# Upgrading Emode GaNFET for Better Reliability and Compatibility

## 1. DMODE and EMODE GaNFET

Depletion mode gallium nitride field effect transistors (DMODE GaNFET) has the longest history and started its journey of commercial application from the early 2010's. The basic structure of a cascode DMODE GaNFET is as indicated in Figure 1. The two-dimensional electron gas (2DEG) sandwiched between the GaN and AlGaN were formed right after the EPI layers are formed from MOCVD. A Schottky contact is formed on the top of the AlGaN which does not alter the conduction state of the 2DEG unless a negative voltage is applied to the Schottky contact. Commercial application require a normally-off low voltage MOSFET be put in series (cascode) to turn the DMODE GaNFET off (see Figure 1). The conduction state is always there making the GaNFET very reliable if cascoded MOSFET is. At this stage of technology, low voltage vertical MOSFET is already very mature and reliable, therefore, DMODE GaNFET has been famous for its better reliability than its EMODE counterpart. Another advantage of Cascoded DMODE is the LV MOSFET has higher Vgth (turn-on threshold voltage of about 4V), which is common and compatible for conventional MOSFET circuits. Because of the above advantages, DMODE GaNFET achieved commercial success in the early 2010's.

The dominance of DMODE GaNFET in commercialization lasted some years before EMODE (enhancement mode) caught up in recent years. Structure of EMODE is shown in Figure 2 and it has the advantage of more simple to fabricate (no need for LV MOSFET cascode) and better switching performance since it does not rely on MOSFET which is a slower device. However, an uncomfortable shortcoming is the p-GaN gate turns on the device at around Vgth=1.4V, a value considered too low for many system designers who value a high turn-on voltage as a safety protection, that is any noisy fluctuation in driving voltage shall not turn on the device by mistake leading to damage or system failure. Another uncomfortable aspect is the driving range is relatively low (6V versus previous 12V or 15V) this is not compatible with existing MOSFET or SiC circuit which uses 12V or 15V as driving voltages.

Another shortcoming of EMODE is its gate reliability: the 2DEG channel is interrupted by a small piece of p-GaN above the AlGaN layer. A high current EMODE device consists of multiple fingers of SGD arranged in parallel circuits. Or in another word, a EMODE GaNFET consists of tens or hundreds of smaller EMODE GaNFET. If any part of the p-GaN is defective due to mechanical or thermal stress, one smaller GaNFET starts to leak current even when Vg is below the nominal Vgth=1.4. Such kind of failure reveals itself as Vgth down shift in reliability tests.

The gate reliability due to low Vgth and gate driving range being small has become a major road block for applications requiring high reliability.

## 2. All-GaN-IC Solution

GaNPower International Inc. (www.iganpower.com) invented an all-GaN-IC method (Figure 3, patents pending) that increases the Vgth from 1.4 to 3.5 to 4.0 (Figures 4(a) and 4(b)). Furthermore using a previously disclosed method [1], the input driving voltage range has been increased to up to 20V, using an integrated regulator circuit. When packaged in a TO247-4, this upgraded EMODE GaN has similar pin-out, driving voltage and Vgth than a SiC MOSFET. This new technology is given a nickname pin-to-pin (p2p) for its compatibility with SiC MOSFET and SJ MOSFET.

While the detailed methods are not yet disclosed due to pending patent applications, one can imagine the achievement of higher Vgth is through some form of multiple GaNFET integrated in series, so that one FET turn-on depends on another. If the p-GaN gate of one FET are over stressed and experiences a Vgth down shift, the p-GaN gates in other FETs are still intact. The Vgth may still experience a down shift but the 4V Vgth is still high enough to the power switch from erroneous turn-on. As a result, the gate reliability of power switch is enhanced and can match that for DMODE cascode.

## 3. Good switching performance

One may recall that DMODE cascoded with normally-off MOSFET is also some form of multiple FET forming a circuit copackaged within a single power device unit. It is well known that DMODE cascode degrades the switching performance substantially. The question is then why the new regulator integrated circuit is more advantageous than the MOSFET+DMODE combination? The answer is that the p2p design is all-GaN technology and therefore maintains the high speed and high performance. Monolithic integration makes the FET interaction seamless and avoids the parasitics common in co-packages.

