon, A K Wang, H Xing, S Rajan, D Jena 2006 *Appl. Phys. Lett*. **88** pp. 042109
[14] Shibin Li, Morgan Ware, Jiang Wu, Paul Minor, Zhiming Wang, ZHiming Wu, Yadong Jiang, and Gregory J Salamo 2012 *Appl. Phys. Lett.* 101, pp. 122103
[15] Siddharth Rajan, Huili Xing, Steve DenBaars, Umesh K Mishra and Debdeep Jena 2006 *Appl. Phys. Lett.* **84**
[16] Yulong Fang, Zhihong Feng, Jiayun Yin, Xingye Zhou, Yuangang Wang, Xubo Song, Yuanjie Lv, Chengming Li and Shujun Cai 2014 *IEEE Trans. Electron Devices* **61** pp. 4084
[17] Santino D Carnevale, Thomas F Kent, Patrick J Phillips, Michael J Mills, Siddharth Rajan and Roberto C Myers 2012 *Nano Letters* **12** pp. 915
[18] Z Li and T P Chow 2013 *IEEE Trans. Electron Devices* **60** pp. 3230
[19] H Ishida, D Shibata, H Matsuo, M Yanagihara, Y Uemoto, T Ueda, T Tanaka and D Ueda 2008 in *Proc. IEDM*
[20] Bo Song, Mingda Zhu, Zongyang Hu, Kazuki Nomoto, Debdeep Jena and Huili Xing 2015 in *Proc. ISPSD* pp. 273
[21] Peng Fu, Yang Chao, Deng Siyu, OuYang Dongfa, Zhang Bo, Wei Jie and Xiaorong Luo 2018, *SCIENCE CHINA Information Sciences*.