AlGaInN Power Transistors: Status and Prospects

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ABSTRACT

InN, GaN, AlN and their alloys were first studied in the 1960's for application to short wavelength emitters and for high power/high temperature electronics. These efforts languished due to the lack of a bulk substrate technology and the inability to produce low defect and low impurity heteroepitaxy films. In light of this, the compound semiconductor community moved on to Arsenide- and Phosphide-based materials that resulted in the device technologies now driving microwave wireless communications and many military electromagnetic systems. AlGaInN materials, however, are now poised to challenge the conventional III-V semiconductors for power generation, at least up to K-band, as a result of drastic material improvements driven, initially, by photonic applications. In this talk, the status of AlGaN/GaN high electron mobility transistors (HEMTs) and heterojunction bipolar transistors (HBTs) will be presented. Ongoing and future work to increase the operating frequency and output power will also be addressed.

INTRODUCTION

As with the early development of GaAs and InP, the United States Department of Defense (DoD) is the primary supporter of wide bandgap electronics in the United States. This is driven by ever increasing requirements on DoD electromagnetic systems including radar, communications, and electronic warfare. Future systems are envisioned that will simultaneously perform all of these functions over a broad, up to 5:1, bandwidth. Since the upper frequency limit of a power amplifier is inversely proportional to the gate-to-source capacitance (C_{GS}) of the transistor, C_{GS}, or equivalently the watts/pF, should be minimized. This requirement means high power density transistors are needed. The required performance can not be met by conventional semiconductors, therefore AlGaInN based devices with 10 times greater electrical breakdown and up to four times higher current densities than conventional III-V technologies are being aggressively pursued. Commercial industry is also moving to develop this technology for communication base stations and satellite links.

AlGaN HEMTs: STATE-OF-THE-ART

To date, AlGaN/GaN HEMTs have out-performed the best GaAs devices by roughly five times in power density at C- (7.1 W/mm at 6 GHz), X- (6.8 W/mm at 10 GHz) and K-band (3.1 W/mm at 18 GHz).[1,2,3] Simultaneous power, gain, and efficiency has also exceeded GaAs with a demonstration of 3.2 W/mm, 13.9 dB gain, and 62 % PAE for AlGaN HEMTs on SiC at 10

GHz.[4] Similar results have also been achieved for devices grown on sapphire.[5] These results are still well below the theoretical predictions of 10 to 20 W/mm at X-band. If such power densities are realized, the parts will be limited by the package's ability to dissipate heat and not the semiconductor.

These results are still limited by carrier trapping that reduces the large signal gain and output power.[6,7] Detailed studies on the origin of the traps are ongoing but surface states and defects in the buffer layer are the primary candidates. Similar trapping phenomena were also seen in early GaAs devices but later minimized with improved material quality, device design, and process technology.

Device scaling to large gate peripheries has received less effort, although a 3 mm wide device has yielded 9 W at 7.5 GHz.[8] The key issue is the material uniformity to yield the large devices. Molecular beam epitaxy (MBE) may play a critical role in this arena due to its inherent high uniformity. Good HEMT electron mobilities (1800 cm^2/Vs at room temperature) and microwave power densities (3.6 W/mm at 6 GHz) have been realized for MBE grown active layers on MOCVD grown buffers.[9] The trapping effects mentioned above must also be minimize to move to large transistors widths since the traps tend to be spatially non-uniform and reduce the available output power and efficiency.

AlGaN HEMT CIRCUITS

The first AlGaN HEMT amplifiers have been made with a 4-8 GHz hybrid design delivering 35 dBm over the band that is roughly twice that produced by a GaAs part of a similar size.[10] With the improved HEMTs recently reported, this circuit power would increase five to seven fold. GaN MMICs are also under development. Issues for full MMIC realization and initial circuit results will be discussed. A key for MMIC implementation is fabrication of through wafer vias for improved source grounding. Initial vias through SiC substrates have been reported but the manufacturablity (e. g. yield, process cost, etc.) has not been documented. The strong chemical bonds of SiC make it difficult to etch using conventional processes. Work has focused on developing etch masks that hold up during prolonged reactive ion etching (RIE) or higher density inductively couple plasma (ICP) etching. Beyond the thermal limitation of sapphire substrates, the difficulty in forming substrate vias will hamper high frequency circuit implementation based on GaN-on-sapphire unless a new configuration is developed. Wafer thinning will also be required for thermal management and to enable the via etching both for SiC and sapphire. Here again, the hardness of the SiC and sapphire substrates makes thinning by mechanical lapping and/or combined chemical/mechanical lapping challenging. These areas require further work.