Another advantage of the regulator is that it is immune to gate driving loop ringing noise since noisy ringing  peaks are regulated down to 6V as indicated in Figure 4(b).

To confirm the good switching performance, a 900V/30A rated GaNFET monolithically integrated with regulator went through double pulse testing (DPT).   As indicated in Figure 5,

DPT (with dynamic Ron measurement) at 125C showed good waveforms  at Vbus=900V, 500KHz even for a conventional TO package.

To demonstrate its power switching performance, a Buck convertor power stage was constructed (Figure 6).  As indicated in Figure 7, a peak efficiency of 97% and maximum power output of 3.7kW were obtained.

In conclusion, monolithic integration capability of lateral EMODE GaNFET offers opportunity for  improving the reliability of EMODE GaNFET and GaNPower's  p2p technology makes the power device more compatible with circuits design for SiC.

[1] US 10,686,411 B2, Li et al., "Gate drivers and voltage regulators for gallium nitride devices and integrated circuits."

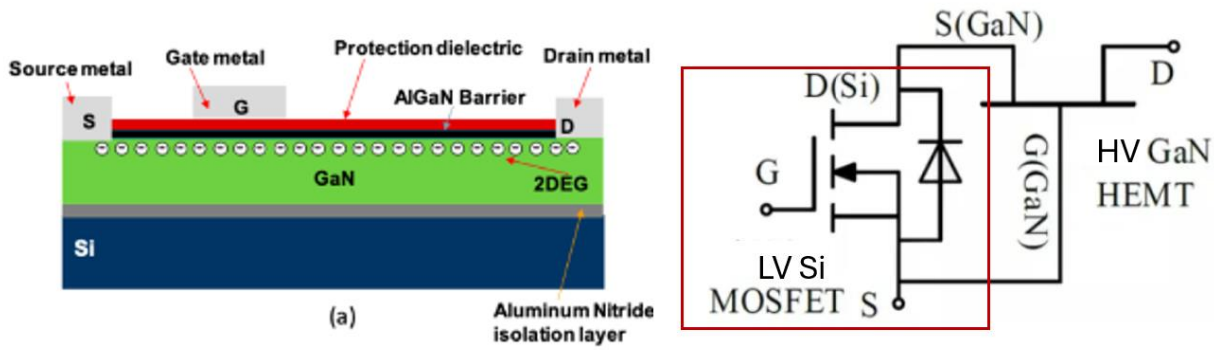



Figure 1 The natural state of GaN 2DEG is normally-on which is not suitable

for application as power switches. To make it normally-off, additional silicon MOSFET or related circuits must be co-packaged with normally-on GaNFET (cascode).

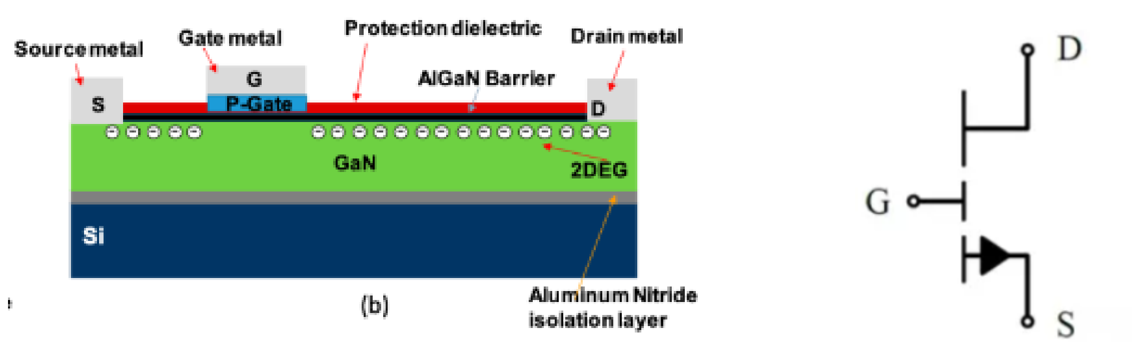



Figure 2. Structure of EMODE GaN HEMT.

