Fermi Level Unpinning of GaSb(100) using Plasma Enhanced ALD Al_2O_3 Dielectric

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Antimonide based compound semiconductors have gained considerable interest in recent years due to their superior electron and hole transport properties [1-3]. Among the various high mobility material systems (Fig. 1), arsenic-antimonide based MOS-HEMTs have great potential to enable complementary logic operation at low supply voltage. Integrating a high quality dielectric is key to demonstrating a scalable arsenic-antimonide MOS-HEMT architecture for 15 nm logic technology node and beyond. It is hypothesized that an ultra-thin GaSb surface layer is more favorable toward high-κ integration than $In_{0.2}Al_{0.8}Sb$ barrier as it avoids Al at the interface and the associated surface oxidation. Here, we study the effects of various surface passivation approaches on the capacitance-voltage characteristics (C-V) and the surface chemistry of Te-doped n-GaSb(100) MOS capacitors made with ALD and Plasma Enhanced ALD (PEALD) Al_2O_3 dielectric. We demonstrate for the first time, unpinned Fermi level in GaSb MOS system with high-κ PEALD Al_2O_3 dielectric using admittance spectroscopy and XPS analysis.

N-type and p-type GaSb (100) wafers were degreased in acetone and IPA. For some samples HCl etch was used to remove surface oxide and a dilute ammonium sulfide solution was used to passivate the surface. GaSb MOS capacitors were fabricated with Al_2O_3 deposited by ALD at 300°C from trimethylaluminum (TMA) and water or by PEALD at 200°C from TMA and CO_2. PEALD was employed to reduce the thermal budget of dielectric deposition, particularly important for antimonide semiconductors [4]. Fig. 2 shows the C-V measurements on the n-type ALD Al_2O_3-GaSb MOS capacitors. The control sample without surface preparation showed a pinned Fermi level, and the HCl and ammonium sulfide treated ALD samples showed weakly pinned C-V characteristics with very fast interface trap (D_{it}) response. Fig. 3 shows C-V and G-V (conductance) characteristics of the n-type PEALD samples which shows very good Fermi level modulation. The accumulation side of the admittance data was analyzed using the standard depletion/accumulation model and the inversion side using the model shown in Fig. 4(a) [5]. The circuit model in inversion accounts for the supply of minority carriers along with interface state contribution which enables accurate modeling of the admittance data in weak inversion. The modeled data and extracted quasi-static C-V corrected for D_{it} is also shown in Fig. 3 which is in good agreement with the measured data. Fig. 4(b) shows the Arrhenius plot of the minority carrier (hole) conductance in the n-type PEALD sample which gives an activation energy of 0.1eV. This is much less than the activation energy for SRH generation through mid-level traps in the depletion region (Eg/2=0.36 eV). It could be possible the second ionization level of the native acceptor defects (at 0.1eV from valence band due to Ga vacancies and antisite defects [6]) is supplying the minority carriers for inversion.

Fig. 5 shows C-V characteristics of the ALD and PEALD devices on the p-type GaSb sample for different temperatures. The ALD device shows strongly pinned C-V characteristics with both accumulation and inversion regimes completely dominated by interface states. For the PEALD device, there is minimal dispersion of capacitance in accumulation due to less D_{it} near valence band and the inversion regime shows contributions from minority carriers as well as interface states. Fig. 6 shows the monochromatic XPS analysis of the ALD and PEALD samples with and without sulfide wet treatments of the GaSb. All PEALD and ALD samples show presence of Ga-oxides, while the PEALD samples also indicate Ga-Ga bond formation at the interface (not shown). The ALD samples show no detectable Sb-oxides where as the PEALD samples still have significant Sb-oxides. It is important to note that the Sb_2O_3 reacts with GaSb forming Ga_2O_3 and elemental Sb: $Sb_2O_3 + 2GaSb \rightarrow Ga_2O_3 + 4Sb$. The kinetics of this reaction is significant at higher temperatures >200°C [7]. The ALD which was done at 300°C could therefore result in significant formation of elemental Sb, thereby consuming the entire Sb_2O_3. In contrast, the PEALD was done at 200°C where the reaction is significantly suppressed. The 4d orbital binding energy of elemental Sb is same as that of the Sb 4d orbital in GaSb. Hence, due to the Al_2O_3 thickness, it is difficult to say whether the PEALD samples are free from elemental Sb. However, the absence of Sb_2O_3 peaks is consistent with the Sb_2O_3 consumption. Hence the surface Fermi level pinning in the case of ALD deposited Al_2O_3 is likely due to the presence of elemental Sb at the interface leading to a high density of states within the band gap. The absence of water in PEALD, coupled with low thermal budget, leads to a better quality interface. Fig. 7 shows the D_{it} extracted from the n-type and p-type samples. The D_{it} extracted from the n-type MOSCAP data using the inversion model (Fig. 4) is consistent with the analysis on the p-type sample.

