AlGaN channel high electron mobility transistors on Si for power electronics

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***Abstract*—This work is focused on the assessment of several $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ high electron mobility transistors on Si. The evolution of electron density, electron mobility, breakdown electric field, current densities and on/off ratio as a function of the Al fraction in the channel is reported. The temperature dependence of current densities, threshold voltage and subthreshold slope was studied. In addition, breakdown voltage measurements were performed as a function of gate-drain distance. The data are compared with previous works from the literature using other substrates.**

1. INTRODUCTION

Ultrawide bandgap semiconductors have emerged as a promising solution for the power market development. They can withstand higher voltages than silicon, SiC, or GaN at thinner thicknesses. Future technologies are developing around these materials in order to reduce energy losses in power components while decreasing the size of systems.

AlGaN channel high electron mobility transistors (HEMT) are surpassing traditional GaN channel HEMT due to the higher critical electric field of AlGaN compared to GaN [1]. However, to expect a development on the power market, it is essential to fabricate these transistors on large and cost-effective substrates such as silicon.

In this work, $Al_{XB}Ga_{1-XB}N/Al_{XC}Ga_{1-XC}N$ HEMTs on Si with three different Al contents in the channel were studied. The results are discussed and compared with the literature of AlGaN and GaN channel HEMTs.

2. DEVICE STRUCTURES, SIMULATIONS AND MEASUREMENTS

AlGaN channel heterostructures were grown on a 3 inches diameter Si (111) substrate using ammonia molecular beam epitaxy. The structure consists of a 200 nm AlN nucleation layer, a 450 nm AlGaN channel, a 1 nm AlN spacing layer, a 10 nm AlGaN barrier, and a 1 nm GaN cap layer. Three couples of Al molar fractions were chosen for AlGaN layers with values fixed at 10%/60%, 30%/70% and 60%/90% in the channel/barrier, respectively.

Ohmic contacts were fabricated by partially etching the AlGaN barrier followed by e-beam evaporation of 12/200/40/100 nm Ti/Al/Ni/Au metal stack and a rapid thermal annealing set at 850–875°C during 30 s. Mesa isolation of 220 nm depth was achieved by inductively coupled plasma etching technique. Plasma enhanced chemical vapor deposition of 30 nm thick SiN was used for the passivation of the surface. A 20/200 nm Ni/Au metal stack was evaporated on top of SiN as a gate contact for transistors. The gate contact is 50 µm long and 2 µm wide, with a gate-source distance of 2.75 µm and a gate-drain distance of 15 µm (Figure 1a).

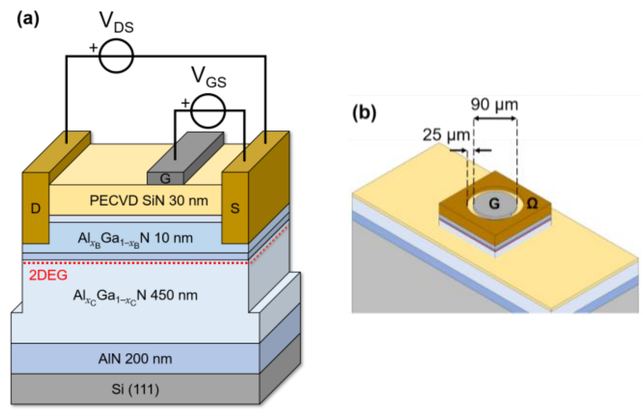

Figure 1: 3-dimensional schematic view of (a) a HEMT and (b) a circular device.

Hall effect measurements were carried out on Hall bridges from 10 to 600 K to study the evolution of the Hall density and electron mobility in the two-dimensional electron gas (2DEG). The Hall bridge is 700 µm long and 70 µm wide. The current was injected with a Keithley 6220 and the voltage was acquired with a Keithley 2010.

Electrical simulations of the heterostructures were realized in one dimension with the Schrödinger-Poisson solver Nextnano to extract the electron density in the channel [2].

The detection of defects in the AlGaN channel was carried out using deep level transient spectroscopy (DLTS) with an FT 1230 DLTS system from PhysTech, between 77 K and 325 K, on circular devices (Figure 1b). The central gate contact (noted G) has a diameter of 90 µm and is spaced 25 µm apart from the ohmic contact (noted Ω). The spectrum simulation was realized considering the b1 correlator of the Fourier transform DLTS [3].

Transistor transfer and output characteristics were acquired from 300 to 600 K with a Keithley 2612B.