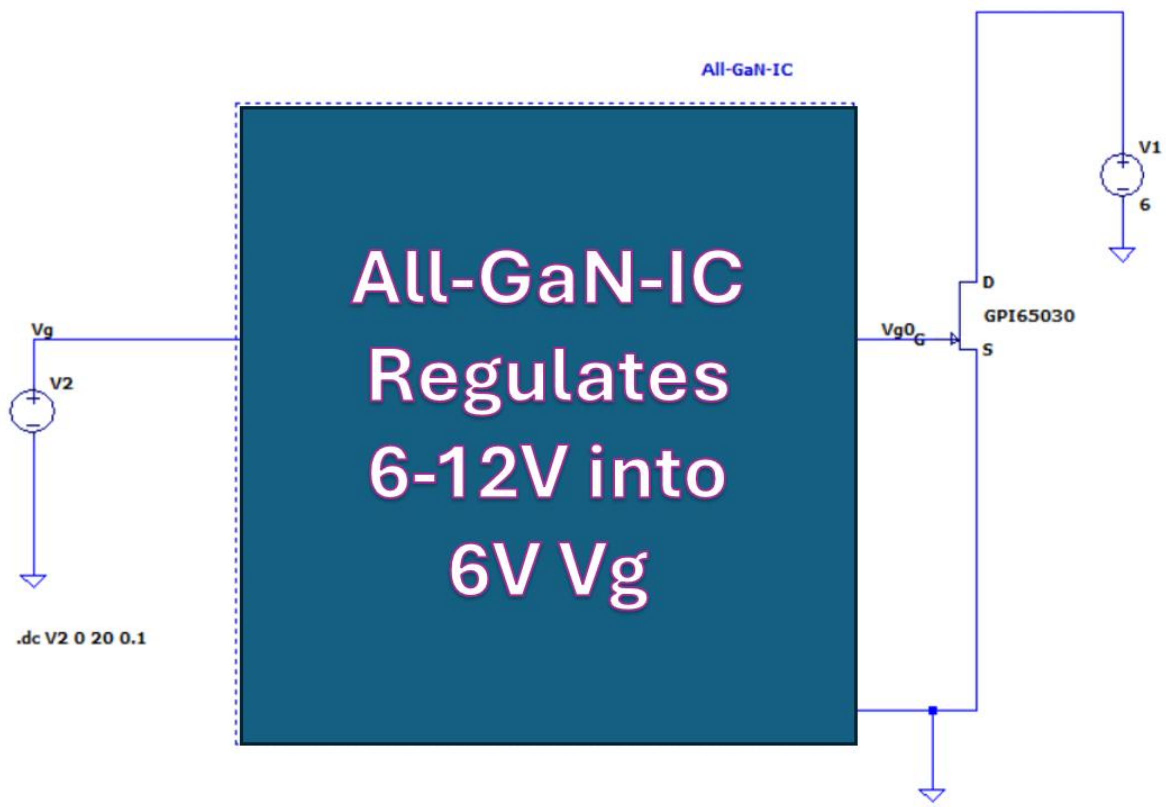
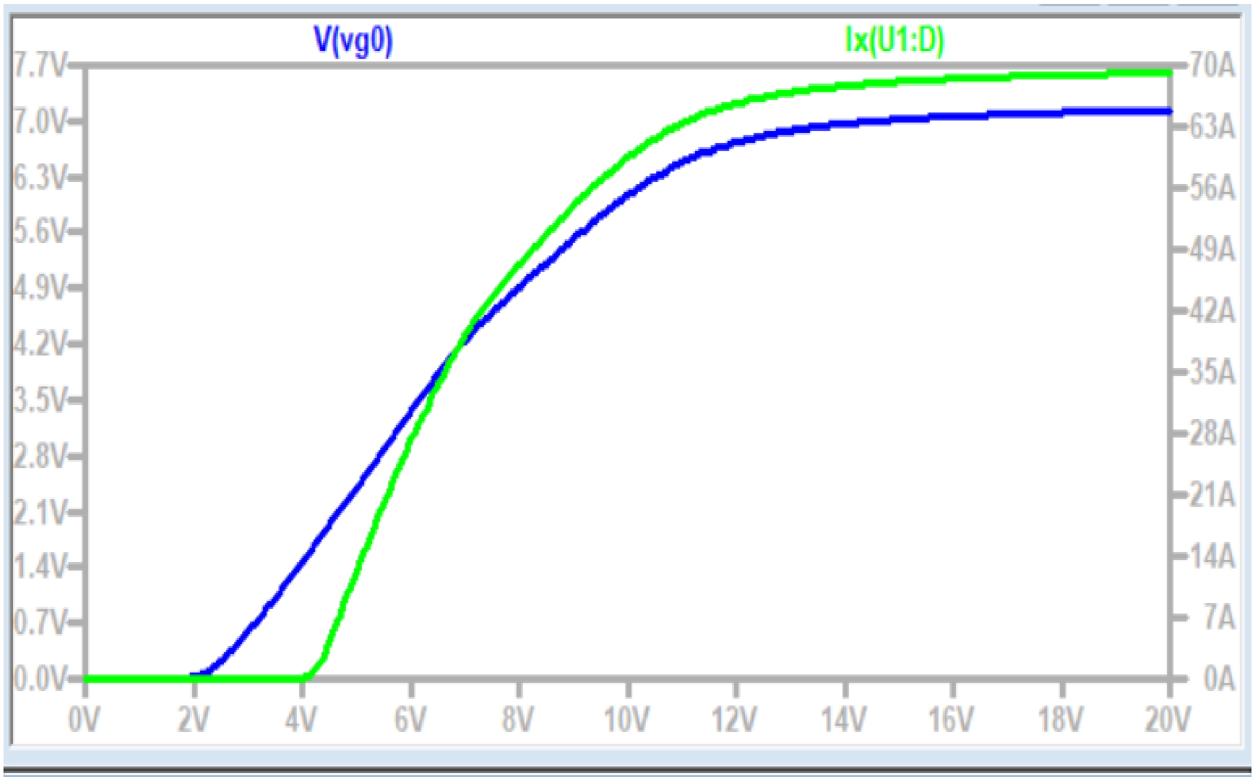