Another approach to broadband power is to implement a common source (CS)/ common gate (CG: rf grounded second gate) cascode pair in a single dual gate transistor. This has the advantage that the current handling and high frequency gain is determined by the CS device and the voltage capability is set by the CG device. Therefore, the bandwidth can be maintained while still achieving high powers. The first dual gate AlGaN HEMT has been reported but not yet optimized.[11] The transistor had equal gate lengths (0.6 μm) for both the CS and CG (preferably the CS should have a short gate length for good gain and the CG should have a large gate length for high breakdown) but still achieved 2.5 W/mm at 4 GHz.

AlGaN HBTs

While AlGaN HEMTs are rapidly maturing, heterojunction bipolar transistors (HBTs) in this material system are still in their infancy. AlGaN HBTs are desirable for their linearity, power performance, and low phase noise. The first DC AlGaN/GaN HBTs were demonstrated in 1998 but with modest performance ($\beta = 3$ to 10).[12,13] The HBTs were limited by the low free hole concentration in the base and the correspondingly poor base ohmic contacts. P-doping is the singular greatest challenge for AlGaN HBTs due to the large acceptor ionization energy and the solubility limit of Mg (the preferred acceptor) in GaN. The approaches presently being pursued to achieve useful microwave HBTs include, piezoelectric enhancements, superlattice doping, regrown external base and/or emitter regions, and aggressive emitter scaling.

As first proposed by Schubert, et al., use of a p-type AlGaN/GaN superlattice will reduce the effective acceptor ionization by promoting acceptor ionization into the lower bandgap region.[14] The initial work predicted a 10 fold increase in the free hole concentration if the valence band discontinuity was equal to the acceptor ionization energy in the bulk material. The prediction has been verified experimentally with a free hole concentration of up to 2.5×10^{18} cm^{-3} measured for an optimum superlattice periodicity of 8.8 nm and 10 % Al.[15] The effective ionization energy was also determined from the temperature dependence of the resistivity to approach 0 meV (i. e. full ionization at room temperature) compared to 230 meV for a bulk $Al_{0.1}Ga_{0.9}N$ sample or the 170 meV reported for GaN. Theoretical modeling of this result clearly showed the importance of including the built-in polarization induced field which contributes to the enhance free hole concentration through field ionization. The approach appears promising but further effort is needed for insertion into vertical transport devices such as HBTs since the same band discontinuities that enhances the lateral hole conductivity can impede the electron transport perpendicular to the interface. This may be alleviated by introducing grading at the interfaces.

Initial device simulations suggest that AlGaN/GaN HBTs should obtain an $f_t > 25$ GHz and $f_{max} > 40$ GHz if a free hole concentration of 2×10^{18} cm^{-3} can be achieved in the base and good base ohmic contacts with a specific contact resistivity of $< 1\times10^{-5}$ Ω-cm^2 can be achieved.[16,17] This will enable useful AlGaN HBT power amplifiers at least up to 20 GHz.

FUTURE DIRECTIONS

To push the AlGaN/GaN HEMT technology to produce useful power above 20 GHz, new design concepts will be needed. The most obvious is to incorporate Indium in the channel region to enhance the mobility and electron velocity in a fashion analogous to InGaAs-based HEMTs. However, addition of a significant amount of In to GaN results in phase segregation that will degrade the transport properties. Hence, significant work will be needed to optimize such an approach with the use of MBE, as opposed to the more widely employed MOCVD for AlGaN, an attractive option.

Finally, to fully meet the DOD needs, new circuit approaches are being developed. Some of these, such as the class B push/pull design, have been applied to lower frequency amplifiers but have not been widely used in the microwave frequencies. The high breakdown strength of the group III-Nitride materials is enabling these approaches to be consider up to K-band for ultra-wideband amplifiers. The use of f_T-doubler circuits that extend device performance to achieve compact, wide bandwidth designs are also being developed.[18,19] The details of these circuit topologies will be presented.

SUMMARY

AlGaN HEMTs have shown dramatic performance improvements over the last several years. They now appear poised for transistion to manufacturing and insertion into military and commercial systems. Future research thrusts will include AlGaN/GaN HBTs and enhanced HEMTs with Indium containing channels.

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