Antimonide NMOSFET with Source Side Injection Velocity of 2.7x10^7 cm/s for Low Power High Performance Logic Applications

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Abstract: Antimonide (Sb) quantum well (QW) MOSFETs are demonstrated with integrated high-κ dielectric (1nmAl_2O_3-10nm HfO_2). The long channel Sb NMOS exhibits effective electron mobility of 6,000 cm^2/Vs at high field (2 x 10^{12} /cm^2 of charge density (N_s)), which is the highest reported value for any III-V MOSFET. The short channel Sb NMOSFET (L_G = 150nm) exhibits a cut-off frequency (f_T) of 120GHz, f_T - L_G product of 18GHz.µm and source side injection velocity (v_{eff}) of 2.7x10^7 cm/s, at drain bias (V_{DS}) of 0.75V and gate overdrive of 0.6V. The measured f_T and f_T x L_G are 2 x higher, and v_{eff} is 4x higher than Si NMOS (1.0-1.2V V_{DD}) at similar L_G, and are the highest for any III-V MOSFET.

Introduction: $InAs_xSb_{1-x}$ quantum-well (QW) heterostructure with high electron mobility integrated with high hole mobility strained $In_xGa_{1-x}Sb$ QW, can potentially enable III-V CMOS and share the same metamorphic buffer on Silicon (Fig. 1a) [1]. In this paper, we report $InAs_{0.8}Sb_{0.2}$ NMOSFETs with integrated high-κ dielectric, which exhibit record high long channel electron mobility, short channel electron velocity and high-frequency small-signal performance, for the first time. The effects of interface trap density (D_{it}) which degrades the DC drive current and transconductance (g_m) is studied in detail using pulsed I-V and radio frequency (RF) measurements.

Device Fabrication and Characterization: Fig. 1(b) shows the schematic of $InAs_{0.8}Sb_{0.2}$ nMOSFET with 1nmAl_2O_3/10nm HfO_2 high-κ gate dielectric. We obtain Hall mobility of 13,500 cm^2/Vs at a carrier density of 2.2x10^{12} /cm^2 for the as-grown device layers without dielectric. Fig. 1(c) shows the tilted view SEM of a device, fabricated using a process detailed in [2], with 150nm L_G and source-to-drain separation of 500nm.

Development of a Scaled Gate Stack for Antimonide MOSFETs: A high quality gate stack is needed for integration with $InAs_xSb_{1-x}$ QW, with low EOT and J_{OX}, excellent interface properties and high carrier mobility in the channel. We use an ultra-thin (1nm) GaSb cap layer on top of the upper barrier for dielectric integration, to prevent oxidation of the $In_{0.2}Al_{0.8}Sb$ barrier layer. Using ALD Al_2O_3/HfO_2 bilayer dielectric on n and p type GaSb, we demonstrate MOSCAPs with unpinned Fermi level across gap and scaled EOT (Fig.2). The extracted D_{it} (Fig. 2b) is low towards valence band of GaSb which results in good nMOS turn off, while the high D_{it} from midgap to conduction band can affect drive current.

DC Characterization: Fig. 3(a-f) shows the transfer and output characteristics of Sb nMOSFETs with 5µm, 450nm and 150nm gate lengths. The long channel devices exhibit good I_{ON}-I_{OFF} ratio and excellent saturation in the output characteristics. Contact resistance limits the drive current in the 150nm L_G device which has an I_{DSAT} of 525µA/µm at V_{DS} of 1.0V. The sub-threshold characteristics and short channel effects degrade as L_G is scaled, due to the non-optimized barrier and oxide thickness and the thick quantum well structure (EOT=4.5nm).

