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Authors	O'Mahony, Aileen; Monaghan, Scott; Provenzano, G.; Povey, Ian M.; Nolan, M. G.; O'Connor, Éamon; Cherkaoui, Karim; Newcomb, Simon B.; Crupi, Felice; Hurley, Paul K.; Pemble, Martyn E.
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University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Structural and electrical analysis of the atomic layer deposition of $\text{HfO}_2/n\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$ capacitors with and without an Al_2O_3 interface control layer

A. O'Mahony¹, S. Monaghan, G. Provenzano, I. M. Povey, M. G. Nolan, É. O'Connor, K. Cherkaoui, S. B. Newcomb, F. Crupi, P. K. Hurley, and M. E. Pemble

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Structural and electrical analysis of the atomic layer deposition of $\text{HfO}_2/n\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$ capacitors with and without an Al_2O_3 interface control layer

A. O'Mahony,^{1,a)} S. Monaghan,¹ G. Provenzano,^{1,2} I. M. Povey,¹ M. G. Nolan,¹ É. O'Connor,¹ K. Cherkaoui,¹ S. B. Newcomb,³ F. Crupi,² P. K. Hurley,¹ and M. E. Pemble¹

¹Tyndall National Institute, University College Cork, Lee Maltings, Prospect Row, Cork, Ireland

²Dipartimento di Elettronica, Informatica e Sistemistica, Università della Calabria, Via P. Bucci, 41C I-87036 Arcavacata di Rende (CS), Italy

³Glebe Laboratories, Glebe Scientific Ltd., Newport, County Tipperary, Ireland

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High mobility III-V substrates with high- k oxides are required for device scaling without loss of channel mobility. Interest has focused on the *self-cleaning* effect on selected III-V substrates during atomic layer deposition of Al_2O_3 . A thin (~ 1 nm) Al_2O_3 interface control layer is deposited on $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ prior to HfO_2 growth, providing the benefit of *self-cleaning* and improving the interface quality by reducing interface state defect densities by $\sim 50\%$ while maintaining scaling trends. Significant reductions in leakage current density and increased breakdown voltage are found, indicative of a band structure improvement due to the reduction/removal of the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ native oxides. © 2010 American Institute of Physics. [doi:10.1063/1.3473773]

A critical technological challenge in the integration of high k -dielectrics on III-V channels is the control of the high- k /III-V interface. Although the interfacial chemistry of the high- k /Si system is similar to the SiO_2/Si system,¹ the high- k /III-V system is more complex, due to competition between the various native oxide species at the interface,² resulting in growth of a poor quality interfacial layer.^{3–6} In recent work,³ reductions in interface state defect densities (D_{it}) were achieved by pre-treatment of the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ surface prior to atomic layer deposition (ALD) of HfO_2 [$k \sim 16$ – 25 , band gap (E_g) ~ 5.8 – 6.0 eV].^{7–9} The native oxides of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ (Ga_2O_3 , In_2O_3 , and As_2O_3) have low band gaps (3.6–4.8 eV) (Refs. 2 and 9) and k -values of 8–10 when relating the reported^{9,10} k -value for Ga_2O_3 and In_2O_3 with the approximate refractive indices ($n \sim 1.9$ for all)² through the equation $n^2 \propto k$ and the Moss Inverse Law¹¹ for the refractive index, k -value and energy band gap. They are detrimental to the band structure of high- k /III-V devices by increasing the leakage current and creating potential wells in the native oxide layer between the high- k oxide and the substrate. The *self-cleaning* Al_2O_3 ALD process is reported to reduce or remove the III-V native oxides.^{12–15} However, devices employing Al_2O_3 ($k \sim 8.6$ – 11.6 , $E_g \sim 8.8$ eV) (Refs. 8, 9, and 12) as the gate oxide are limited for scaling due to its low k -value.

In this work, the structural and electrical properties of $\text{Pd}/\text{HfO}_2/n\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$ devices (HfO_2 : nominal thickness ~ 3 , ~ 4 , and ~ 5 nm) with/without an ~ 1 nm Al_2O_3 interface control layer (ICL), are examined using high resolution transmission electron microscopy (HR-TEM) and current/capacitance/conductance versus voltage measurements (JV, CV, and GV, respectively). The devices are labeled: $s1_3$, $s1_4$, $s1_5$ (e.g., sample, ~ 1 nm Al_2O_3 , ~ 5 nm HfO_2 is labeled $s1_5$). As a control, devices were fabricated without the Al_2O_3 ICL [nominal ~ 5 nm HfO_2 only (label:

$s0_5$)]. The motivation for this work is: (i) to detect any improvement in the quality and structure of the interface using the bilayer approach; (ii) to investigate if an Al_2O_3 ICL improves the electrical performance of devices by modifying the metal-oxide-semiconductor (MOS) band structure; (iii) to determine if scaling is possible with an Al_2O_3 ICL using reducing thicknesses of HfO_2 .

