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Invited

Electronic Applications of GaN Devices

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1. Introduction

The explosion of the mobile electronics markets has increased the need to develop component technologies such as power transmitters, receivers and displays. The two major underlying requirements for all these technologies are that of efficiency and low cost. Power amplifier market needs are currently satisfied with Silicon/ III-V based solid state solutions and thermionic cathode based vacuum tubes . The display markets are supplied by LCD and LED based solutions. Therefore a new technology has to a large extent a difficult task, that of providing a better solution not a unique one. AlGaN/GaN based semiconductors promise the potential of a single technology which either aids conventional implementations or creates affordable new configurations with AlGaN/GaN HEMTs providing solid-state power solutions and GaN-based vacuum microelctronics providing cold cathodes for vacuum tubes and displays. In particular the GaN based family of semiconductors grown on sapphire is attractive as, it has technological and cost advantages over competing semiconductors (e.g. SiC) . First GaN possesses attractive electronic material properties such as a large band-gap (3.4 eV), high breakdown field ($3x10^6$ Vcm^{-1}), the existence of modulation doped AlGaN/GaN structures with attendant high electron mobility (1500 $cm^2V^{-1}s^{-1}$) and extremely high peak ($3x10^6$ cms^{-1}) and saturated electron velocity ($2x10^6$ cms^{-1}). Secondly, the AlN/GaN/InN based family of semiconductors is highly piezoelectronic, affording design possiblities not possible in the conventional III-Vs. Lastly, it has the technology development costs amortized over several large electronic and opto-electronic applications and therefore could potentially be a low cost solution. In this paper recent progress of AlGaN/GaN based electronics at UCSB on sapphire is presented in two areas; AlGaN/GaN HEMTs, and GaN based vacuum-microelectronics.

2. AlGaN/GaN based HEMTs

Design rules for high performance HEMTs dictate structures that yield a high sheet charge density with concomitant high mobility (for high current) while maintaining a breakdown voltage appropriate for the application. This dictates utilizing AlGaN with the maximum Al mole fraction without degrading the two dimensional sheet conductivity. To establish a design parameter space epi-films were grown on C plane sapphire substrates by MOCVD and had the same layer structure: a 200 Å GaN nucleation layer, 2 μm insulating GaN (i-GaN) and a 200 Å AlGaN donor-barrier layer. The AlGaN layer consisted of a 30 Å unintentionally doped (UID) spacer, a 150 Å Si doped region and a 20 Å UID cap. The Al mole-fractions of the AlGaN were chosen as 15 %, 25 %, 35 % and 50 %. Theoretically, a higher Al-content leads to a larger ΔE_c and allows a higher 2DEG density. Experimentally, the highest sheet densities achieved were $8x10^{12}$ cm^{-2}, $1x10^{13}$ cm^{-2}, $1.2x10^{13}$ cm^{-2} and $1.2x10^{13}$ cm^{-2}, respectively. The inability to increase carrier density with X_{Al} greater than 35 % is attributed to the reduced doping efficiency. Mobilities as a function of temperature are shown in Fig.1. Each measured sheet carrier density was essentially constant through out the temperature range of 20 ~ 320 K. The low-temperature (20 K) mobility does reduce with increasing Al-content, which may be due to either the interface-roughness scattering enhanced by the higher piezo-electric charge density, or the enhanced remote alloy scattering. The 300 K mobilities, however, are nearly the same, indicating that phonon scattering is dominant. For devices operating at room temperature and above, a high Al-content up to 50 % should introduce little increase in channel resistance.

Devices were fabricated on epi-films with Al-contents of 25 % and 50 %. The fabrication process was a conventional mesa isolated process with chlorine reactive-ionetching (RIE) used for mesa definition. Ti/Al was used for ohmic contact formation and Ni/Au for the gate metal. Transfer ohmic contact resistances were measured as 0.5 and 1 Ω-mm, respectively. The higher contact resistance for the latter $Al_{0.5}Ga_{0.5}N/GaN$ HEMT is attributed to the high Al composition of the layer. The corresponding gate-lengths of the devices were 0.9 and 0.7 µm, both obtained by optical lithography. Fig. 2 shows the output I-V characteristics of both devices. Both devices showed a maximum drain current of over 1A/mm and gate-drain breakdown voltages of around 100, 160 and 220 V for gate-drain separations of 1, 2, and 3 µm respectively. The corresponding values for the $Al_{0.5}Ga_{0.5}N/GaN$ devices were generally 20 % higher.The transconductances varied between 225 and 255mS/mm. Fig.3 is the high-voltage I-V characteristics of an $Al_{0.5}Ga_{0.5}N/GaN$ HEMT with a gate-drain spacing of 3 µm, showing a gate-drain breakdown > 284 V and a three-terminal voltage > 200 V before punching-through. These voltages and the current density of 1 A/mm correspond to an ultra-high I-V product per unit width of $(I_{max}V_{max})$ > 200 VA/mm. While a power maximum density of $(I_{max}V_{max})/8$ = 25 W/mm is calculated, further work need to be done to verify this potential.