3. Results

From Hall effect measurements, Hall densities n_H of 1.88×10^{13}, 1.41×10^{13} and 0.57×10^{13} cm^{-2}, and Hall mobilities μ_H of 390, 224 and 99 cm^2 V^{-1} s^{-1} have been extracted at room temperature for channels with 10%, 30% and 60% of Al, respectively. The electron mobility in the AlGaN channel heterostructures is mainly limited by the alloy disorder, whose impact is stronger for Al-rich channels. The interface roughness scattering also appears to be a limitation for the AlGaN channel with 10% of Al. At high temperature, polar optical phonons are responsible for the electron mobility drop, but are less impactful as the Al molar fraction in the channel increases [2]. The Al enrichment of the channel leads to an increase of the resistivity and a reduction of the electron mobility (Figure 2).

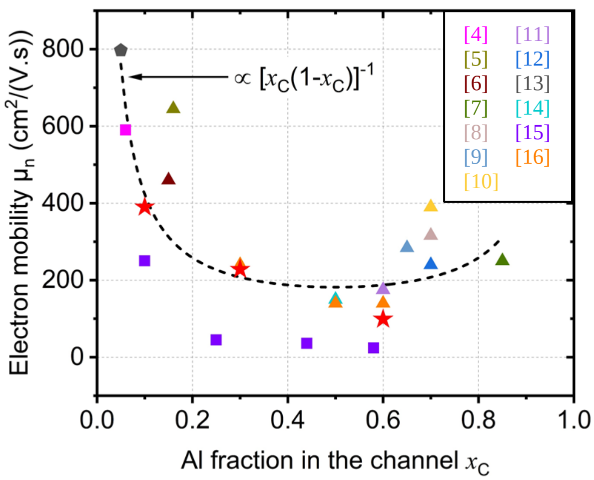

Figure 2: Evolution of electron mobility as a function of Al fraction in the channel at room temperature. Red stars: this work (Si substrates), triangles: sapphire substrates, squares: SiC substrates, pentagon: Si substrate.

In figure 3, we see that the studied heterostructures grown on silicon substrate exhibit transport properties comparable to state-of-the-art and a record of electron mobility clearly appears for the HEMT with 10% of Al in the AlGaN channel.

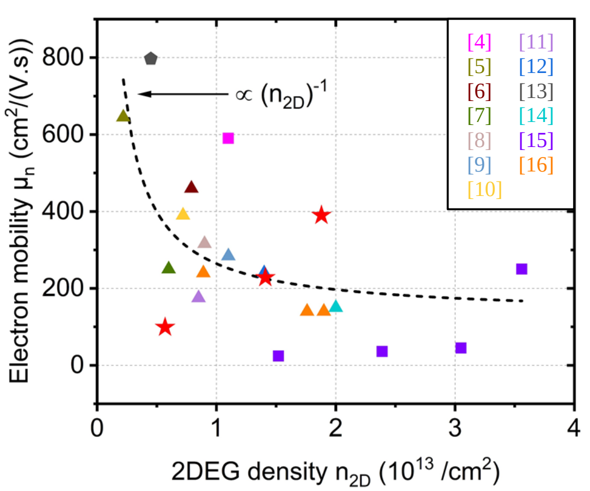

Figure 3: Evolution of electron mobility as a function of 2DEG density for several Al fraction in the channel at room temperature. Red stars: this work (Si substrates), triangles: sapphire substrates, squares: SiC substrates, pentagon: Si substrate.

It results from calculations a two-dimensional electron gas (2DEG) density of 1.71×10^{13}, 1.39×10^{13}, and 0.65×10^{13} cm^{-2} at room temperature for 10%, 30% and 60% of Al in the channel, respectively. These values are close to the experimental data found by Hall effect measurements. However, at low temperature (T < 300 K), a lower Hall density than expected for the structure with 60% of Al in the channel has been observed (Figure 4).

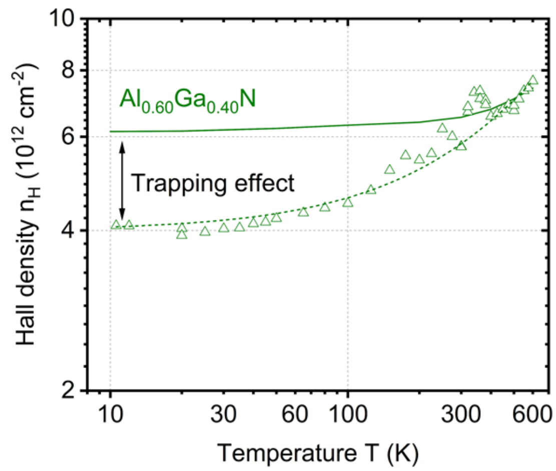

Figure 4: Comparison of the calculated (straight line) and measured (symbols) Hall densities as a function of temperature for $Al_{0.6}Ga_{0.4}N$ channel HEMT.