The ~ 2 μm n -type ($S: \sim 4 \times 10^{17} \text{ cm}^{-3}$) $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ channels had a ~ 0.1 μm InP buffer layer ($S: \sim 2 \times 10^{18} \text{ cm}^{-3}$) on a ~ 350 μm InP substrate ($S: 3$ – $8 \times 10^{18} \text{ cm}^{-3}$). All $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ layers were grown by MOVPE. An *ex situ* three-stage surface pre-treatment process [HCl , NH_4OH , and $(\text{NH}_4)_2\text{S}$] was performed on the $n\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$ substrates which has previously been shown to be beneficial to device performance.³ The Al_2O_3 and HfO_2 layers were deposited in a Cambridge NanoTech Fiji F200LLC ALD system, at 250°C . The ALD of Al_2O_3 and HfO_2 employed alternating pulses of TMA [$\text{Al}(\text{CH}_3)_3$]/ H_2O and tetrakis(ethylmethylamino)hafnium (TEMAH) [$\text{Hf}[\text{N}(\text{C}_2\text{H}_5)(\text{CH}_3)_4]$]/ H_2O , respectively. MOS structures were completed by vacuum evaporation of ~ 200 nm of Pd at a deposition rate of 2.5 Å/s using a lift-off process. No ohmic back contacts were formed.

Figures 1(a) and 1(b) present cross-sectional HR-TEM micrographs of $s1_5$ and $s0_5$, confirming the physical oxide and nominal thicknesses are in close agreement: $s1_5$ [Fig. 1(a)] has a ~ 5.3 nm HfO_2 layer, and a ~ 1.2 nm Al_2O_3 layer. $s0_5$ [Fig. 1(b)], has a ~ 4.9 nm HfO_2 layer. All oxide layers are amorphous. Comparison between Figs. 1(a) and 1(b) shows a ~ 0.7 nm native oxide layer at the high- $k/n\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$ interface when no Al_2O_3 ICL is deposited, which is indicative of an Al_2O_3 *self-cleaning* effect on the native oxide, for sample $s1_5$.

Figure 2(a) presents a cross-sectional HR-TEM micrograph of $s1_3$. The physical thicknesses of HfO_2 and Al_2O_3 are ~ 3.2 nm and ~ 1.2 nm, respectively. Figure 2(b), a plan-view HR-TEM micrograph for sample $s1_5$, reveals the epitaxial $2 \mu\text{m}$ $n\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$ layer to be defect-free,

^{a)}Electronic mail: aileen.omahony@tyndall.ie.

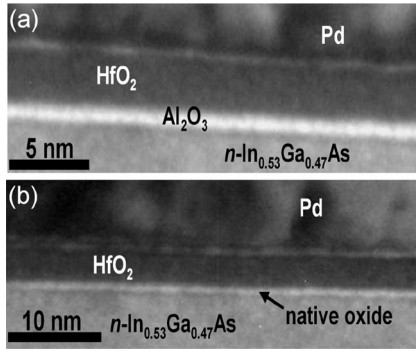


FIG. 1. Cross-sectional HR-TEM micrographs of (a) *s1_5*, with ~ 5.3 nm HfO₂ and ~ 1.1 nm Al₂O₃ and (b) *s0_5*, with ~ 4.9 nm HfO₂ and a ~ 0.7 nm native oxide layer.

with an associated negligible root mean square (rms) surface roughness of <1 nm.

Figure 3 shows (a) JV responses and (b) the measured 1 kHz CV responses, along with the simulated¹⁶ CV curves for all samples. The inset to Fig. 3(a) shows the capacitance equivalent thickness (CET) versus HR-TEM extracted HfO₂ physical thickness plot for the bilayer sample set (*s1_3*, *s1_4*, *s1_5*), with a linear fit. Figure 3(a), when assessing the bilayer sample set only, shows that leakage current density increases with reducing HfO₂ thickness, and the dielectric breakdown voltage increases with increasing HfO₂ thickness. This is expected for a dominant quantum-mechanical (QM) tunneling leakage mechanism with similar energy barrier height and shape, and for a dominant electrically-controlled oxide breakdown process.¹⁷ However, the leakage current density response for sample *s0_5* is substantially higher (approximately three orders of magnitude at 3 V) than for sample *s1_5*, showing that the absence of an Al₂O₃ ICL changes the tunneling barrier height/shape to conduction beyond a thickness-dependency regime only and introduces an additional, highly temperature-dependent (not shown), trap-assisted conduction mechanism that adds magnitude and fluctuation to the response.¹⁸ Figure 3(b) shows that the accumulation maximum capacitance at 2 V scales correctly with oxide thickness for the bilayer sample set. The simulated curves confirm that surface accumulation is achieved at 2 V for all samples.³ The accumulation maximum capacitance is greater for the measured data compared to the simulated data, showing the existence of a QM correction factor. This difference could be due to additional states inside the conduction band at the oxide/*n*-In_{0.53}Ga_{0.47}As