Small-signal rf measurements yielded current-gain and power-gain cutoff frequencies (f_t & f_{max}) of 15 and 35 GHz for the 0.9-µm gate-length $Al_{0.25}Ga_{0.75}N/GaN$ devices, 17.5 and 44

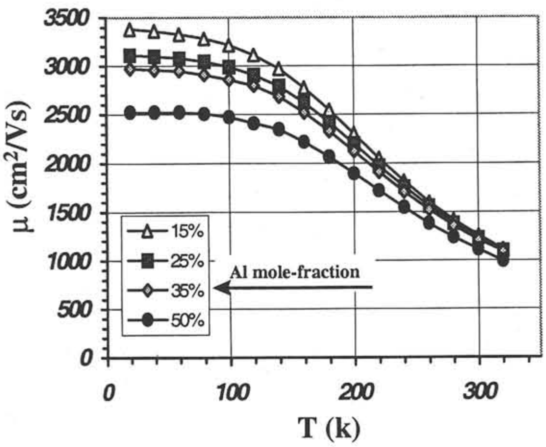
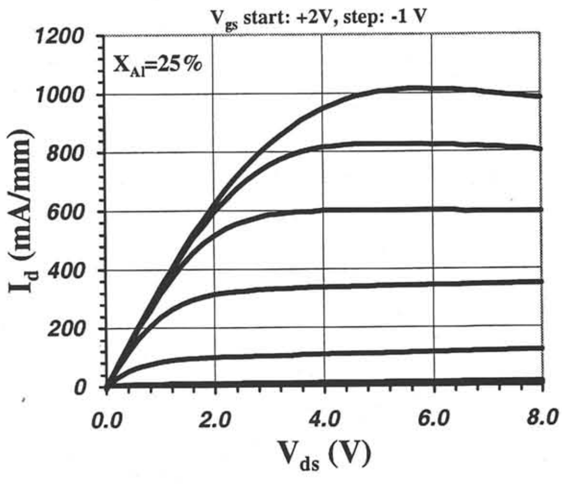
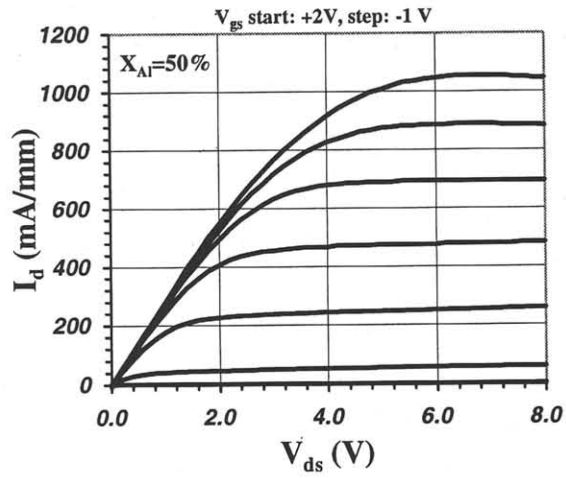


Fig. 1. Two-dimensional-gas mobility as a function of temperature for various Al compositions.



(a)



(b)

Fig. 2. DC I-V characteristics of AlGaN/GaN HEMTs with 25 and 50 % Al

GHz for the 0.7-µm gate-length $Al_{0.5}Ga_{0.5}N/GaN$ devices, respectively. Devices with 0.25-0.28 µm gate length exhibited an f_T of 52 GHz and simultaneously an fmax of 90 GHz (limited by the ohmic contact resistance).

Figure 4 shows the power density as a function of Al composition as measured by active load-pull techniques. The HEMTs with Al composition of 50% had a maximum power density of 2.7W/mm at 8GHz. 0.25 µm devices demonstrated a record maximum power density of 3.1W/mm at 18 GHz, as shown in figure 5.

