$In_{0.53}Ga_{0.47}As(001)$-(2x4) and $Si_{0.5}Ge_{0.5}(110)$ surface passivation by self-limiting deposition of silicon containing control layers

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INTRODUCTION

Metal oxide semiconductor field effect transistors (MOSFETs) are diverging from the exclusive use of silicon and germanium to the employment of compound semiconductors such as SiGe and InGaAs to further increase transistor performance. A broader range of channel materials allowing better carrier confinement and higher mobility could be employed if a universal control monolayer (UCM) could be ALD or self-limiting CVD deposited on multiple materials and crystallographic faces. Silicon uniquely bonds strongly to all crystallographic faces of $InGa_{1-x}As$, $In_xGa_{1-x}Sb$, $In_xGa_{1-x}N$, SiGe, and Ge enabling transfer of substrate dangling bonds to silicon, which may subsequently be passivated by atomic hydrogen. Subsequently, the surface may be functionalized with an oxidant such as HOOH(g) in order to create a UCM terminating Si-OH layer, or a nitriding agent such as N_2H_4(g) in order to create an Si-N_x diffusion barrier and surface protection layer. This study focuses on depositing saturated Si-H_x, and Si-OH seed layers via two separate self-limiting CVD processes on InGaAs(001)-(2x4), and depositing a Si-N_x seed layer on $Si_{0.5}Ge_{0.5}(110)$ via an ALD process. XPS in combination with STS/STM were employed to characterize the electrical and surface properties of these silicon containing control layers on InGaAs(001)-(2x4) and $Si_{0.5}Ge_{0.5}(110)$ surfaces. MOSCAP device fabrication was performed on n-type InGaAs(001) substrates with and without a Si-H_x passivation control layer deposited by self-limiting CVD in order to determine the effects on $C_{max,}$ frequency dispersion, and midgap trap states.

EXPERIMENTAL

The 350°C self-limiting CVD procedure includes a decapped $In_{0.53}Ga_{0.47}As(001)$-(2x4) surface dosed with total 21 MegaLangmuir Si_2Cl_6 followed by 500 Langmuir atomic hydrogen or 210.55 MegaLangmuir total anhydrous HOOH(g) to create Si-H_x or Si-OH surface termination. Complete saturation of silicon coverage is determined to occur once further dosing with Si_2Cl_6 leads to no further increase in the silicon 2p peak or further decrease in the substrate gallium 3p peak areas. Complete surface saturation of Si-O_x on InGaAs(001)-(2x4) was determined to occur once no further increase in the O 1s peak was seen with additional anhydrous HOOH(g) doses. Following Si-O_x surface saturation, 300,000 Langmuir TMA was dosed at 250°C, and XPS shows the emergence of the Al 2p and C 1s peaks indicative of TMA surface nucleation. The 275°C silicon nitride ALD procedure was studied on a p-type $Si_{0.5}Ge_{0.5}(110)$ surface that underwent an ex-situ wet organic clean followed by a dip into a 2% HF/water solution with a toluene layer on top. The sample was pulled through toluene and loaded into UHV. The as-loaded sample was dosed with 315 MegaLangmuir anhydrous hydrazine to create the N-H_x surface termination, as evident from the presence of the N 1s signal seen in XPS. Next, a 21 MegaLangmuir Si_2Cl_6 dose followed by 17 cycles of 3 MegaLangmuir hydrazine and 3 MegaLangmuir Si_2Cl_6 lead to the increased silicon nitride growth as evident by the increase in Si2p and N1s XPS signals.

MOSCAP fabrication was performed on n-type InGaAs(001) substrates cleaned by 3 min dip in 6:1 buffered oxide etchant (BOE) followed by 10 seconds of water rinse. After drying the sample by N_2 gas, it was transferred to the ALD reactor with minimal air exposure. Next 30 cycles of 100 ms long Si_2Cl_6 pulses (3 MegaLangmuir total exposure) were dosed at 350°C followed by 30 s of H_2 remote plasma at with 50 W forward power. Afterwards, 20 cycles of 45 ms TMA pre-pulses and 60 cycles of 200 ms TMA and 50 ms H_2O were dosed to deposit Al_2O_3 with approximately 6.0 nm physical thickness. After each TMA and H_2O pulse, a 6 s Ar purge was employed. After Al_2O_3 ALD, Ni gate metals and Ni back contacts were deposited using thermal evaporation.