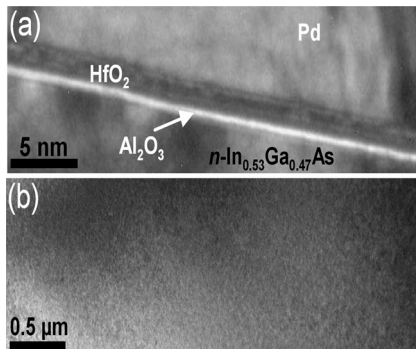


FIG. 2. HR-TEM micrographs of (a) *s1_3* (cross-sectional), with ~ 3.2 nm HfO₂ and ~ 1.2 nm Al₂O₃; (b) *s1_5* (plan-view) shows a defect free *n*-In_{0.53}Ga_{0.47}As substrate layer.

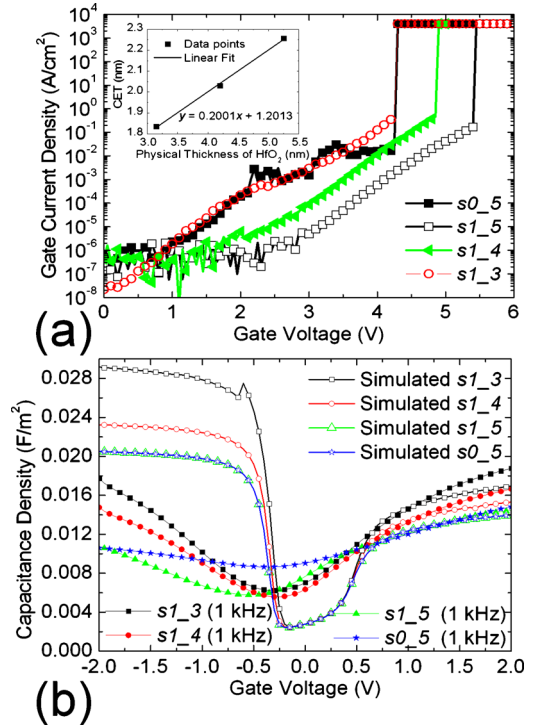


FIG. 3. (Color online) (a) JV responses for all samples, with significantly lower leakage for the *s1_5* (Al₂O₃ ICL) devices, compared to *s0_5* devices. (b) Measured and simulated (from the 1D Poisson–Schrödinger solver) 1 kHz CV responses for all samples. Inset to (a) shows the CET vs physical thickness with a linear fit.

interface,¹⁹ and/or charge quantization leading to X and L satellite valley occupation in the conduction band.²⁰ We see a similar maximum accumulation capacitance for the ~ 5 nm HfO₂ samples with/without Al₂O₃ (*s1_5* and *s0_5*, respectively), showing that the overall equivalent oxide thickness of these oxide stacks are similar. The observed variation in the maximum accumulation capacitance (~ 0.003 F/m²) for sample *s0_5* is likely due to native oxide layer thickness variation not observable by HR-TEM. Given the large difference in leakage current density between these samples (*s1_5* and *s0_5*), it is evident that the Al₂O₃ ICL substantially reduces the native oxide layer thickness while increasing the barrier height to electron tunneling from the In_{0.53}Ga_{0.47}As conduction band. The linear fit of the inset to Fig. 3(a) shows that the reduction in HfO₂ thickness for the bilayer structures produces the required scaling trend. This linear fit can be used to extract an intercept CET value, which has contributions from Al₂O₃, any underlying native oxide layer (if present), and the QM correction contribution from the *n*-In_{0.53}Ga_{0.47}As accumulation layer. HR-TEM [Figs. 1(a), 1(b), and 2(a)], in combination with the electrical results [Figs. 3(a), 3(b), 4(a), and 4(b)], indicate that no substantive underlying native oxide layer is present for the bilayer sample set. Assuming this is the case and since we can extract the contributions from Al₂O₃, we can thereby determine a QM correction factor of ~ 0.7 nm. From the slope of the linear fit we can estimate the HfO₂ *k*-value to be ~ 20 , which is within the reported range.⁷ Reasonable assumptions used were: (i) the *k*-value of both Al₂O₃ and any native oxide^{2,10,12} layer is ~ 9 and (ii) the physical thicknesses used for sample *s1_4* are nominal thicknesses proportionally corrected using HR-TEM/nominal-thickness ratios and ALD cycle ratios for other samples. The absence of an underlying native oxide

