D-3-01 (Invited) Extended Abstracts of the 2021 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2021, pp213-214

Progress in CMOS Integration in Wide-bandgap Electronics

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Abstract

This talk will review recent progress in Gallium Nitride p-channel devices, and the potential for their integration to enable CMOS style architecture within the wide-bandgap world.

1. Introduction

As GaN High Electron Mobility Transistors (HEMTs) have achieved footholds across numerous industries, recent research efforts have turned to tightening the integration of HEMTs into increasingly complex systems. Given the difficulty in leveraging fast-switching but discrete HEMTs from parasitic-heavy designs, the move to GaN integrated chips (ICs), with monolithic gate driver/control circuitry, can lead to simpler, more performant and more robust systems [1], [2].

In the context of such wide-bandgap ICs, a complementary design (ie CMOS-style) could allow for simple, energy-efficient topologies, if only p-channel transistors were available [3]. Accordingly, recent years have seen an explosion of attempts at developing a p-channel complement suitable to GaN HEMTs (either within the III-Nitrides, or even incorporating other material systems such as Diamond [4], [5]). This talk will report on recent progress in p-HFETs in various III-Nitride junctions (with emphasis on GaN/AlN) and highlight work towards integrated GaN CMOS (emphasizing the more studied GaN/AlGaN/GaN heterostructure).

2. Ternary/Quaternary P-channel Devices

Achievements in various platforms in terms of on-current and modulation ratio are benchmarked in Fig 1, with the structures overviewed in Fig 2. Among III-Nitrides, the least investigated platform is InGaN/GaN [6], with only sub-mA/mm currents to date. However it remains to be seen whether this platform, with further investment in scaling and contacts, could match the others or whether there are fundamental limitations from the alloy channel. Conversely, the most investigated devices are the GaN/AlGaN/GaN structures [7]–[10], which have mixed mobilities and moderate tunable densities. This platform has demonstrated E-mode devices and inverter operation. Suggestively, these junctions appear naturally in p-GaN gated HEMTs [9]. Perhaps one of the most interesting side-benefits is the synergy of the 2DHG and 2DEG to form polarization superjunctions to enhance their breakdown voltages [2]. These can also be studied in both polarities and stacked into superlattice layers to achieve the highest integrated hole densities available at high mobility if engineered carefully [11], [12]. Next, the most precise demonstrations are the GaN/AlInGaN/GaN structures, which have achieved the cleanest modulation at many mA/mm current densities. These quaternary, lattice-matched structures have the highest hole mobilities reported yet for the III-Nitrides [13], [14].

3. Binary (GaN/AlN) P-channel Devices

The GaN/AlN heterostructure is the simplest platform from which to study the two-dimensional hole gas (2DHG) in isolation, because it contains only one relevant interface, all binary materials, and no regions for parasitic (and more mobile) electrons to interfere with precise physical measurements. First evaluated by Li [15] at Notre Dame, advances in growth at Cornell have achieved hole gases of 4-5x10^{13}/cm^2 with mobilities around 20 cm^2/V·s, for the lowest single-junction p-sheet resistances in the III-Nitrides [16], which were used to make E-mode devices in 2018 [17]. Researchers have recently demonstrated that adding a p-InGaN cap layer allows for excellent contacts to the highly-conductive gas on the order of ~5 Ω·mm, and based on this structure, two generations of Schottky gated devices have been designed [18], [19]. As shown in Fig 2(f), these devices combine InGaN contact regions containing high hole density with a recessed gate region where the density is small enough to be modulated. While the low on/off ratio of only two orders of magnitude suggests further work is needed to improve the gate control, the most scaled devices (Lg/Lsd=120 nm/ 680 nm) demonstrate on-currents exceeding 400 mA/mm, and f_T/f_{MAX} ~ 20 GHz, a testament to the highly conductive 2DHG and its performant InGaN contacts. Together with the lower-current/higher-modulation E-mode devices achieved earlier [17], these high-current devices sweep out a curve of possibilities, indicating that there is significant room to enhance p-channel performance. Toward that end, the platform has also appeared in computational studies [20] exploring mobility-enhancing strains to elevate performance nearer to the order of magnitude seen in HEMTs, and work continues toward elusive integration with AlN/GaN/AlN-based n-channel devices [21].

4. Integration & Conclusion

Fully-wide-bandgap CMOS inverters have been demonstrated in both the GaN/AlGaN/GaN and GaN/AlInGaN/GaN structures by various means, as shown in Figure 2(a/c/d/g/h). Methods include both (1) selective regrowth as well as (2) etch-differentiated structures, each method facing its own constraints. Ultimately, no authors expect the mobility-limited p-channel devices to reach anywhere near parity with n-channel HEMTs, but the present aim is to have a complementary logic sufficient for basic low-power-overhead integrated control and high-speed driving. The potential performance of p-channel devices has long been a pessimistic unknown for GaN power ICs, but, as diverse demonstrations in this field compete and continue to advance rapidly, authors may soon be able to quantify which applications may be transformed.