Long Channel Device Characterization: Fig. 4(a) shows the measured and simulated split C-V characteristics of L_G=20µm device. The stretch-out in the measured C-V compared to the simulated C-V is due to D_{it}. Fig. 4(b) shows the electron drift mobility extracted from the output conductance and measured C-V characteristics. We report a record high effective electron mobility of 6,000 cm^2/Vs at 2x10^{12} /cm^2 of N_s, which is 15x higher than Si NMOS inversion layer mobility and 3x higher than that of InGaAs NMOS[3]. The Sb NMOSFET electron mobility is 2.2x lower than the Hall mobility. This is further investigated in detail using pulsed IV (2µs pulsed width) and RF measurements. Figs. 4 (c-d) show the output and transfer characteristics of the 450nm L_G device using DC and pulsed measurements. The pulsed I_D-V_D data shows significant improvement (by 35% at 0.75V gate overdrive) in I_{ON} and I_{ON}-I_{OFF} ratio compared to the DC. Fig 4(e) shows extrinsic g_m comparing DC, pulsed IV and RF measurements. Peak extrinsic RF g_m improves by 30% compared to DC G_m for a gate overdrive of 0.6V. This improvement is due to reduced charge trapping in the dielectric at very high frequencies. This confirms that the reduction in FET mobility compared to Hall mobility is due to overestimation of charge from split C-V, and the actual electron mobility in Sb MOSFET should be at least 30-40% higher than the measured DC value of 6000 cm^2/Vs.

Short Channel Device Characterization: Fig. 5(a) shows the measured and modeled scattering parameters of the 150nm L_G device from 100MHz to 50GHz and Fig. 5(b) shows the extracted circuit elements. Excellent agreement between the measured and simulated S-parameters confirms the extracted circuit element values. Fig. 5(c) shows the measured and modeled small signal current gain, $|h_{21}|$, vs frequency for L_G=150nm, 300nm and 450nm. The devices have cut-off frequencies of 120GHz, 55GHz and 27GHz, respectively. From the extracted parameters from small signal modeling, we evaluate the source side injection velocity (v_{eff}) of these devices as g_m/slope(C_{gs} vs L_G). Figs. 5(d-e) benchmark the v_{eff} and f_T of the Sb NMOS devices with state-of-the-art Si and III-V NMOS. The 150nm L_G Sb NMOS exhibits a v_{eff} of 2.7x10^7 cm/s and f_T.L_G product of 18GHz.µm, which are the highest reported for III-V MOSFETs till date.

Enhancement Mode Operation: While above mentioned devices operate in depletion mode (normally ON) due to thick EOT, enhancement mode (normally OFF) operation is required for logic applications. We have recently demonstrated e-mode Sb nMOS devices with scaled barrier and quantum well [2], as shown in Fig. 6.

Conclusions: Long channel Sb NMOS devices are demonstrated with high field effective electron mobility of 6,000 cm^2/Vs. Short channel Sb NMOS exhibit cut-off frequency (f_T) of 120GHz, f_T - L_G product of 18 GHz.µm and source side injection velocity (v_{eff}) of 2.7x10^7 cm/s, at V_{DS}= 0.75V and V_{GS} – V_T =0.6V. The measured f_T, f_T x L_G are 2x higher, while v_{eff} is 4x higher than Si NMOS (1.0-1.2V V_{DD}), and are the highest among III-V MOSFETs. The 150nm L_G device exhibits a drive current of 525 µA/µm at V_{DS} of 1.0V.

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References

[1]M. Hudait, S. Datta, R. Chau et al.; US Patent No. 7429747 [2]A. Ali et al.; EDL 2011 [3]S.Kim et al.; IEDM 2011 [4]M. Radosavljevic et al.; IEDM 2009

I. Motivation for Antimonide CMOS and Device Fabrication

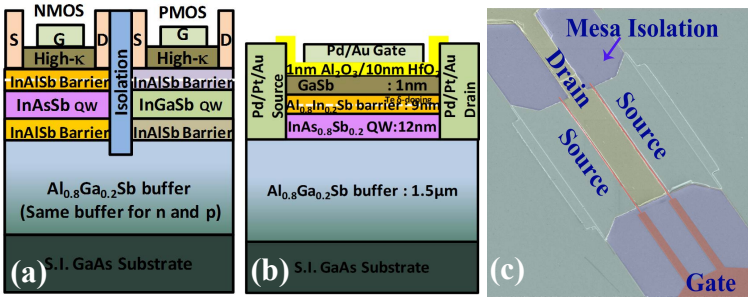


Fig. 1 (a): Schematic of Sb CMOS with common buffer technology; (b) Schematic of the Sb NMOS with 1nmAl_2O_3/10nm HfO_2 dielectric; (c) SEM image of the fabricated device with 150nm L_G and 500nm source-to-drain spacing