Figure 3. Block diagram of a gate regulator circuit monolithically integrated with a main EMODE GaNFET


V(vg0)
Ix(U1:D)
7.7V
7.0V
6.3V
5.6V
4.9V
4.2V
3.5V
2.8V
2.1V
1.4V
0.7V
0.0V
70A
63A
56A
49A
42A
35A
28A
21A
14A
7A
0A
0V
2V
4V
6V
8V
10V
12V
14V
16V
18V
20V

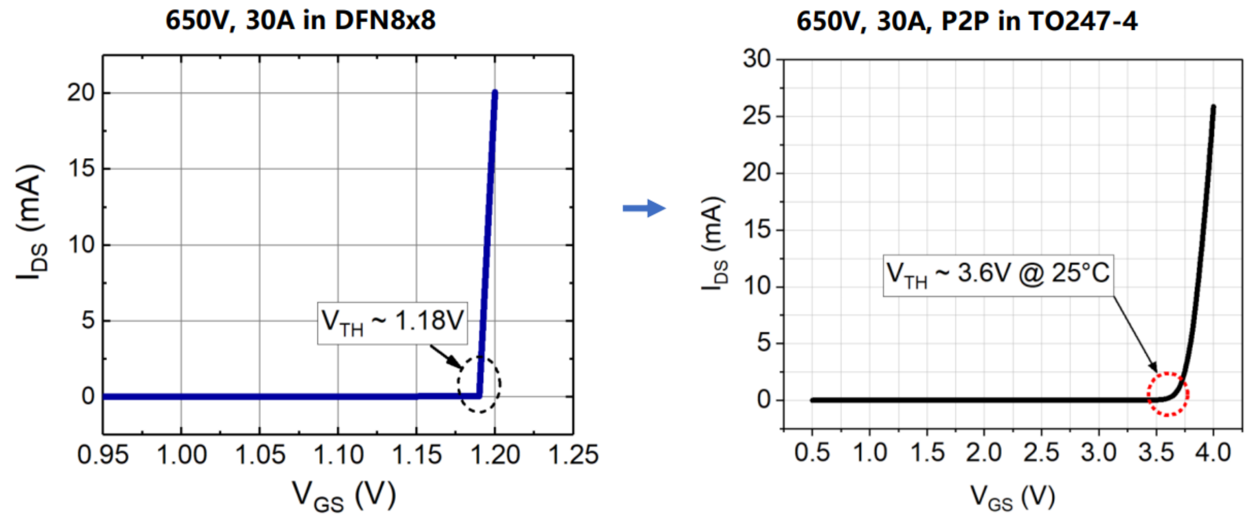



Figure 4.  Simulated (a) input bias, original gate bias and GaNFET drain current, as well as measurement (b).