In summary, we have demonstrated GaSb MOS capacitors with unpinned Fermi using PEALD Al_2O_3 by minimizing elemental Sb at the GaSb/Al_2O_3 interface. The D_{it} is low near valence band which makes GaSb-PEALD Al_2O_3 a good interface for InAsSb MOS HEMTs where the surface Fermi level sweeps below midgap of GaSb.

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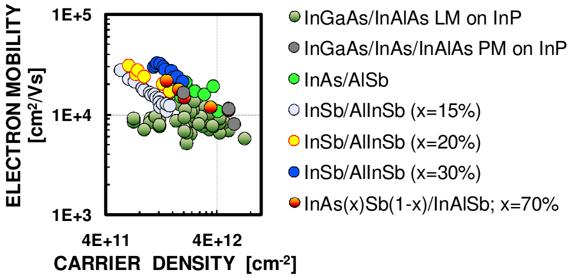

Fig. 1: Quantum well electron mobility for III-V HEMTs

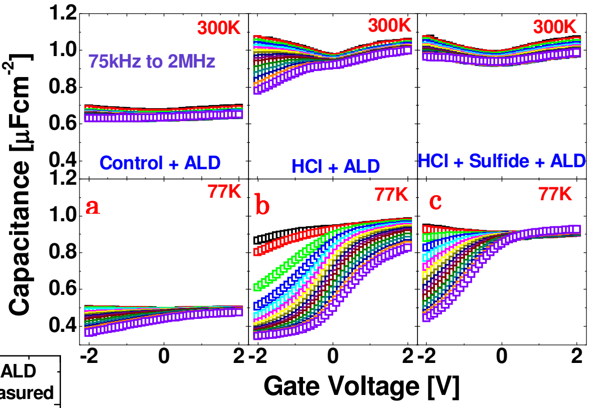

Fig. 2: C-V characteristics of n-type (a) Control sample (no surface passivation) (b) HCl treated sample and (c) Ammonium Sulfide treated samples. Control sample is pinned; other ALD samples show weak Fermi level modulation.

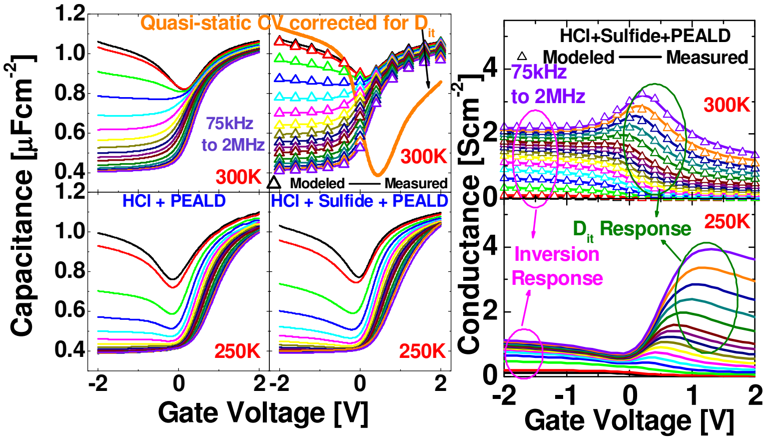

Fig. 3: C-V and G-V of n-type PEALD samples with HCl and ammonium sulfide treatments. The extracted quasi-static C-V using the model in Fig. 4(a) shows that the inversion CV is less affected by D_{it} than the accumulation C-V.