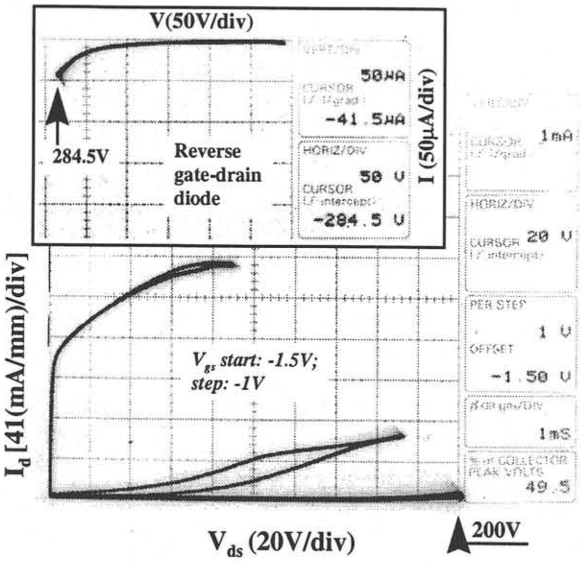


Fig. 3 Al.5Ga.5N/GaN HEMTs with 0.7 μm gate length

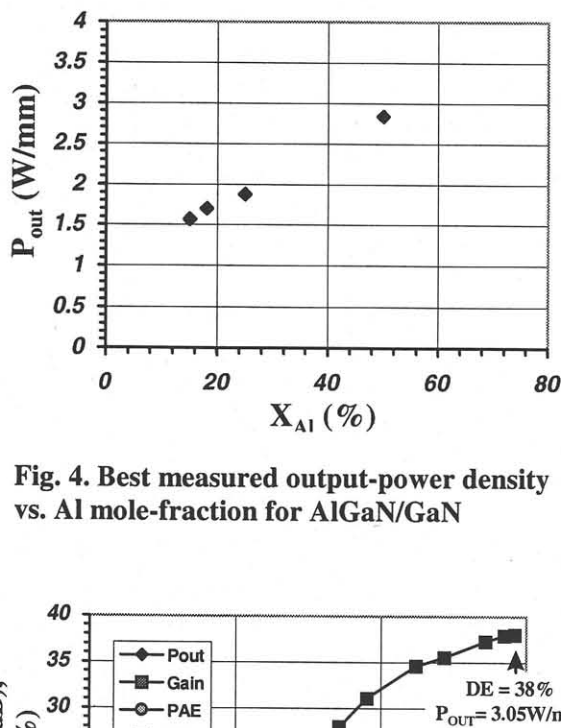


Fig. 4. Best measured output-power density vs. Al mole-fraction for AlGaN/GaN

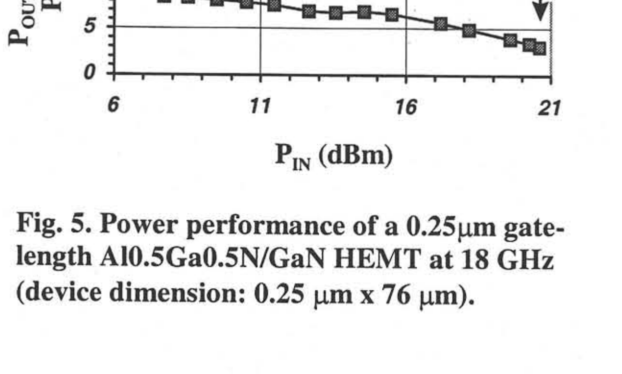


Fig. 5. Power performance of a 0.25μm gate-length Al0.5Ga0.5N/GaN HEMT at 18 GHz (device dimension: 0.25 μm x 76 μm).

The development of thermal management is crucial to scale the AlGaN/GaN HEMTs to generate large power output. This has been achieved to date by flip-chip bonding HEMTs with large periphery onto thermally conductive substrates such as AlN. The maximum power achieved from a 2 mm device in this manner is 3.16 W with a power added efficiency of 30%.

3. GaN-based Cold Cathodes

The operating characteristics of field emitters are exponentially dependent on two device parameters: the field enhancement factor and the surface energy barrier height. In addition to these device parameters, the practical use of field emitters as electron sources is dependent on the stability and uniformity of field emission. We have investigate field emission from GaN field emitters because GaN has a low electron affinity (2.1-4.0 eV), a high resistance to sputtering and is chemically inert. One drawback of GaN field emitters is that they are not easily sharpened. Thus, to lower the operating voltage of GaN-based field emitters we have investigated the lowering of the surface energy barrier using a strained-layer of InGaN on GaN field. The piezoelectric polarization produced in the strained InGaN forms a dipole much like the dipole formed by coating a surface with an electropositive adsorbate.

Calculations and measurements of hexagonal nitride semiconductors indicate large piezoelectric constants. Consequently, a strained layer of $In_xGa_{1-x}N$ on a GaN layer will produce a dipole that lowers the effective surface barrier. The dipole has the effect of pulling the conduction band and vacuum level of the InGaN surface down with respect to the GaN conduction band as shown in Figure 6. The barrier lowering has been numerically calculated using a band diagram calculation program. The effective electron affinity versus InGaN thickness with In mole fraction as a parameter is shown in Figure 7. The simulations show that it may be possible to lower the effective electron affinity by a factor of 4 compared to GaN field emitters.