To study this reduction of electron mobility, we carried out DLTS measurements between 77 and 325 K. The device was reverse biased with a voltage of – 5 V applied to the gate contact. A pulse voltage of – 0.5 V was used to fill the traps with a duration of 1 ms. Capacitance transients generated by the thermally emitted electrons were recorded at a frequency of 1 MHz between times t_0 and $t_0 + T_W$, where t_0 is the cut-off time (or delay) and T_W is the measurement period width, fixed at 10 ms. In figure 5, the broad DLTS signal recorded with the $Al_{0.6}Ga_{0.4}N$ channel heterostructure reveals the presence of several deep traps. The reduction of electron density in the 2DEG below 300 K is expected to result from electron trapping by the detected deep traps.

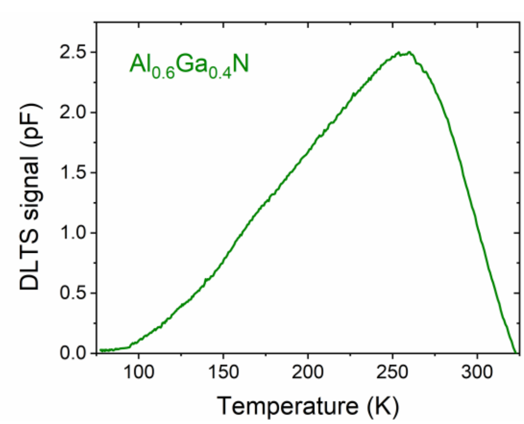

Figure 5: DLTS spectrum of $Al_{0.6}Ga_{0.4}N$ channel HEMT recorded with a reverse bias of – 5 V, a pulse voltage of – 0.5 V, a filling time of 1 ms and a period with of 10 ms.

x_C (%)	x_B (%)	$J_{DS,ON}$ ($A.mm^{-1}$)	$J_{DS,OFF}$ ($A.mm^{-1}$)	$J_{DS,ON}/J_{DS,OFF}$
10	60	1.9×10^{-1}	1.1×10^{-5}	1.8×10^{4}
30	70	6.1×10^{-2}	1.6×10^{-7}	3.9×10^{5}
60	90	4.6×10^{-3}	3.8×10^{-8}	1.2×10^{5}

Table 1: On-state drain current density $J_{DS,ON}$ at V_{DS} = 4V and V_{GS} = 2V, off-state drain current density $J_{DS,OFF}$ at V_{DS} = 4V and V_{GS} = – 12V and $J_{DS,ON}/J_{DS,OFF}$ ratio for the three AlGaN heterostructures with an Al content of x_C in the channel and x_B in the barrier. Data have been recorded at 300K.

At 300K, when increasing the Al fraction in the channel, the on-state and off-state current densities decrease (Table 1). The on/off ratio of the drain current density is higher than 10^5 for Al-rich AlGaN channel heterostructures.

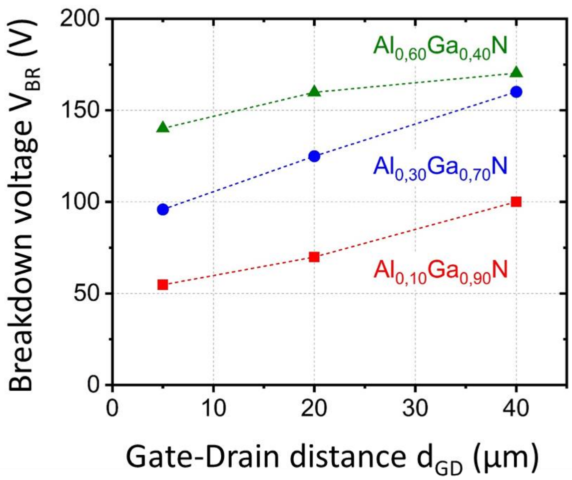

Figure 6: Breakdown reverse voltage as a function of the gate-drain distance at room temperature.

In figure 6, the breakdown voltage is plotted as a function of the gate-drain distance. When increasing the Al content in the AlGaN channel, the heterostructure withstands a higher reverse voltage.

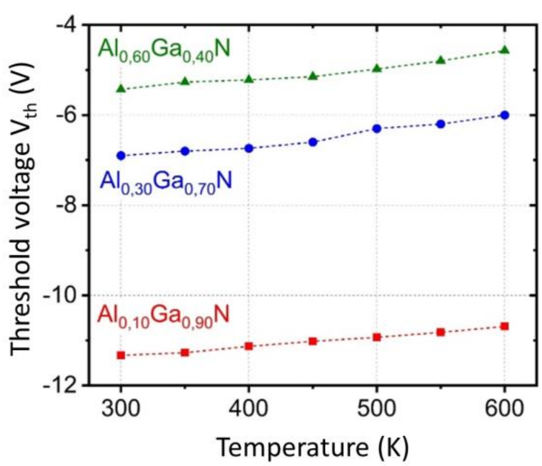

Figure 7: Threshold voltage as a function of temperature at V_{DS} = 4 V.

