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Abstract

This work aims to understand the origin of propagation losses in GaN-on-Si devices at microwave frequencies thanks to original AFM's electrical modes such as scanning capacitance microscopy (SCM) and scanning spreading resistance microscopy (SSRM). AlN films on Si substrate were grown using Metalorganic Vapor Phase Epitaxy (MOVPE) technique. SCM and SSRM measurements evidence a p-type conductive channel as well as a pn-junction beneath the AlN/Si interface. The diffusion depths of Al and Ga atoms obtained by Secondary Ion Mass Spectroscopy (SIMS) are in good agreement with those deduced from SCM and SSRM. Sample grown at lower temperature (1000°C) exhibits a conductive channel and a junction over a shallow depth explaining its lower propagation losses in comparison with those synthesized at higher temperature (1150°C). Thus, monitoring the dopant diffusion beneath the AlN/Si interface is crucial to achieve efficient GaN-on-Si microwave power devices.

Introduction

GaN-on-Si High Electron Mobility Transistors (HEMTs) have received strong attention for high power and radio frequency (RF) applications due to their interesting material and device characteristics [1-4]. Furthermore, GaN-on-Si HEMTs offer the capability to fabricate low cost devices since high quality Si wafers with a large diameter are commercially available at low price. However, the reliability and efficiency of these devices are still under consideration. Thus, establishing a close relationship between material crystalline quality and electrical property remains a key point for improving the device performance. In this work, the electrical activity at the AlN/Si interface was investigated using scanning capacitance microscopy (SCM) and scanning spreading resistance microscopy (SSRM). The obtained results were correlated to the measured contactless sheet resistance, propagation losses and epitaxy conditions.

Experimental

Three samples A, B, and C were grown by MOVPE in an Aixtron close-coupled showerhead system [5]. Native oxide was removed under H_2 before growing 20 nm nucleation layer at a low temperature of ~ 900°C. Nucleation temperature was increased up to 1000°C for sample B and 1150°C for samples A and C while thickening the AlN buffer up to ~ 200 nm. The crystalline quality of the AlN films was checked by XRD.
Al and Ga diffusion depth into AlN were determined using the SIMS technique. The sheet resistance of these samples grown on intrinsic high resistivity Si(111) (n-type ρ>5kOhm.cm) was measured with a high frequency contactless setup. Propagation losses were measured in the 0.25-67 GHz frequency range on coplanar wave guides fabricated on such templates. SCM and SSRM measurements were performed using a Bruker Dimension Icon provided with a Nanoscope V controller and equipped with SCM and SSRM application modules. SCP-PIT-V2 and DDESP-V2 tips purchased from Bruker were used for SCM and SSRM measurements, respectively. Due to the expected shallow diffusion depth and taking into account the thickness of the AlN layer, the area of interest was expanded by angle bevelling (magnification factor of 5.76).

Results and discussion

The chemical profiles obtained by SIMS (sample A is shown in figure 1.a) reveal that both Al and Ga thermally diffuse into the silicon substrate for the three samples. Ga stems from the minor traces after previous growths in spite of the reactor preparation. The acceptor dopant diffusion depth beneath the AlN/Si interface is ~ 0.4 µm for sample B and ~1 µm for samples A and C. These values indicate the location where the metallurgical junctions for the three samples should be found on such low n-type wafers.

Hence, AFM electrical mode measurements were carried out to highlight the electrical activity in the samples. As an example SCM Data and SSRM resistance 2D images for sample A are shown in figure 1.a and b. Firstly, the AlN layer exhibits low SCM Data of 60 mV corresponding to the SCM electronic noise evidencing that AlN film is not electrically active, as expected. SCM profile highlights the presence of *p*-type conductive channel (positive signal), a space charge region (SCR) as well as an electrical junction (EJ, dC/dV = 0V) beneath the AlN layer inside the Si substrate. The EJ is an intrinsic surface within the SCR where electron and hole concentrations are equivalent. The Si substrate corresponds to *n*-type (negative signal). Secondly, AlN buffer displays resistance as high as 10^{13} Ω highlighting its insulating properties. Underneath the AlN layer, the resistance drops down to $1 \cdot 10^6$ and $6.3 \cdot 10^6$ Ω then reaches an maximum value of $5 \cdot 10^7$ and $1 \cdot 10^8$ Ω before stabilising at $2 \cdot 10^7$ Ω far from the interface for the B and A samples, respectively. Sample C shows similar trend than sample A. The maximum resistance value corresponds to the metallurgical junction (MJ) of the *pn*-junction. It can be noted that, the voltage drops down mostly in the SCR due to the fixed background ions. The depletion width (i.e. $W_n + W_p$, see table 1) of the *pn*-junction deduced from SCM is 0.69 ± 0.02 µm, 2.02 ± 0.02 µm and 2.21 ± 0.01 µm for samples B, A and C, respectively. Figure 1.a highlights that the diffusion depth deduced from SSRM is in good agreement with that of SIMS for the sample A. As shown in table 1, the diffusion depth deduced from the SSRM measurement is 0.27 ± 0.02 µm and 1.13 ± 0.02 µm for samples B and A, respectively. The *p*-type channel in combination with the *pn*-junction can raise the overall losses of the RF devices. However, sample B will displays better performance than samples A and C due its low diffusion depth. Indeed, Table 1 shows that the sheet resistance of sample B is noticeably higher than the one of samples A and C. The measured propagation losses at 40 GHz are 0.7, 2 and 5.7 dB/mm for samples B, C and A, respectively, in agreement with the measured sheet resistances.