II. Scaled Gate Stack Development

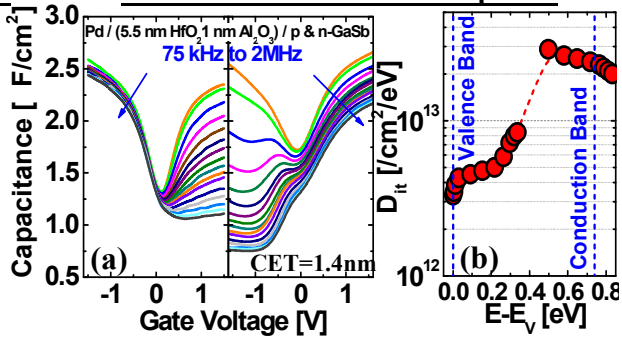


Fig. 2 (a): C-V of n and p type GaSb MOS capacitors with 1nmAl_2O_3-5.5nm HfO_2 dielectric; (b) Extracted D_{it} vs energy

III. DC Characterization

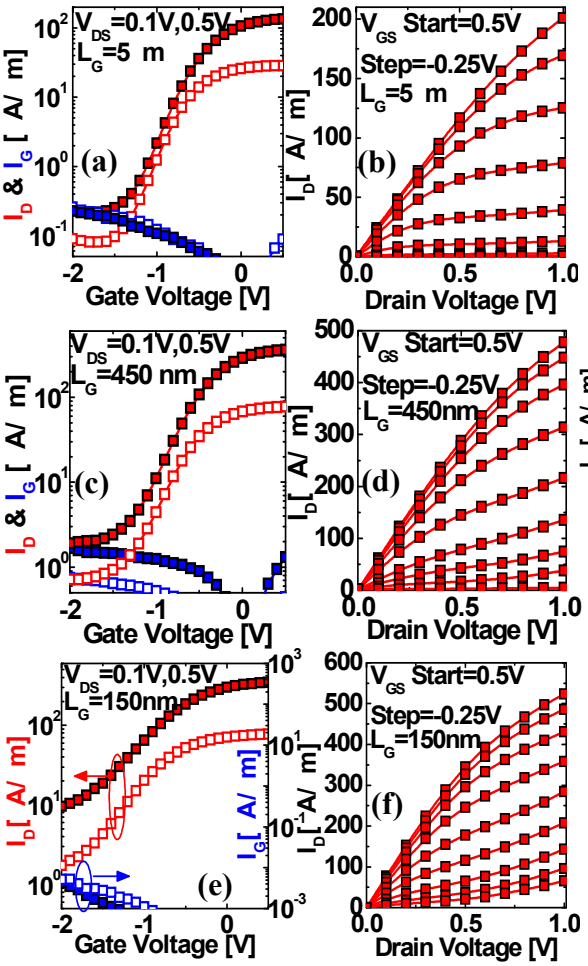


Fig. 3 (a-f): Transfer and output characteristics of Sb nMOSFETs with 150nm, 450nm and 5μm L_G.