Emission current measurements have been taken on the control sample and samples with 100 and 200 nm of InGaN. Figure 8 gives a summary of the turn-on voltages measured for the control and InGaN/GaN field emitter arrays. It is seen that the turn-on voltage is lower for

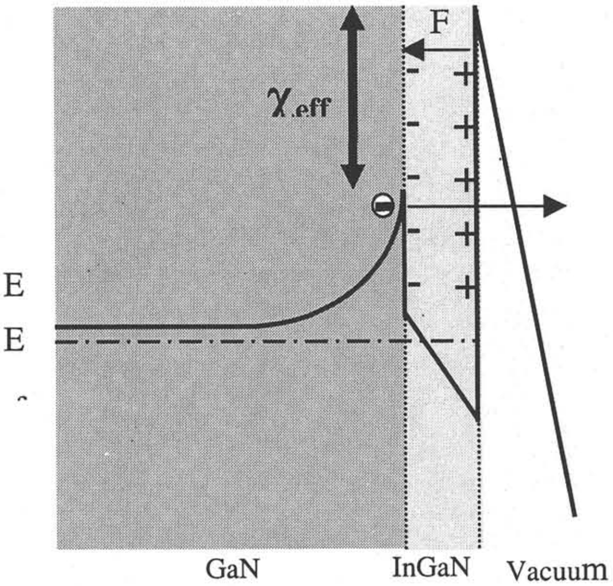


Figure 6. Schematic band diagram of InGaN/GaN field emitter.

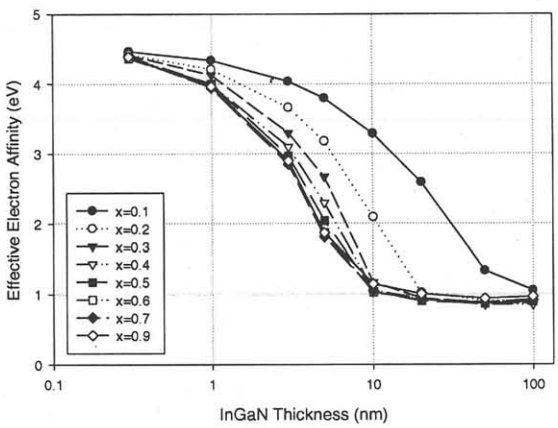


Figure 7. Calculated effective electron affinity versus InGaN thickness with In mole fraction as a parameter.

arrays with a 100 nm layer of InGaN than the control sample by factors of 1.5 and 3. The arrays with 200 nm of InGaN have a higher turn on voltage than the control sample. This could be the result of relaxation of the InGaN, loss of piezoelectric field, and the consequence that the higher electron affinity of InGaN would increase the turn-on voltage. Figure 9 shows the measured turn-on voltage for the arrays of 5 tips versus InGaN thickness (turn on is defined when the current is 10 nA). Analysis of the current-voltage characteristics indicate that the changes in I-V characteristic of the 100 nm and 200 nm InGaN field emitters can be attributed to a

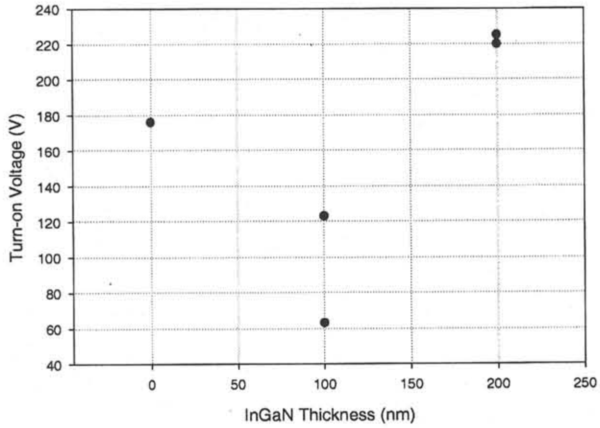


Figure 8. Turn-on voltage versus InGaN layer thickness. Turn-on voltage is defined as the voltage at which 10 nA is emitted.

change in surface barrier height. This technique is not limited to use in a field emitter structure. By using an AlGaN/InGaN double layer, an even larger barrier-lowering effect can be produced which will allow the design of planar cold cathode. Nitride-based planar cold cathodes have several advantages over field emitters including more uniform emission, insensitivity to vacuum environment, and easier fabrication and processing.

5. Conclusions

AlGaN/GaN HEMTs on sapphire have showed remarkable promise as microwave power sources demonstrating maximum output power of 3.16 W at 4 GHz from a 2mm wide device. The key to its acceptance into the market place is contingent on effective thermal management, reduced cost and improved power added efficiency relative to the current workhorses, the GaAs PHEMT and MESFET. The piezoelectric nature of the material, while helping the HEMT, has helped lower the surface work function of GaN so as to make non-cesiated electron emission feasible from even planar emitters. This could potentially impact the vacuum tube industry and also the display industry.

6. Acknowledgments

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