High-power GaN HEMTs battle for vacuum-tube territory

The vacuum tubes used in today's millimeter-wave transmitters face an increasing threat from GaN HEMTs. Cree's **Yifeng Wu** and **Primit Parikh** are leading the GaN charge with designs that incorporate field plates, iron-doped buffer layers and a thin AlN interlayer to deliver a record power at 30 GHz.

US NAVY

Vacuum tubes are currently used in many radar systems, but the US military has pumped millions of dollars of research money into the development of solid-state GaN devices, which will be smaller, cheaper, more reliable and quicker to build.

The market for millimeter-wave power amplifiers includes applications in military, commercial and consumer sectors. The armed forces use the devices in transmitters for the detection of small targets and target imaging, in radar equipment, communications and smart weapons systems. In the commercial sector the amplifiers are widely used in high-data-rate communication systems such as digital radio links, SATCOM and wireless LAN, while the consumer market is expected to turn to millimeter-wave systems for applications such as automotive radar.

Vacuum tubes are used in the vast majority of high-power amplifiers operating at millimeter-wave frequencies. However, this incumbent technology is under threat from solid-state power amplifiers (SSPAs) that are smaller, cheaper, more reliable and quicker to build.

Although these SSPAs could be constructed from GaAs and InP HEMTs, these devices can only operate at low voltages and low powers. These limitations mean that multiple amplifiers or MMICs must be combined in order to deliver the output powers required, which leads to highly complex systems operating at relatively low efficiencies. GaN HEMTs can deliver high powers at higher voltages, and promise simple, efficient millimeter-wave power amplifiers.

Traps and other obstacles

GaN HEMTs are clearly excellent devices on paper. However, in practice they can suffer from high trap densities, and at millimeter-wave frequencies their performance can be adversely affected by insufficiently low channel resistance and poor pinch-off characteristics (a relatively large gate voltage is required to extinguish the drain current).

High trap densities are exacerbated by the large strain and high polarization charges in the AlGaN/GaN structures. The trapping effect severely reduces AC current under large-signal operation, and subsequently deteriorates the output power and efficiency.

At the relatively high millimeter-wave frequencies, to maintain an acceptable power output it is essential to achieve a low channel resistance while maintaining good pinch-off characteristics as the device gate length shrinks. Low channel resistance results from a high value for the product of the charge density and mobility. However, if the charge density of the 2DEG is increased by raising the aluminum content in the AlGaN layer, alloy scattering also increases, which degrades the mobility and consequently compromises the charge-mobility product.

The advantages of GaN

GaN's wide bandgap increases the breakdown field by five times and the power density by a factor of 10 to 20, compared with GaAs-based devices. The GaN components are therefore smaller and have a lower capacitance for the same operating power, which means that amplifiers can operate over a wider bandwidth while exhibiting good input and output matching.

GaN devices are also highly efficient because they can operate at higher voltages (24–35 V, compared with 5–8 V for GaAs-based devices at millimeter-wave frequencies), as well as having a lower on-resistance that results from the properties of the two-dimensional electron gas (2DEG) in the AlGaN/GaN system. The high voltage also reduces the bus current, which improves the power supply efficiency, while the 2DEG produces a high electron velocity, ensuring good signal gain at K, Q and even W band frequencies.

In addition, GaN devices built on SiC substrates have a thermal conductivity 10 times higher than those fabricated from GaAs, which means that these wide-bandgap devices can operate at higher power densities. GaN HEMTs can also work at higher temperatures, which reduces the need for cooling and allows for a more compact module design.

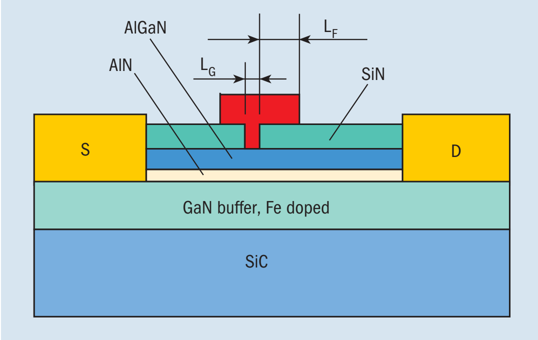
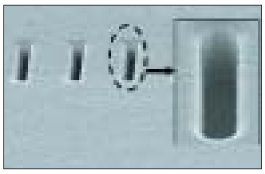


Fig. 1. Cree's GaN HEMTs were grown by MOCVD on a semi-insulating SiC substrate. An AlN nucleation layer was deposited first, followed by a 2–4 μm thick iron-doped GaN buffer, a strained thin AlN layer and a 22 nm thick AlGaN barrier. Ohmic contacts were produced by annealing a Ti/Al/Ni/Au alloy at 880 °C. A Ni/Au contact formed the Schottky gate, after the dimensions were defined by electron-beam lithography and subsequent dry etch through a SiN layer.