The temperature dependence of the drain current density between 300 and 600 K has been studied for the three heterostructures. In figure 7, we see the evolution of the threshold voltage V_{th} for V_{DS} = 4 V. Whatever the temperature, V_{th} shifts towards more negative voltages as Al content rises. The slight increase in V_{th} with temperature could result from the release of electrons trapped in the SiN.

The extracted subthreshold slope is quite similar for the HEMTs with Al fraction of 10 % and 30 % in the channel (253 and 242 mV/dec, respectively at 300 K) and is lower for the HEMT with 60% of Al (151 mV/dec at 300 K) (Figure 8). Increasing the Al content of the channel seems to improve the switching speed of the HEMT. This result is in good agreement with previous work and could be explained by the reduction in interface states between the channel and the barrier thanks to a lower lattice mismatch [8].

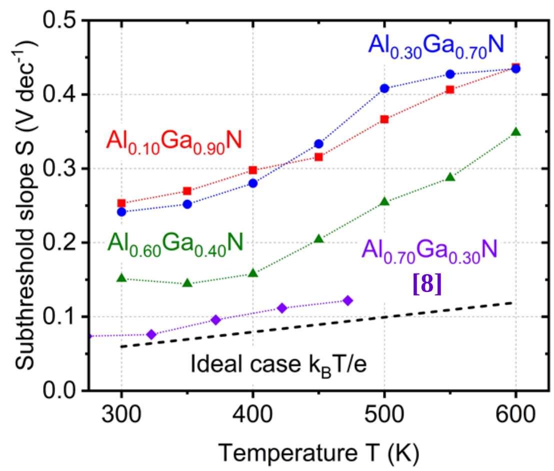

Figure 8: Subthreshold slope as a function of temperature at V_{DS} = 4 V.

The evolution of the normalized on-state current density as a function of temperature is reported in figure 9 for the HEMTs with Al fraction of 10 % and 30 % in the channel and compared with previous works.

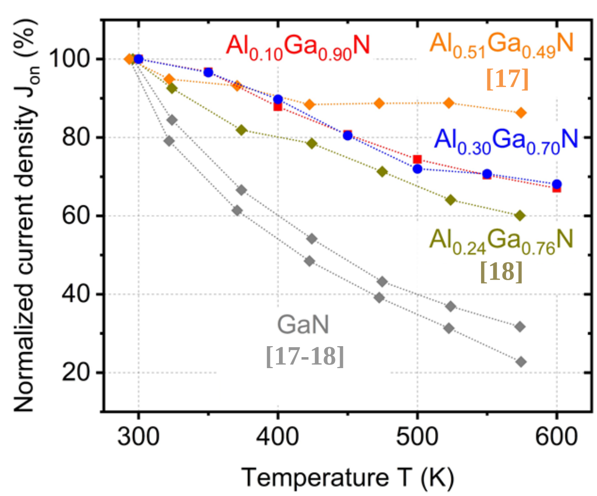

Figure 9: Evolution of the normalized on-state current density as a function of temperature.

We observe a degradation of the on-state current density of – 30 % over the temperature range studied. These results are in good agreement with previous works [17-18].

The specific on-state resistances extracted at 300 and 600 K are 4 and 7 mΩ.cm^2 respectively for the HEMT with Al content of 10 % in the channel and 13 and 19 mΩ.cm^2 respectively for the HEMT with Al content of 30 % in the channel.

Compared with GaN channel HEMTs which present a reduction in on-state current density from – 70 % to – 80 % between 300 and 600 K, AlGaN channel HEMTs are more resistant to high temperatures.

4. Conclusion

The electrical characteristics of AlGaN channel HEMTs on Si with Al contents of 10 %, 30 % and 60 % have been measured as a function of temperature. The extracted parameters were compared with data from previous works on different substrates. By increasing the Al content in AlGaN channel, electron mobility decreases but the switching speed and voltage withstand of the HEMTs are improved. Compared with GaN channel HEMTs, AlGaN channel HEMTs have a much lower degradation of the on-state drain current density at high temperatures.

These results highlight the potential of Al-rich AlGaN channel heterostructures on silicon for high temperature applications. However, by increasing the Al content, the 2DEG density seems to be limited by the presence of deep traps and the contact resistance rapidly increases. These represent the actual limitations of these devices, and outmatch these technological steps is the key to expect further developments.

5. Acknowledgements

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6. References

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