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 In$_{0.53}$Ga$_{0.47}$As, In$_{0.5}$Ga$_{0.5}$Sb, In$_{0.5}$Ga$_{0.5}$N, SiGe, and Ge enabling transfer of 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 nitrifying agent such as N$_2$H$_4$(g) in order to create an Si-N$_2$ diffusion barrier and surface protection layer. This study focuses on depositing saturated Si$_5$H$_{12}$ and Si-Oh seed layers via two separate self-limiting CVD processes on InGaAs(001)-(2x4), and depositing a Si$_5$N$_2$ seed layer on Si$_5$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$_5$Ge$_{0.5}$(110) surfaces. MOSCAP device fabrication was performed on n-type InGaAs(001) substrates with and without a Si$_5$H$_{12}$ passivation control layer deposited by self-limiting CVD in order to determine the effects on $C_{\text{max}}$ 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$_5$Cl$_5$ followed by 500 Langmuir atomic hydrogen or 210.55 MegaLangmuir total anhydrous HOOH(g) to create Si-Oh or Si-OF surface termination. Complete saturation of silicon coverage is determined to occur once further dosing with Si$_5$Cl$_5$ 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$_5$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$_5$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$_5$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$_2$ surface termination, as evident from the presence of the N 1s signal seen in XPS. Next, a 21 MegaLangmuir Si$_5$Cl$_5$ doses followed by 17 cycles of 3 MegaLangmuir hydrazine and 3 MegaLangmuir Si$_5$Cl$_5$ 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$_5$Cl$_5$ pulses (3 MegaLangmuir total exposure) were dosed at 350°C followed by 30 s of H$_2$ remote plasma at 50 W forward power. Afterwards, 20 cycles of 45 ms TMA pre-pulses and 60 cycles of 200 ms TMA and 50 ms H$_2$O were dosed to deposit Al$_2$O$_3$ with approximately 6.0 nm physical thickness. After each TMA and H$_2$O pulse, a 6 s Ar purge was employed. After Al$_2$O$_3$ 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$_5$Cl$_5$ dose at 350°C, there is no real increase in the Si 2p corrected peak area as compared to the 12 MegaLangmuir Si$_5$Cl$_5$ 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$_5$Cl$_5$ 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$_2$O$_3$ deposition at 350°C with Ni gate metals and Al back contacts deposited. The MOSCAP underwent a 15 min. forming gas anneal (5% H$_2$/N$_2$) 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$_2$ passivation layer (30 cycles of 100 ms long Si$_5$Cl$_5$ pulses at 350°C followed by 30 s of H$_2$ remote plasma) after BOE wet cleaning, and before the TMA prepping and Al$_2$O$_3$ 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$_2$O$_3$ leads to lower frequency dispersion, higher $C_{\text{max}}$, and a smaller false inversion indicative of lower D$_n$ at midgap. Fig. 3 shows 315 MegaLangmuir hydrazine is able to remove more than half of the carbon contamination from the as-loaded Si$_5$Ge$_{0.5}$(110) surface and also creates the N-H$_2$ surface termination as seen by the presence of the N 1s signal. Next by dosing 21 MegaLangmuir Si$_5$Cl$_5$ 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.
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°CSi2Cl6 process produces a thin Si-Hx capping layer (2.5 monolayers) and allows for multilayer silicon or Si-Ox growth by ALD through cyclically dosing Si2Cl6 with either atomic hydrogen or anhydrous H2O(2). STM and STS measurements show the Si2Cl6self-limiting CVD process on InGaAs(001)-(2x4) produces an atomically locally ordered and electrically passivated surface, with the surface Fermi level (EF) shifting from the valence to the conduction band for p-type vs. n-type samples consistent with an unpinned Ef. XPS, STM, and STS results of an Si-Ox control layer on the InGaAs(001)-(2x4) surface will be presented and compared with that of the Si-Hx 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-Nx diffusion barrier and surface protection capping layer on the Si1-xGe1-x(110) surface was achieved by an ALD process at 275°C through cyclically dosing Si2Cl6 and anhydrous N2H4 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


Figure 1 (a) XPS corrected peak areas for 3 MegaLangmuir Si2Cl6, 12 MegaLangmuir Si2Cl6, 21 MegaLangmuir Si2Cl6, and 21 MegaLangmuir Si2Cl6 with 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 Si2Cl6 doses. (b) filled state STM images following 21 MegaLangmuir Si2Cl6 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 Al2O3 with approximately 6.0 nm physical thickness. After Al2O3 ALD, Ni gate metals and Al back contacts were deposited. The MOSCAP shown underwent a 15 minute forming gas anneal (5% H2/95% N2) at 250°C (b) InGaAs(001) sample first underwent the BOE clean. Next 30 cycles of 100 ms long Si2Cl6 pulses were dosed at 350°C followed by 30 s of H2 remote plasma at with 50 W forward power. This exposure is equivalent to 3 MegaLangmuir total exposure of Si2Cl6 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 H2O were dosed to deposit Al2O3 with approximately 6.0 nm physical thickness. After Al2O3 ALD, Ni gate metals and Ni back contacts were deposited. The MOSCAP shown underwent a 15 minute forming gas anneal (5% H2/95% N2) at 250°C. As can be seen, the MOSCAP with the silicon passivating layer deposited by Si2Cl6 shown in (b) contains less frequency dispersion, higher Cmax, and a smaller false inversion hump compared with the MOSCAP shown in (a) without the silicon passivating layer.

Figure 3 XPS corrected peak areas for wet cleaned as-loaded Si,Ge (110) surface, Si,Ge(110) surface following 315 MegaLangmuir hydrazine at 275°C, and Si,Ge (110) surface following 315 MegaLangmuir hydrazine plus 21 MegaLangmuir Si2Cl6 plus 17 silicon nitride ALD cycles all dosed at 275°C. Each silicon nitride ALD cycle consists of 3 MegaLangmuir Si2Cl6 followed by 3 MegaLangmuir hydrazine at 275°C.