Cree offers both epiwafers and device/MMIC foundry services for Ka- and Q-band applications. Through these services, Cree's customers can gain access to the company's field-plated, electron-beam lithography GaN MMIC technology. An individual source via process (shown above) has recently been applied to SiC substrates, enabling microstrip MMICs delivering even higher total power, gain and efficiency than those of the devices described in this article.

The pinch-off characteristics are related to the energy of the Fermi level of the GaN buffer layer below the active channel. Although this Fermi level can be increased by adding p-type dopants or other impurities, this action also creates unwanted drain lags that are attributed to buffer traps.

Designed for power

At Cree we have designed and built a GaN HEMT that overcomes all the issues that we have highlighted by incorporating a field plate, an AlN interlayer and an iron-doped buffer layer into the device (see figure 1).

The T-shaped structure built into the SiN layer is an integrated field plate. Traditionally, field plates were introduced to reduce peak electric fields in silicon LDMOS devices and GaAs FETs, which increased their breakdown voltages. In GaN HEMTs, however, the onset of electron trapping only occurs at high fields, so the field plate can reduce or even eliminate trapping effects. We achieved extremely high power densities of greater than 30 W/mm with good efficiencies at 4–8 GHz using this scheme. The drawback of a field plate is the addition of gate-to-drain capacitance, which acts as a path of negative feedback, reducing power gain.

If GaN HEMTs are to operate at millimeter-wave frequencies, the gate and field-plate dimensions must be scaled down accordingly. In our design the lengths of the gate (L_G) and field plate (L_F) are 0.15–0.18 μm and 0.3 μm, respectively, giving typical current-gain and power-gain cutoff frequencies (f_t and f_{max}) of 60 and 120 GHz. Although this f_t is lower than that of non-field-plated devices of similar gate length (65–70 GHz), we believe that the improved large-signal characteristics more than compensate for this.

In our devices a thin AlN layer at the AlGaN/GaN interface significantly reduces alloy scattering in AlGaN, and this decreases the transistor's channel resistance. The insertion of this layer has delivered a substantial reduction in the sheet resistance throughout the aluminum content range that was investigated (see figure 2).

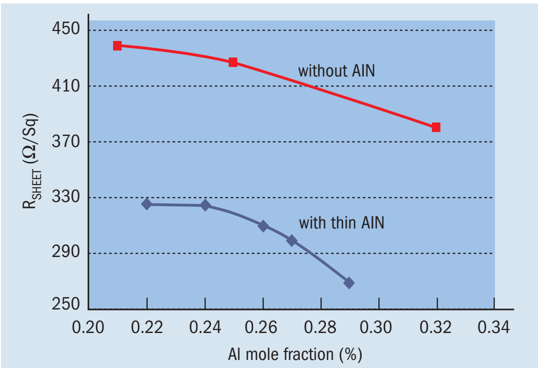


Fig. 2. Inserting an AlN interlayer reduces the channel resistance and improves GaN HEMT operation at higher frequencies.

Adding an iron-doped GaN buffer layer addresses short-channel effects that can cause poor pinch-off characteristics (see figure 3). The iron dopant drastically cuts the transistor's buffer conductivity without degrading its large-signal performance.

Power measurements of unit cell devices clearly demonstrate the performance improvements resulting from our design (see figure 4). The 100 μm wide device generates 0.86 W of output power, or 8.6 W/mm, at 40 GHz. Linear gain is 6 dB, while associated power gain and power-added efficiency (PAE) at peak power are 4.1 dB and 34%, respectively. This is a significant step up from previous values of 3–4 W/mm and 20–30% PAE, which were produced using generic electron-beam-gate GaN HEMT structures.

Scaling up

We have also scaled up the device periphery using an oversized air-bridge structure to produce the output powers required for transmit power-amplifier applications. This structure provides minimum grounding resistance and inductance without the need for via-hole etching in applications where co-planar waveguide transmission line systems are preferred. The scaling was suitable for 1.5 and 1 mm peripheries for devices

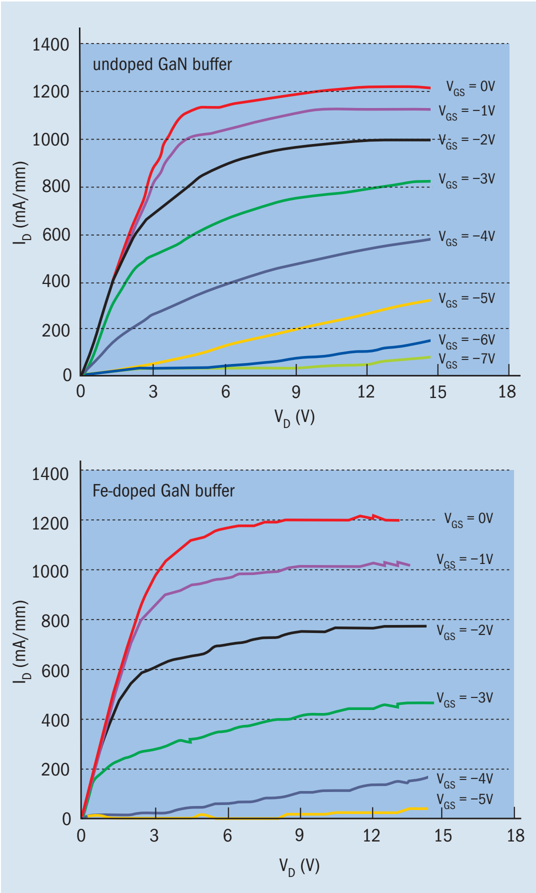


Fig. 3. Switching from an undoped to an iron-doped buffer improves the HEMTs' pinch-off characteristics (a smaller gate voltage is required to extinguish the drain current), and consequently increases the device's output power and efficiency.