RESULTS AND DISCUSSION

Silicon coverage on InGaAs(2x4) is seen in Fig. 1 (a) which shows corrected XPS peak areas of Si 2p, As 2p, Ga 2p, and In 3d for 3, 12, and 21 MegaLangmuir total doses at 350°C. Following the 21 MegaLangmuir Si_2Cl_6 dose at 350°C, there is no real increase in the Si 2p corrected peak area as compared to the 12 MegaLangmuir Si_2Cl_6 dosed surface, indicative of saturated silicon coverage. Note the decrease in the substrate peaks with increase in Si coverage consistent with a uniform coverage of Si. The XPS data is consistent with a self-limiting CVD process. Fig. 1 (b) shows the saturation dose of Si_2Cl_6 followed by 500 Langmuir atomic hydrogen on InGaAs(2x4) leaves the surface with regions of ordered rows along the same direction as the underlying (2x4) surface rows with nearly identical row spacing showing silicon locally adsorbs in a commensurate structure. Fig. 2 (a) shows MOSCAP fabrication results on an InGaAs(001) sample prepared by buffered oxide etchant (BOE) clean, followed by 20 cycles of TMA pre-pulses and 60 cycles of Al_2O_3 deposition at 350°C with Ni gate metals and Al back contacts deposited. The MOSCAP underwent a 15 min. forming gas anneal (5% H2/N2) at 250°C. Fig 2 (b) shows MOSCAP fabrication results on an InGaAs(001) sample with the same procedure as that shown in (a), in addition to the insertion of a Si-H_x passivation layer (30 cycles of 100 ms long Si_2Cl_6 pulses at 350°C followed by 30 s of H_2 remote plasma) after BOE wet cleaning, and before the TMA prepulsing and Al_2O_3 deposition at 350°C. These Initial MOSCAP fabrication results shown in Fig. 2 indicate the deposition of a silicon passivation layer on the InGaAs(001) surface prior to the ALD of Al_2O_3 leads to lower frequency dispersion, higher C_{max}, and a smaller false inversion indicative of lower D_{it} at midgap.[1]Fig. 3 shows 315 MegaLangmuir hydrazine is able to remove more than half of the carbon contamination from the as-loaded $Si_{0.5}Ge_{0.5}(110)$ surface and also creates the –N-H_x surface termination as seen by the presence of the N 1s signal. Next by dosing 21 MegaLangmuir Si_2Cl_6 followed by 3 MegaLangmuir hydrazine, and the 17 silicon nitride cycles, a large increase in the Si 2p and N 1s corrected peak areas is seen, as well as a decrease in the Ge 3d substrate peak, and the C 1s and O 1s surface

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contamination peaks . These results are consistent with silicon nitride ALD deposition occurring with no indication of unwanted contaminants being deposited within the silicon nitride film.

CONCLUSION

Deposition of a thin silicon hydride capping layer on the InGaAs(001)-(2x4) surface has been achieved by a self-limiting CVD process as shown by XPS. The 350°CSi_2Cl_6 process produces a thin Si-H_x capping layer (2.5 monolayers) and allows for multilayer silicon or Si-O_x growth by ALD through cyclically dosing Si_2Cl_6 with either atomic hydrogen or anhydrous HOOH(g). STM and STS measurements show the Si_2Cl_6self-limiting CVD process on InGaAs(001)-(2x4) produces an atomically locally ordered and electrically passivated surface, with the surface Fermi level (E_F) shifting from the valence to the conduction band for p-type vs. n-type samples consistent with an unpinned $E_{F.}$ XPS, STM, and STS results of an Si-O_x control layer on the InGaAs(001)-(2x4) surface will be presented and compared with that of the Si-H_x passivating layer. The initial MOSCAP fabrication results show the deposited silicon layer with hydrogen termination on InGaAs(001) seeds high-K gate oxide nucleation, and improves device performance. Deposition of an Si-N_x diffusion barrier and surface protection capping layer on the $Si_{0.5}Ge_{0.5}$(110) surface was achieved by an ALD process at 275°C through cyclically dosing $Si_2Cl_6$and anhydrous N_2H_4 as confirmed by XPS measurements. Initial surface characterization by STM, and STS will be presented to highlight the effects of surface nitridation on SiGe(110) electronic and surface defect states in aims to improve channel mobility by decreasing surface roughness and interfacial trap states.