IV. Long Channel Device Characterization and Benchmarking

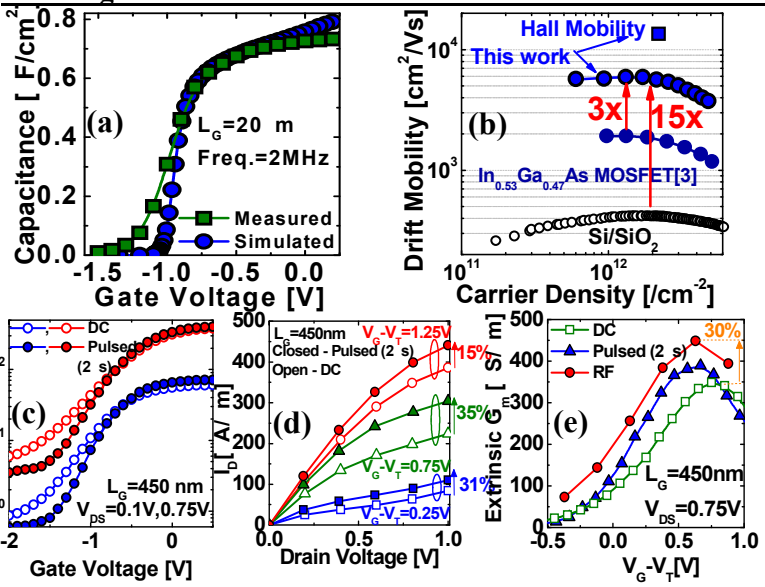
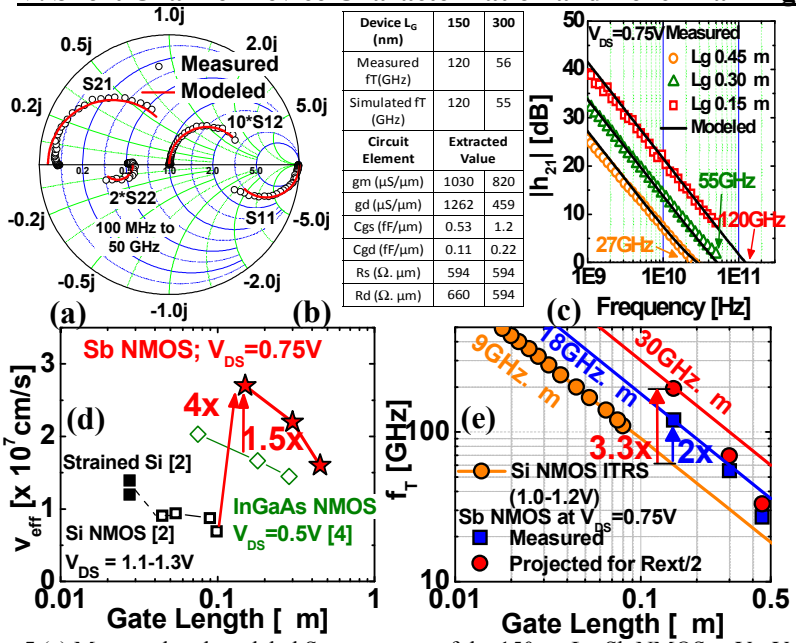


Fig. 4 (a) Measured and modeled split C-V characteristics; (b) Extracted drift mobility vs N_s showing record high mobility; (c-d) Pulsed IV characteristics showing significant enhancement in I_{ON} and I_{ON}/I_{OFF} over DC; (e) Extrinsic RF g_m showing 30% enhancement over DC g_m due to less charge trapping in RF.

V. Short Channel Device Characterization and Benchmarking



Device L_G (nm)	150	300
Measured fT(GHz)	120	56
Simulated fT (GHz)	120	55
Circuit Element	**Extracted Value**	
gm (μS/μm)	1030	820
gd (μS/μm)	1262	459
Cgs (fF/μm)	0.53	1.2
Cgd (fF/μm)	0.11	0.22
Rs (Ω. μm)	594	594
Rd (Ω. μm)	660	594

Fig. 5 (a) Measured and modeled S-parameters of the 150nm L_G Sb NMOS at V_G-V_T= 0.6V and V_{DS}=0.75V; (b) Extracted circuit elements from the small signal model; (c) Measured and modeled $|h_{21}|$ (d) Extracted source injection velocity; (e) f_T vs L_G. The measured f_T, f_T x L_G and v_{eff} are the highest among III-V MOSFETs.

VI. Enhancement Mode Operation

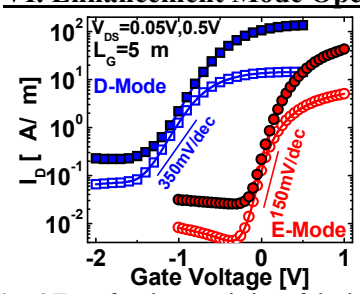


Fig. 6 Transfer characteristics of depletion and enhancement mode device. Scaling the QW and barrier, results in enhancement mode operation.