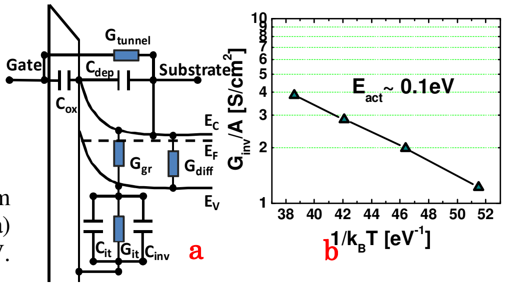

Fig. 4: (a) Equivalent circuit model for MOS capacitor in weak and strong inversion incorporating SRH generation and D_{it} effect. (b) Arrhenius plot of the inversion specific conductance for n-type PEALD sample with HCl and Sulfide treatment.

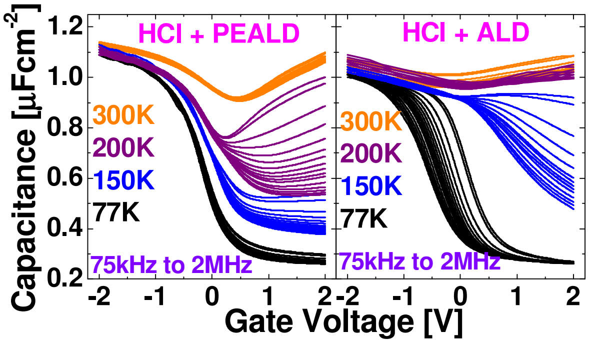

Fig. 5: C-V characteristics of p-type PEALD and ALD samples with HCl treatment. PEALD samples show inversion response at positive bias along with small D_{it} effect. ALD samples show very high D_{it} effect and strong Fermi level pinning.

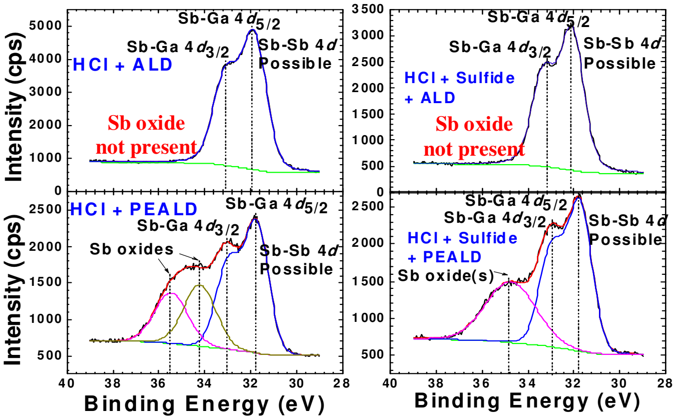

Fig. 6: XPS data comparing the concentration of Sb_2O_3 in ALD and PEALD samples. Absence of Sb_2O_3 in the ALD samples is indicative of presence of elemental Sb which pins the Fermi level at the GaSb-ALD Al_2O_3 interface.

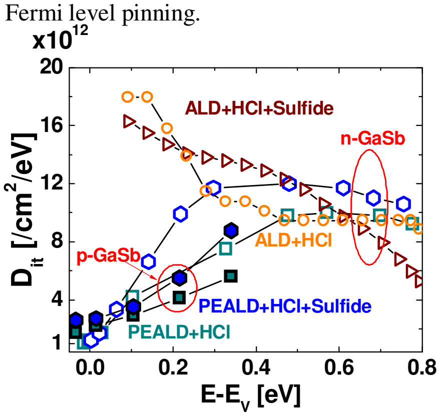

Fig. 7: Extracted D_{it} from p-type and n-type samples showing low D_{it} near valence band for PEALD devices. The circuit model in Fig. 4(a) was used to extract D_{it} in the inversion side for the n-type samples which is consistent with the data obtained from p-type samples.