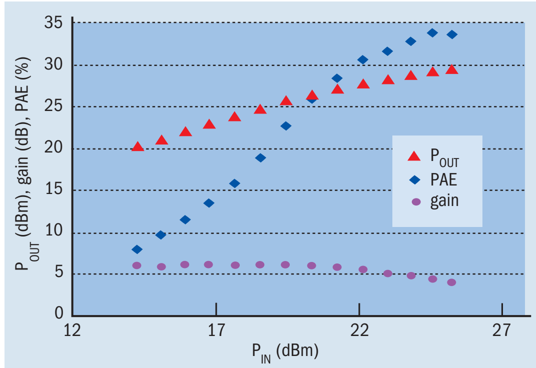


Fig. 4. Cree's latest 100 µm wide devices can deliver 8.6 W/mm at 40 GHz with a power-added efficiency (PAE) of 34%. This is a significant improvement over the performance of generic GaN HEMTs produced using electron-beam lithography, which generate 3–4 W/mm at PAEs of 20–30%.

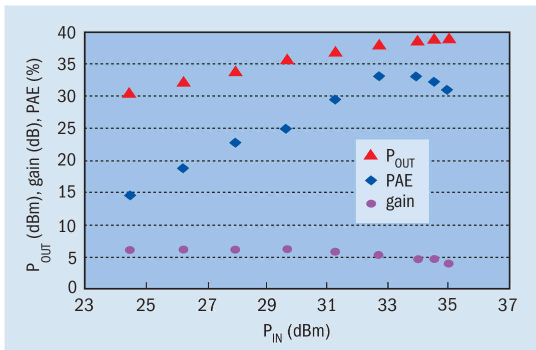


Fig. 5. GaN HEMTs can slash the footprint of the power amplifier. This GaN-based pre-matched 1.5 mm wide device generates a record 8.05 W at 30 GHz. To produce the same power with GaAs MMIC requires a device 10 times wider.

operating at 30 and 40 GHz, respectively.

Two single-stage amplifiers were designed using 1.05 mm wide devices with on-wafer pre-matching circuits operating at 30 and 35 GHz. On the millimeter-wave test bench the 30 GHz amplifier generated 5.4 W at a 36% PAE, while the 35 GHz amplifier produced 5.2 W and a 31% PAE. The associated gains were 6 and 5 dB at the respective frequencies (the pre-matching loss was allocated to the devices and not included in the calibration). This result is a substantial improvement over previous values of 3.5–3.6 W and 22–26% PAE obtained from non-field-plated devices of the same size at the same frequencies, and confirms the advantages of our design.

To determine the maximum scalability of a single-cell GaN HEMT, we have also built a single-stage amplifier with a 1.5 mm wide device. The pre-matched GaN HEMT delivered 8.05 W of output power at 30 GHz with a 31% PAE and 4.1 dB associated gain (see figure 5). We believe that this is the highest power generated by a GaN transistor operating at millimeter-wave frequencies. The output is equivalent to that of a GaAs-based MMIC with a 14.7 mm wide output device, but delivered by a component with a periphery just one-tenth of that size. The higher operating voltage for the GaN HEMT of 28 V, compared with 5 V for the GaAs MMIC, also reduces the bus current requirements and improves the conversion efficiency of the power supply.

Although significant progress has been made, in terms of power output and efficiency, the reliability of millimeter-wave GaN HEMTs remains a challenge. However, we expect that additional innovations to the design will not just improve the reliability of these devices, but also signal gain and manufacturability. These advancements will lead to the emergence of next-generation HEMTs that will benefit many aspects of military and commercial communication systems.

Although GaN HEMTs will initially be a replacement technology vying to take market share from established products, their compact size, lower cost and high performance will eventually increase system efficiency and reduce costs. Cost savings will be transferred to customers, and this will drive increased sales that will eventually lead to the growth of new markets for these devices.

Further reading

Y-Fu Wu *et al.* 2005 *IEEE IEDM Digest* 193
Y-Fu Wu *et al.* 2003 *IEEE IEDM Digest* 579.

About the authors
Yifeng Wu (left) has been a lead research scientist on GaN power devices and amplifiers for eight years, working first at Widegap Technology LLC, before moving to Nitres and then Cree.
Primit Parikh (right) is currently managing the GaN electronics effort at Cree Santa Barbara Technology Center.

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