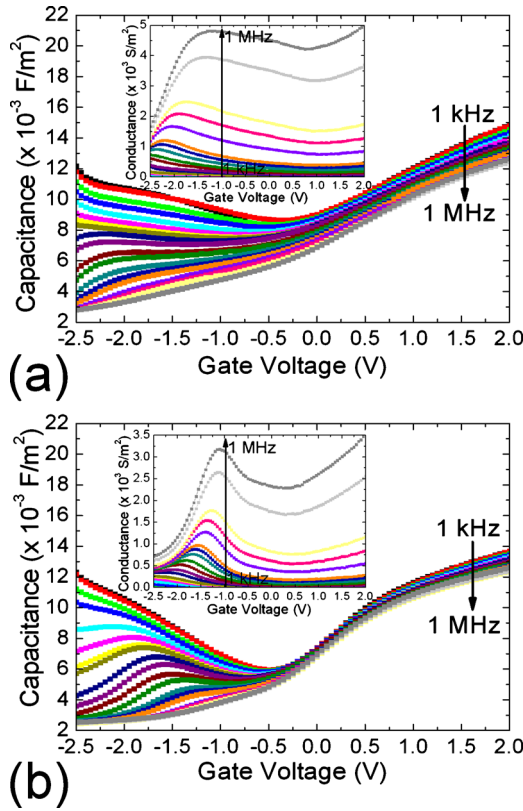


FIG. 4. (Color online) (a) and (b) show CV responses (20 frequencies; 1 kHz–1 MHz) for samples $s0_5$ and $s1_5$, respectively. The insets to (a) and (b) show the corresponding GV responses.

layer, evidenced by HR-TEM in combination with the electrical results, indicates that the Al_2O_3 is likely to be removing the native oxides via the *self-cleaning* process.

Figures 4(a) and 4(b) show the multifrequency CV responses for samples $s0_5$ and $s1_5$, respectively. The insets to Figs. 4(a) and 4(b) show the corresponding GV responses. We observe an increased D_{it} response in both the CV and GV profiles for sample $s0_5$ when compared to the equivalent response for sample $s1_5$, which includes (over the entire voltage range) an increased CV and GV stretch-out and frequency dispersion. In the voltage range -1 to 0.25 V, the absence of minority carriers is assumed, corresponding to the depletion regime. An approximation to the Conductance Method²¹ indicates that samples $s0_5$ and $s1_5$ have estimated D_{it} values of $\sim 8 \times 10^{12} \text{ cm}^{-2} \text{ eV}^{-1}$ and $\sim 4 \times 10^{12} \text{ cm}^{-2} \text{ eV}^{-1}$, respectively. Due to the absence of distinct equivalent parallel conductance (G_p/ω) peaks as observed in SiO_2/Si systems, this is derived assuming zero standard deviation in band bending using values of G_p/ω at -1 V and taken at 30 kHz. While it is noted that the G_p/ω magnitudes may be affected by the approximation conditions, and any possible minority carrier contribution, the relative difference provides a valid estimate. There is approximately a 50% reduction in D_{it} when including an Al_2O_3 ICL.

In summary, it is found that the inclusion of a thin Al_2O_3 ICL (~ 1 nm) at the $\text{HfO}_2/\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ interface improves the structural and electrical properties of $\text{Pd}/\text{HfO}_2/n\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$ devices. The inclusion of the Al_2O_3 ICL improves the breakdown voltage and reduces leakage current densities by approximately three orders of

magnitude at 3 V by increasing the barrier height to tunneling from the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ conduction band into the oxide. No apparent native oxide layer is observed at the high- $k/\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ interface when using an Al_2O_3 ICL, suggesting that the Al_2O_3 ALD process is *self-cleaning* the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ native oxides. Comparing the electrical performance for the bilayer samples with different HfO_2 thicknesses we find that device scaling trends can be achieved. Combining the structural and electrical results we find a QM correction factor of ~ 0.7 nm. The inclusion of an ICL causes an approximate 50% reduction in D_{it} , thereby improving the quality of the interface.

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