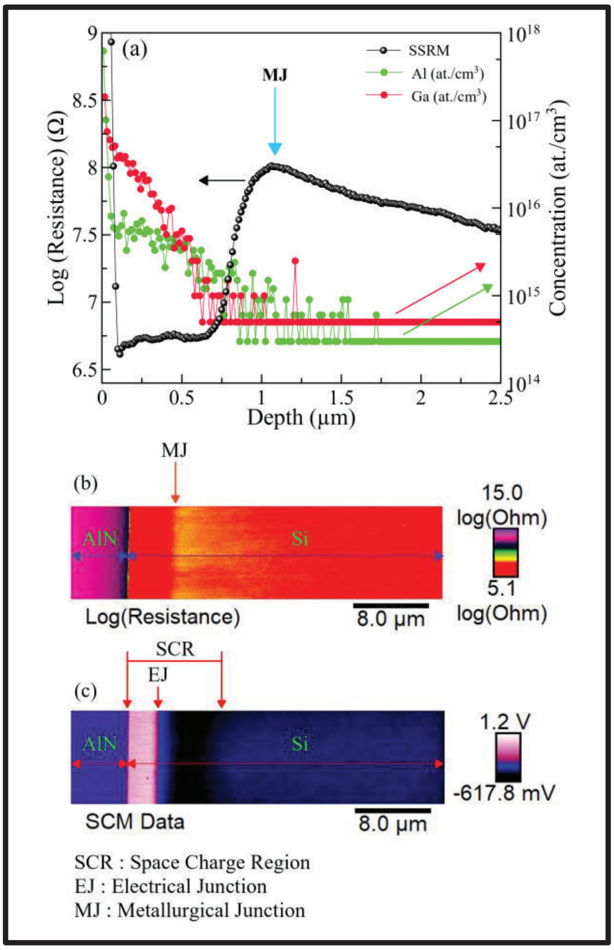

Figure 1. (a) SIMS profile of Al and Ga concentrations as a function of depth. SSRM profile is added for comparison. (b) SSRM resistance does not reveal anything about the doping type (c) SCM Data gives information about doping type and level.

Sample		A	B	C
W_n/W_p (SCM)		1.5	1.7	1.2
d_{MJ} (SIMS) (µm)		1	0.4	1
d_{MJ} (SSRM) (µm)		1.13	0.27	1.13
N_a (at./cm³)	Al	6.2×10^{17}	1.2×10^{19}	-
	Ga	1.9×10^{17}	0.2×10^{19}	-
Rsh (Ohm/sq)		980	9560	3190
Losses at 40 GHz (dB/mm)		5.7	0.7	2

Table 1. Physical characteristics of samples A, B and C: W_n and W_p are the width of the immobile positive and negative ions in the *pn*-junction, d_{MJ} is the diffusion depth of the acceptor doping atoms (Al and Ga), N_a is acceptor doping concentration in the p-type conductive channel.

Conclusions

This work highlights that a *p*-type conductive channel as well as a *pn*-junction are created beneath the AlN/Si interface after AlN films deposition by MOVPE in a close coupled showerhead system. Complementary SCM and SSRM profiles confirmed the diffusion depth of Al and Ga atoms inside the *n*-Si substrate obtained by SIMS. The low temperature deposition (i.e. at 1000°C) of the AlN films permits the *p*-type channel and the *pn*-junction over a shallow depth inside the *n*-Si substrate to be attained, minimising thus parasitic channel conductivity and propagation losses in devices performed on GaN-on-Si. These promising results constitute a key step in the development of efficient devices at low cost.

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