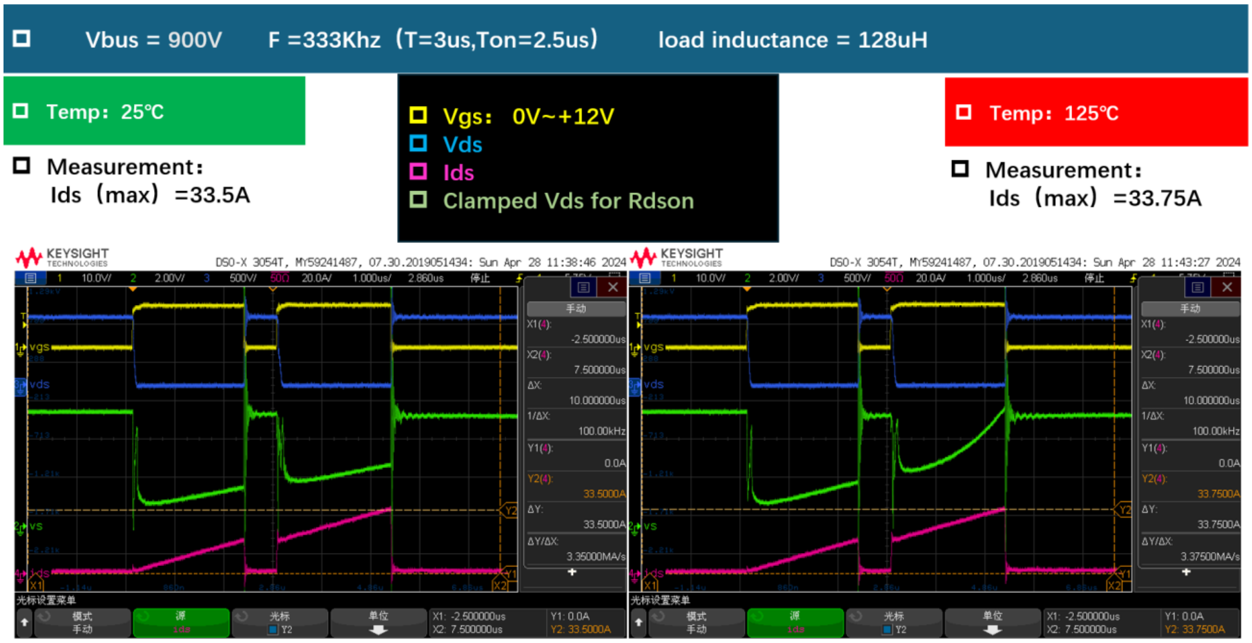



Figure 5. Experimental waveforms showing good switching performance at 125C and 900V.

