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Demonstration of Submicron-gate AlGaN/GaN High-Electron-Mobility Transistors on Silicon with CMOS-compatible Non-Gold Metal Stack

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We have demonstrated 0.15-µm gate-length AlGaN/GaN high-electron-mobility transistors (HEMTs) with direct-current (DC) and microwave performance for the first time using complementary metal-oxide-semiconductor (CMOS)-compatible non-gold metal stack. Si/Ta-based ohmic contacts with low contact resistance value (R_c=0.24 Ω·mm) and with smooth surface morphology. The fabricated GaN HEMTs exhibited g_{mmax}=250 mS/mm, f_T/f_{max} =39/39 GHz, BV_{gd}=90V and drain current collapse <10%. The device Johnson's Figure of Merit (J-FOM =$f_T \times BV_{gd}$) is in the range between 3.51 THz.V to 3.83 THz.V which are comparable to the other reported GaN HEMTs on Si with conventional III-V gold-based ohmic contact process. Our results demonstrate the feasibility of realizing high performance submicron GaN-on-Silicon HEMTs using Si CMOS-compatible metal stack.

GaN High-Electron-Mobility Transistors (HEMTs) have achieved record-high cut-off frequencies (f_T~370 GHz),[1] microwave power density (P_{out}~2.5 W/mm) @40 GHz,[2] which exceeded the existing Si-based device technology limits. Most reported GaN devices with impressive performance were fabricated using non complementary metal-oxide-semiconductor (CMOS)-compatible gold-based metal stacks.[1-8] Now, many industries including existing silicon semiconductor manufacturers are showing increased interests to develop GaN HEMT technology on large diameter Si substrates.[3,8,9] In order to utilize the existing Si fabrication line, non-gold ohmic contacts with low contact resistance, R_c is essential. To date, most of the ohmic contacts with low R_c values make use of gold-based metal schemes. Table I summarizes some of the best reported R_c values for "gold" and "non-gold" based ohmic contacts for AlGaN/GaN HEMTs on Si. The lowest R_c of 0.49 Ω.mm so-far achieved is with non-gold ohmic contact annealed at 870 °C.[10] Till now, researchers have only reported >1.5 μm-gate-length AlGaN/GaN HEMTs using "non-gold" ohmic contacts for low-cost high-power electronics.[8-10] However, for high frequency applications, submicron gate-length HEMTs are necessary. Thus far, to the best of our knowledge, no report exists on the DC and microwave characteristics of sub-micron gate-length AlGaN/GaN HEMTs using CMOS-compatible non-gold metal stack. In this letter, we report for the first time the DC and microwave characteristics of sub-micron gate-length AlGaN/GaN HEMTs using CMOS-compatible non-gold metal stack.

The GaN HEMT structure was grown by metal-organic chemical vapor deposition with 2nm-thick GaN cap-layer, 18nm-thick $Al_{0.26}Ga_{0.74}N$ barrier, 800-nm-thick GaN buffer and 1.4μm-thick transition layer on a 4-in silicon (111) (resistivity >6000 Ω·cm).[6] The grown structure exhibited room temperature 2-Dimensional Electron Gas mobility of 1450 cm^2/V.s and sheet carrier density of 1.1×10^{13} cm^{-2}. This HEMT structure is chosen for this study to benchmark with our HEMTs using standard gold-based process.[11] After the mesa isolation

was formed using dry etching by BCl_3/Cl_2 plasma, Ta/Si/Ti/Al/Ni/Ta (8/2/15/140/30/25 nm) ohmic metal was deposited and annealed at 800°C for 30s in a N_2 environment with a rapid thermal annealing system. Typical R_c of 0.24 Ω·mm (standard deviation of 0.07 Ω·mm) is achieved out of 3 separate runs with an average specific contact resistivity (ρ_c) of $1.25x10^{-6}$ Ωcm^2. The achieved R_c is believed to be the lowest ever reported for non-gold ohmic contacts for conventional GaN HEMTs on Si and it is also lower than the recessed ohmic contacts[10] as shown in Table I. This ohmic metal stack aslo provides smooth surface morphology [see Fig.1(a) and (b)] and good edge-definition. This simple ohmic scheme also avoids the need to use other complicated techniques such as ohmic-recess[10] or re-grown ohmic contact[1] which will further introduce complication in the manufacturing process. The ohmic contact details will be published elsewhere.