REFERENCES

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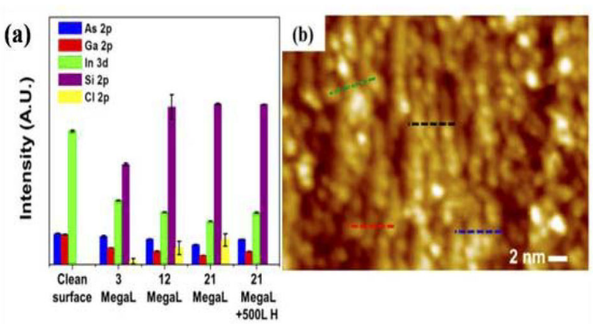

Figure 1 (a) XPS corrected peak areas for 3 MegaLangmuir Si_2Cl_6, 12 MegaLangmuir Si_2Cl_6, 21 MegaLangmuir Si_2Cl_6, and 21 MegaLangmuir Si_2Cl_6 + 500 Langmuir atomic hydrogen on n-type InGaAs(001)-(2x4). All doses done at 350°C. Notice saturation occurs following the 12 and 21 MegaLangmuir total Si_2Cl_6 doses. (b) filled state STM images following 21 MegaLangmuir Si_2Cl_6 dose at 350°C and 500 Langmuir atomic hydrogen dosed at 350°C on n-type InGaAs(001)-(2x4) with no further annealing. Ordering occurs along same direction of decapped InGaAs(001)-(2x4) arsenic dimer rows.

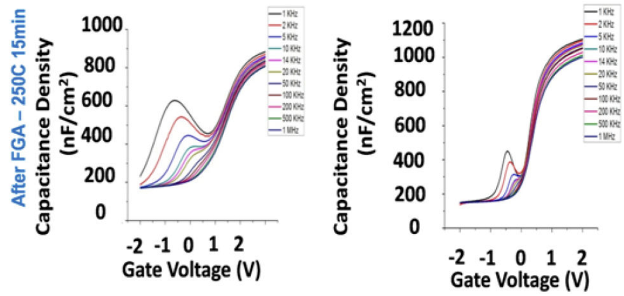

Figure 2. (a) InGaAs(001) sample cleaned by BOE. Afterwards, 20 cycles of 45 ms TMA pre-pulses and 60 cycles of 200 ms TMA and 50 ms H2O were applied in order to deposit Al_2O_3 with approximately 6.0 nm physical thickness. After Al_2O_3 ALD, Ni gate metals and Al back contacts were deposited. The MOSCAP shown underwent a 15 minute forming gas anneal (5% H2/N2) at 250°C (b)InGaAs(001) sample first underwent the BOE clean. Next 30 cycles of 100 ms long Si_2Cl_6 pulses were dosed at 350°C followed by 30 s of H_2 remote plasma at with 50 W forward power. This exposure is equivalent to 3 MegaLangmuir total exposure of Si_2Cl_6 at 350°C which is seen to deposit ~1 monolayer of silicon coverage on InGaAs(001). Afterwards, 20 cycles of 45 ms TMA pre-pulses and 60 cycles of 200 ms TMA and 50 ms H_2O were dosed to deposit Al_2O_3 with approximately 6.0 nm physical thickness. After Al_2O_3 ALD, Ni gate metals and Ni back contacts were deposited. The MOSCAP shown underwent a 15 minute forming gas anneal (5% H2/N2) at 250°C. As can be seen, the MOSCAP with the silicon passivating layer deposited by Si_2Cl_6 shown in (b) contains less frequency dispersion, higher C_{max}, and a smaller false inversion bump compared with the MOSCAP shown in (a) without the silicon passivating layer.

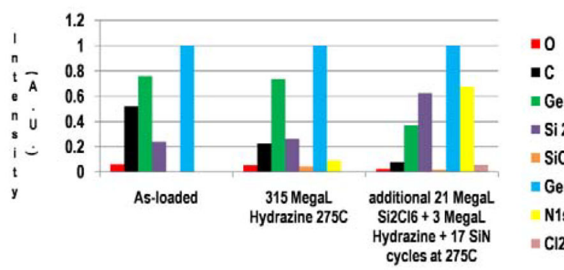

Figure 3 XPS corrected peak areas for wet cleaned as-loaded $Si_{.5}Ge$ (110) surface, $Si_{.5}Ge$(110) surface following 315 MegaLangmuir hydrazine at 275°C, and $Si_{.5}Ge$ (110) surface following 315 MegaLangmuir hydrazine plus 21 MegaLangmuir Si_2Cl_6 plus 17 silicon nitride ALD cycles all dosed at 275°C. Each silicon nitride ALD cycle consists of 3 MegaLangmuir Si_2Cl_6 followed by 3 MegaLangmuir hydrazine at 275°C.