Acknowledgements

This work is based on research conducted at Cornell University, supported by Intel Corporation, by the Air Force Office of Scientific Research under Grant FA9550-17-1-0048, by Semiconductor Research Corporation (SRC) and DARPA through JUMP ComSenter, and by the NSF under Grant 1710298 and Grant 1534303, and was performed in part at the Cornell Nanoscale Facility, an NNCI member supported by the NSF under Grant NNCI-1542081.

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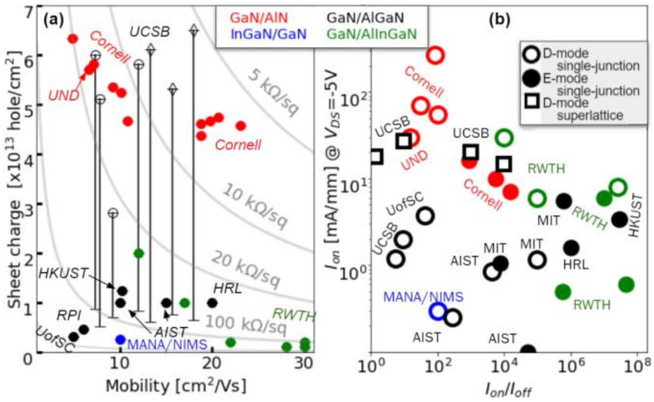

Fig 1. (a) Sheet charge vs mobility reported on heterojunctions [filled shapes] and superlattices [vertical lines linking charge-per-channel at bottom to total-charge at top]. (b) On-current versus modulation ratio for p-HFET demonstrations. Updated from [3].

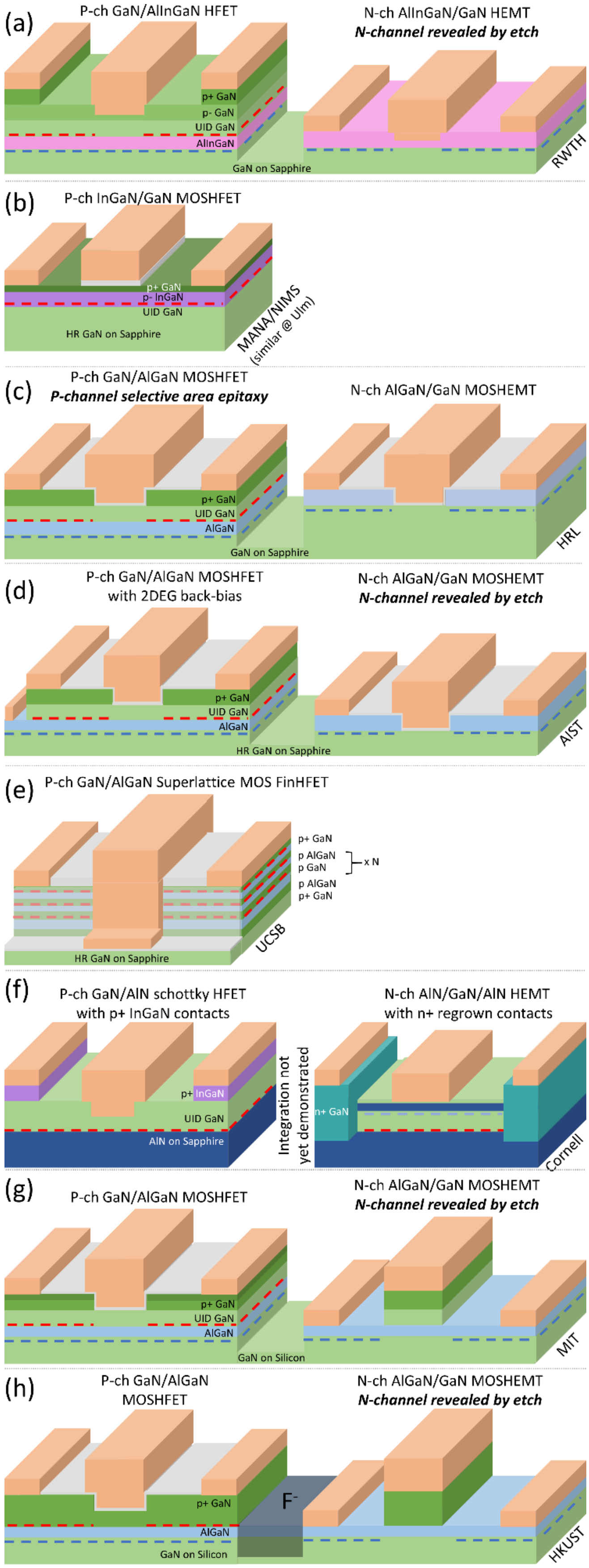

Fig 2. A diverse zoology of GaN 2DHG-based p-channel devices and complementary inverter integration schemes.