To form the T-gate, a first layer of 120-nm thick SiN was deposited by plasma enhanced chemical vapour deposition (PECVD) after the ammonium sulphide $[(NH_4)_2S_x]$ treatment for about 30 min.[11] The 0.15μm foot-print was opened and etched the SiN by CF_4/O_2 plasma. Then 1.0-μm gate-head was subsequently formed with CMOS-compatible non-gold metal stack of Ni/Al/Ta (100/400/30 nm). Finally, the non-gold metal-stack Ti/Al/Ta (50/800/30 nm) as a inter-connect metal was deposited followed by final passivation with 120-nm thick PECVD grown SiN. The metal schemes used for this study (i.e. ohmic-contact, Schottky-contact and interconnect metal lines) are commonly used in the silicon fabrication process line and hence it will not introduce any cross-contamination in the manufacturing lines. The device dimensions used for this study are $L_{sg}/L_g/L_{gd}/W_g$ =0.8/0.15/1.7/(2×75) μm. The fabricated device DC and pulsed I-V characteristics of the HEMTs were measured using Agilent B1500 semiconductor parameter analyzer and Accent Diva D265, respectively. The microwave small signal (from 6 to 40 GHz) measurements

were also carried out using HP 8510C vector network analyzer (VNA).

Figure 1 (c) shows the typical I_{DS}-V_{DS} characteristics of 0.15-μm gate-length GaN HEMTs with CMOS compatible non-gold metal scheme. The devices exhibited -maximum drain current density (I_{Dmax}) of 830 mA/mm, maximum extrinsic transconductance (g_{mmax}) of 250 and mS/mm and threshold voltage (V_{th}) of -3.75 V. The Ni/Al/Ta Schottky gate exhibited a barrier height of 0.88 eV and a reverse gate-leakage current (-20 V) of 3.8×10^{-3} mA/mm.

Figure 2 (a) shows the small signal gain versus frequency for the HEMT with CMOS compatible non-gold metal stack. The devices exhibited a unit current gain cut-off frequency f_T of 39 GHz and maximum oscillation frequencies f_{max} of 39 GHz. This is believed to be the first reported microwave performance of submicron AlGaN/GaN HEMTs using CMOS-compatible non-gold metal stack ohmic contacts. Figure 2 (b) shows the pulsed I-V characteristics (pulse width = 200 ns; pulse period=1ms) of AlGaN/GaN HEMTs with CMOS-compatible non-gold metal stack. Very little current collapse (<10%) was observed for the gate- and drain-quiescent biases (V_{gs0}=-8 V, V_{ds0}=10 V). Three terminal OFF-state breakdown voltage (BV_{gd}) of AlGaN/GaN HEMTs is 90 V which is measured by drain current injection method (see Fig 3).[12)] The J-FOM[13,14)] (= $f_T\times BV_{gd}$) of HEMTs are in the range between 3.51 THz.V to 3.83 THz.V for different gate-drain spacing devices (L_{gd}=1.7 to 3.5 μm). The obtained values are comparable to the J-FOM of 3.3 THz.V for 0.15-μm gate-length GaN HEMTs on Si(111) fabricated using non-CMOS comparable gold metal stack.[15)]

In summary, we have demonstrated for the first time a sub-micron gate-length AlGaN/GaN HEMT on high-resistivity Si substrate with DC and microwave performance using CMOS-compatible non-gold metal stack. After annealing at 800 °C, ohmic contact exhibited smooth surface morphology with a low R_c value of 0.24 Ω·mm. The fabricated 0.15-μm-gate GaN HEMTs exhibited g_{mmax}=250mS/mm, f_T/f_{max} =39/39GHz, BV_{gd}=90V and

drain current collapse <10%. The device Johnson's figure of merit (J-FOM $=f_T \times BV_{gd}$) is in range between 3.51 THz.V to 3.83 THz.V which are comparable to the other reported GaN HEMTs on Si with gold-based metal scheme (3.3 THz.V). These results demonstrate the feasibility of non-gold metallization process to achieve sub-micron gate AlGaN/GaN HEMTs on Si substrate for high-frequency applications.

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Figure Captions:

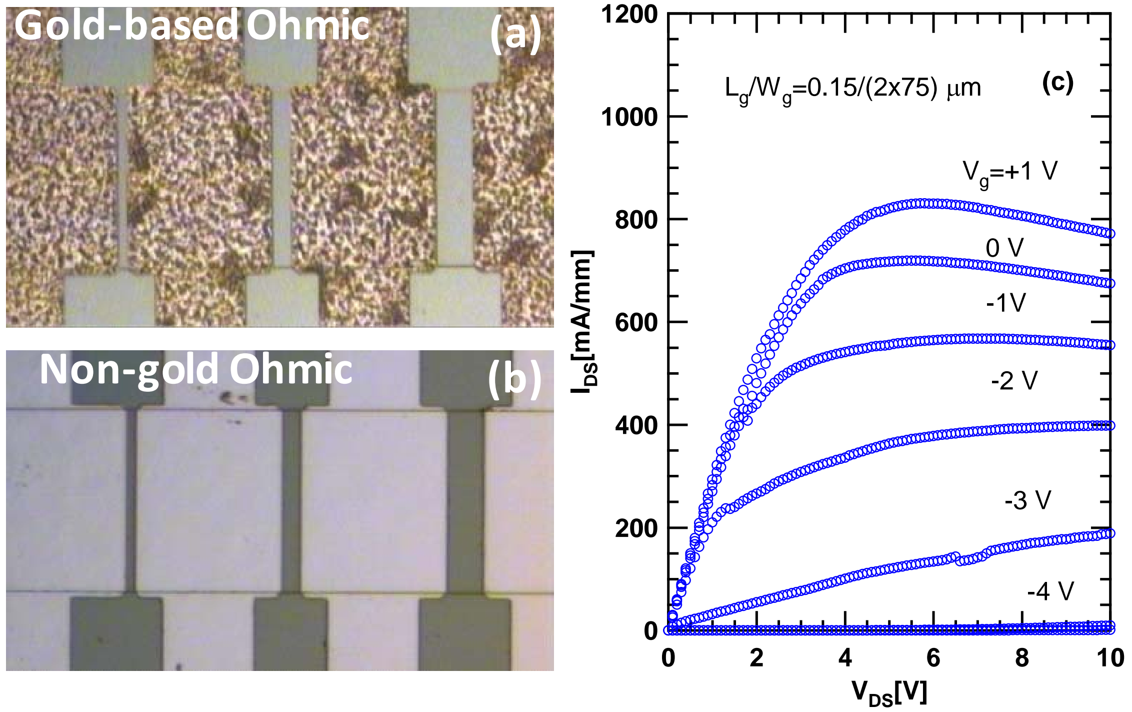
Figure 1. Surface morphology of (a) non-CMOS compatible gold-based (b) CMOS compatible non-gold ohmic contact and (c) I_{DS}-V_{DS} characteristics of 0.15μm-gate AlGaN/GaN HEMTs with CMOS-compatible non-gold metal stack.

Figure 2. (a) Small signal characteristics of AlGaN/GaN HEMTs with CMOS compatible non-gold metal stack. Bias points: V_d=6V, V_g=-2.7V. (b) Pulse I_{DS}-V_{DS} characteristics of 0.15-μm-gate AlGaN/GaN HEMTs with CMOS compatible non-gold metal stack. V_g= +1 to -5 V, step -1V.

Figure 3. Three terminal OFF-state breakdown voltage characteristics of HEMT with CMOS compatible non-gold metal stack. The device is with dimensions of L_{sg}=0.8 μm, L_g=0.15 μm, L_{gd}=1.7 μm and W_g=2×75 μm.

Table I. Contact resistance values for different GaN HEMT structures on Si substrate using III-V compatible gold and CMOS compatible non-gold ohmic contacts.

Research Group	HEMT on Si	Metal Stack	Annealing Temperature [°C]	R_c [Ω·mm]	
				Gold	Non-Gold
Nitronex [4]	AlGaN/GaN	Ti/Al/Ni/Au	825	0.45 (Rough Surface)	-
NTU [5]	AlGaN/GaN	Ti/Al/Ni/Au	825	0.18 (Rough Surface)	-
ETH-Z[6]	AlGaN/GaN	Ti/Al/Ni/Au	850	0.45 (Rough Surface)	-
IEMN [7]	AlGaN/GaN	Ti/Al/Ni/Au	900	0.50 (Rough Surface)	-
MIT [10]	AlGaN/GaN	Ti/Al/W	870 (Ohmic-Recess)	-	0.49 (Smooth Surface)
IMEC [8]	AlGaN/GaN/AlGaN	Ti/Al/W	800	-	0.65
IMEC [9]	AlGaN/GaN/AlGaN	Ti/Al/Ti/TiN	550 (Ohmic-Recess)	-	1.25
This Work	AlGaN/GaN	Ta/Si/Ti/Al/Ni/Ta	800	-	0.24 (Smooth Surface)



