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Recent developments in GaN HEMTs and MMICs for high power electronics

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Abstract

Due to its outstanding materials properties the semiconductor system (Al,Ga)N is a very promising candidate for high power electronic applications covering communication, radar and power conversion. In fact GaN is already considered to be the most important semiconductor besides silicon. In this invited contribution we give an overview of epitaxial growth, device processing, characterization and reliability assessment of electronic devices based on this material.

1. Introduction

GaN combines the properties of classical semiconductors like GaAs and Si with those of insulators. It offers a wide bandgap (3.4 eV), a high breakdown field (3.3 MV/cm), a large current (well above 1 A/mm) and a large saturation velocity (2.7×10^7 cm/s). Its excellent thermal and chemical stability makes it an ideal material for applications in even harsh environments. Compared to traditional semiconductors the devices and systems utilizing GaN can be made significantly smaller and lighter with reduced, if any, cooling requirements. The result is a significant improvement in overall cost and efficiency. In fact, similar to the ongoing replacement of classical light sources by compact and efficient light emitting diodes it is expected that GaN-based electronic devices will gradually replace Si- or GaAs-based devices or even bulky tube amplifiers.

2. Epitaxial Growth

We employ both semi-insulating 4H-SiC(0001) as well as conducting Si(111) substrates for the epitaxial growth by metal-organic chemical vapour deposition. SiC substrates offer a superior thermal conductivity as well as fairly good lattice and thermal expansion coefficient match whereas Si substrates are attractive because of their low costs, availability in large diameters and compatibility with Si-foundries.

The epitaxial structures on SiC substrates consist of an AlN nucleation layer, a thick GaN buffer, an AlGaN barrier layer and a thin GaN cap. We start with a Fe-doped GaN buffer but have a nominally undoped GaN channel below the AlGaN barrier. From capacitance voltage profiles we estimate the residual carrier density in buffer to be below 10^{14} cm^{-3}. In the case of growth on Si(111) substrates an AlGaN transition layer is employed in order to avoid crack formation during cooling due to the high mismatch in thermal expansion coefficients between GaN and Si. The growth conditions of the buffer are chosen such that we achieve both a highly insulating buffer as well as a low trap density near the active region.

3. Device processing

Processing is based on standard III-V equipment with lateral device definition by optical stepper lithography for all layers with critical dimension of at least 500 nm. Smaller structures are defined by electron beam lithography. Processing is performed in microstrip line technology consisting of frontside processing, substrate thinning to 100 µm and front-to-back substrate via holes. Our MMICs (monolithic microwave integrated circuits) feature thin film NiCr resistors having sheet resistance of 50 Ω/sq, high-voltage metal-insulator-metal capacitors and inductors for impedance matching to a 50 Ω environment. Device processing is designed for homogeneity and reproducibility in order to have a high yield of devices: Process windows are chosen for negligible impact of typical equipment fluctuations such as annealing temperature and lithography exposure parameters. We employ gate lengths of up to 2 µm for high-voltage switches, 500 nm for L/S-band communication applications, 250 nm for X-band MMICs and 100 nm for W-band MMICs.

4. Device characterization and reliability

High voltage HEMTs for efficient power conversion

In a detailed comparison [1] of Si MOSFET (metal oxide semiconductor field effect transistor) and IAF GaN HEMT (high electron mobility transistor) devices it was shown that GaN HEMTs have already exceeded the performance of silicon MOSFETs despite the fact that the GaN technology is still by far not as mature as that for Si. Higher switching frequencies enable smaller passive elements and thus significantly reduced system sizes and costs. For competitive power and efficient conversion it is necessary to have GaN HEMT devices on Si substrates with high current capability, large breakdown voltage as well as low static and dynamic on-resistances. We have realized structures with gate widths as large as 260 mm that have output currents close to 100 A in pulsed operation (100 µs). The breakdown voltages of these structures are well above 600 V with corresponding leakage currents around

1 μA/mm. The total static on-resistance R_{ON} is approximately 70 mΩ with an area-specific resistance of $R_{ON}\times A$ of 8 mΩ×cm². An effect known for GaN devices but not observed for Si devices is the dependence of the on-state resistance on previous off-state stress. The origin of this effect (which is also called "DC-to-RF dispersion in the field of microwave devices) is trapping and de-trapping of electrons. The dynamic on-resistance of our GaN technology is examined in double-pulsed measurements where the device is turned off at a high drain voltage (up to 400 V which is the limit of our setup) and 5 μs after switching the device on the drain voltage is measured for a drain current of 3 A. We obtain an increase of 80% in R_{ON} w.r.t. the static case. Despite this observation up-converters using our GaN/Si technology have already shown more than 98% efficiency at 400 V at a switching frequency of 68 kHz.

MMICs for radar and communication

Innovative radar and communication systems require the use of advanced MMICs for amplification. GaN devices offer a significantly improved power density (about a factor of 5) compared to conventional GaAs devices as well as large band widths due to the large impedance levels, thus resulting in significantly reduced system volume. We have developed one-stage and two-stage MMICs for various radar and communication applications.

As a very recent achievement a two-stage GaN MMIC developed at Fraunhofer IAF has been launched into space in May 2013 as an in-orbit demonstration of an experimental GaN X-band transmitter onboard the Proba-V satellite of the European Space Agency. The previously mentioned advantages of GaN are of special importance for space as a reduction in weight and volume is very cost-saving in this field. Necessary prerequisites are sufficient performance and sufficient long-term stability. Radiation hardness of our GaN technology has been demonstrated in single event effect, proton irradiation and gamma irradiation tests.[3] The continuous-wave on-wafer performance in the target band (8-8.5 GHz) is characterized by a power added efficiency (PAE) above 40%, a power gain of 20 dB and an output power close to 10 W – all of these values are within the specification. As a next step the reliability of our packaged MMICs was measured at a frequency of 8.5 GHz under continuous-wave conditions at 30 V drain bias at accelerated temperature conditions. The compression level was about 6 to 7 dB in order to operate the device near maximum efficiency at stress temperature. The thermal resistance of our devices was determined by high-resolution Raman spectroscopy in conjunction with thermal simulation of the chip taking into account the layout and epitaxial structure of our devices under RF operation. The channel temperature represents the sum of the base plate temperature and the self-heating during RF operation. Within our statistics we arrive at a lifetime above 10^5 h at a channel temperature of 200°C, the corresponding activation energy is 1.5 eV [3]. This data passes the reliability requirements for space applications which is 20 years at 175°C channel temperature.

L/S-band power bars for communication

Mobile communication systems such as 3G and 4G require power amplifiers for base station applications with increased efficiency at more stringent back-off requirements as compared to present solutions. In these systems the high-power amplifiers (HPAs) operate at a minimum of 8 dB back-off. This requires HPAs with high output power, high efficiency, and high linear gain [4]. A significant improvement was achieved by replacing source bond wires by individual source vias. We have realized 100 W output power devices operated at a supply voltage of 50 V with a PAE close to 70% and a linear gain around 20 dB at 2.14 GHz. This performance is significantly improved compared with state-of-the-art Si laterally diffused metal oxide semiconductor (LDMOS) devices. Hence, base stations are now more and more equipped with GaN instead of the previously used LDMOS.

5. Summary and conclusion

We have given an overview on epitaxial growth, device processing, performance and reliability of GaN electronic devices for various applications. Outstanding performance and reliability have been demonstrated for high power and high frequency devices with the first European GaN device now already in space as an X-band transmitter in a very recently launched satellite. GaN enables the realization of innovative devices that are ideally suited to subsequently replace conventional Si and GaAs based counterparts.

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