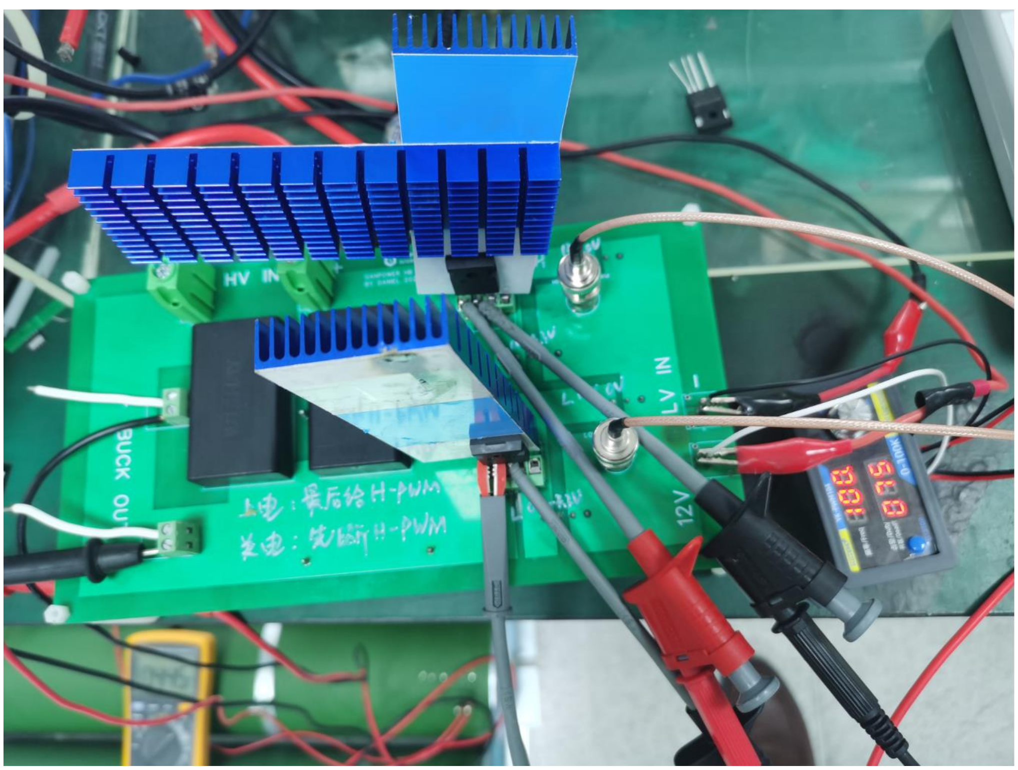



Figure 6. Experimental set up of an air cooled Buck convertor power stage.

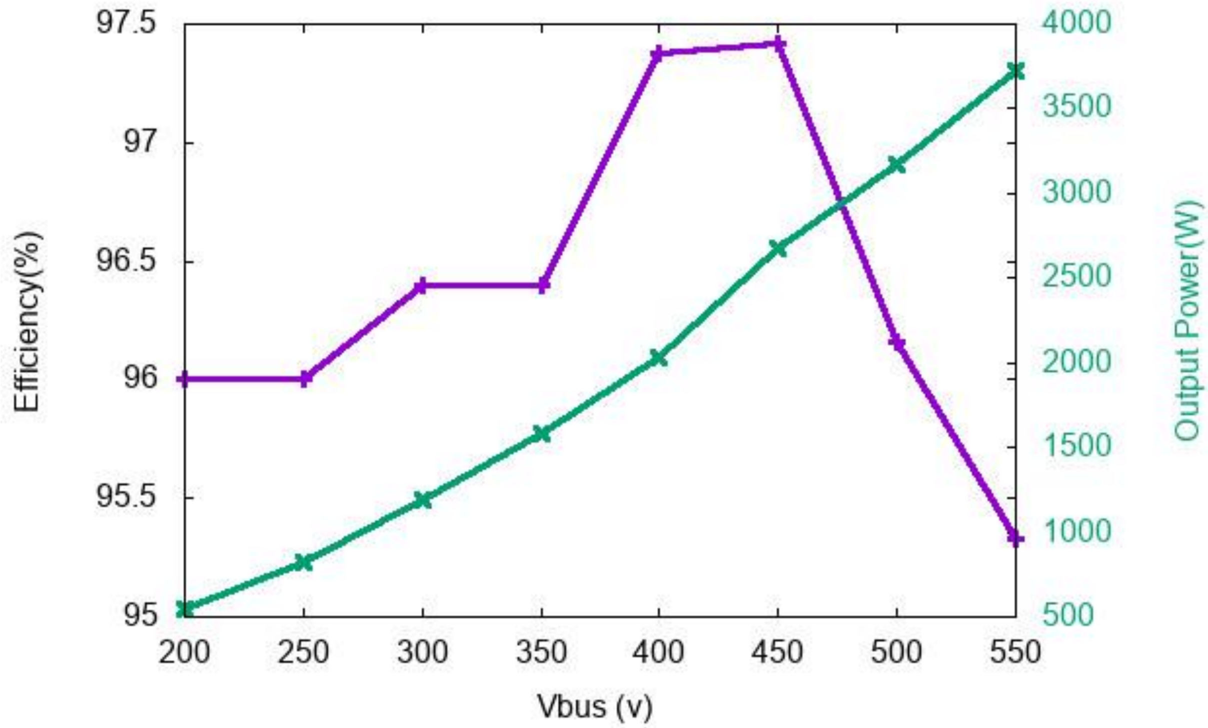



Figure 7 Measured efficiency and output power of the Buck convertor power stage at 100KHz switching frequency.