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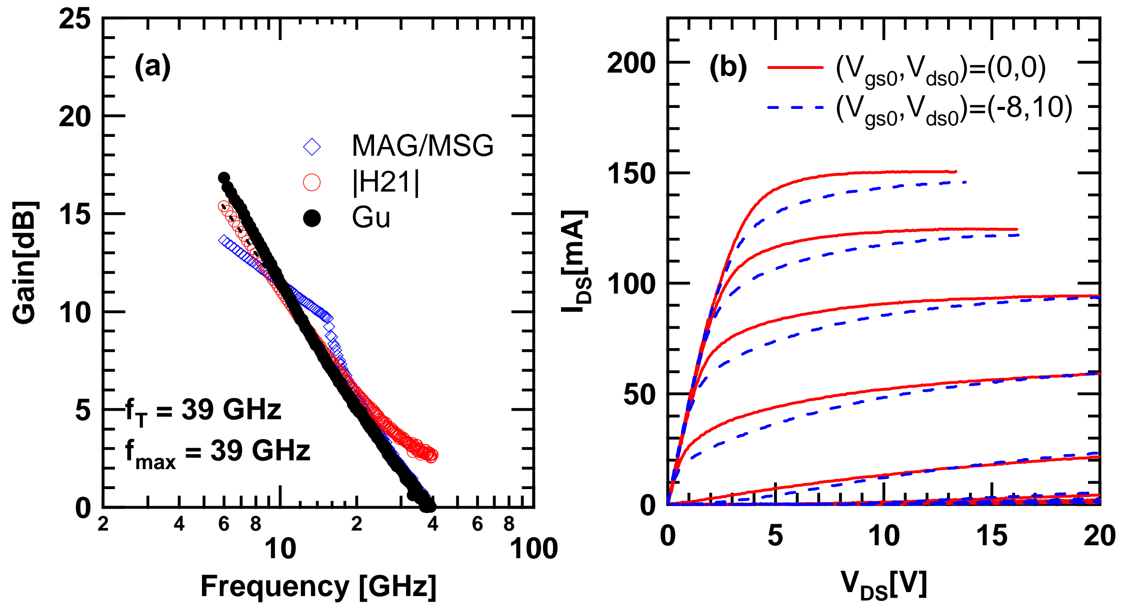

Figure. 2. S. Arulkumaran et al.

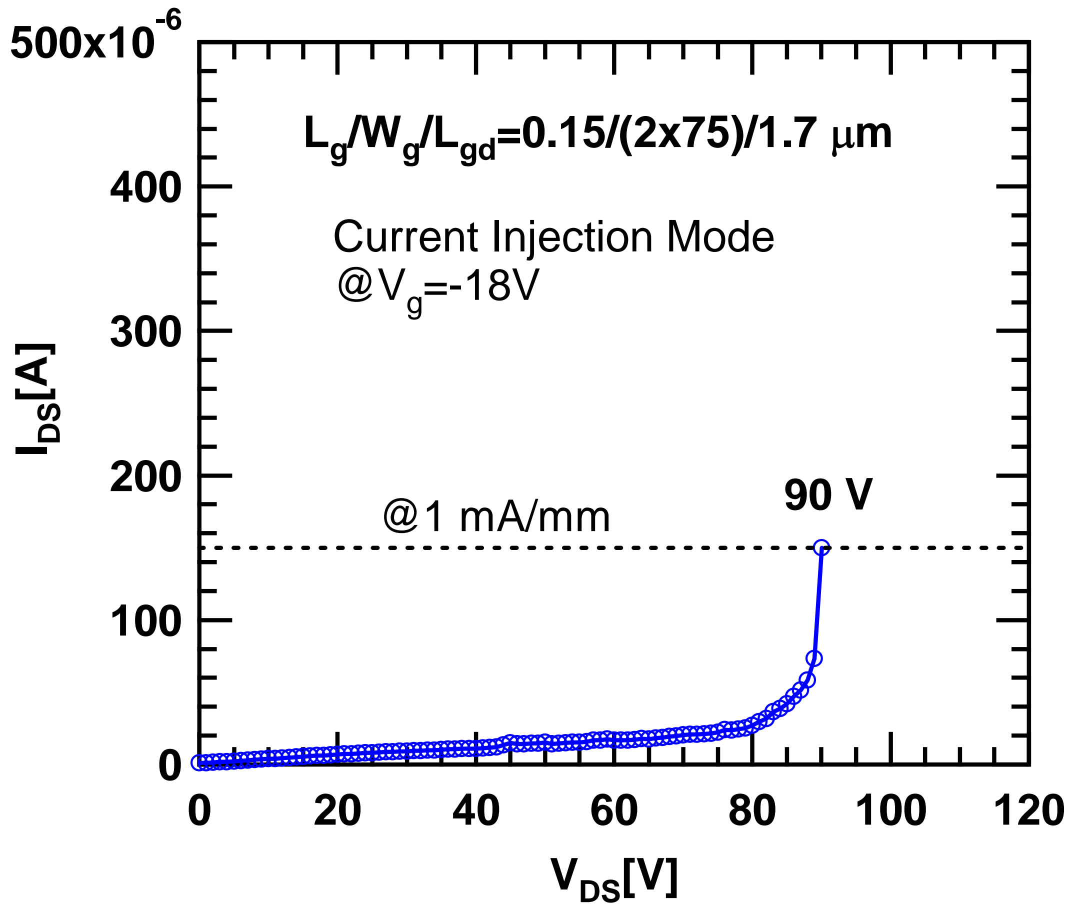

Figure 3. S. Arulkumaran et al.