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Inversion-type indium phosphide metal-oxide-semiconductor field-effect transistors with equivalent oxide thickness of 12 Å using stacked HfAlO_x/HfO₂ gate dielectric

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We present InP metal-oxide-semiconductor capacitors (MOSCAPs) and metal-oxide-semiconductor field-effect transistors (MOSFETs) with stacked HfAlO_x/HfO₂ gate dielectric deposited by atomic layer deposition. Compared with single HfO₂, the use of stacked HfAlO_x/HfO₂ results in better interface quality with InP substrate, as illustrated by smaller frequency dispersion and lower leakage current density. The equivalent oxide thickness of MOSCAPs with 10 Å HfAlO_x/25 Å HfO₂ stacked gate dielectric is 12 Å. The MOSFETs with this gate dielectric achieve two times higher transconductance than those with single 35 Å HfO₂. They also exhibit drive current of 60 mA/mm and subthreshold swing of 83 mV/decade for 5 μm gate length. © 2008 American Institute of Physics. [DOI: 10.1063/1.2943186]

Recently, III-V compound semiconductors have received a great deal of attention for metal-oxide-semiconductor field-effect transistors (MOSFETs) applications due to their higher electron mobility and breakdown field compared to silicon. Among the III-V MOSFETs, inversion-type MOSFETs are preferred over depletion type because of their superior immunity to drain induced barrier lowering effect and punch through leakage and breakdown. Some progress has been made on inversion-type III-V MOSFETs including GaAs MOSFETs with Si or Ge passivation layer and HfO₂ dielectrics,^{1,2} or with molecular beam epitaxy (MBE) Ga₂O₃ (Gd₂O₃) dielectrics,^{3,4} InGaAs MOSFETs with atomic layer deposited (ALD) Al₂O₃ or HfO₂ dielectrics,⁵⁻⁷ or with Si passivation layer and HfO₂ dielectrics,⁸ or with MBE Ga₂O₃(Gd₂O₃) dielectrics,⁹ and InP MOSFETs with ALD Al₂O₃ or HfO₂ dielectrics.^{10,11} GaAs inversion-type MOSFETs usually have problems of low drive current.^{2,3,12} While InGaAs MOSFETs can provide large drive current,^{6,7} they also exhibit fairly high off-current density and large subthreshold swing [e.g., 240 mV/decade (Ref. 6), 330 mV/decade (Ref. 7)]. On the other hand, InP inversion-type MOSFETs with ALD Al₂O₃ have shown the capability of high drive current density,¹⁰ and they can provide much smaller off-current density due to larger bandgap (1.34 eV) compared to InGaAs (0.74 eV for In_{0.53}Ga_{0.47}As). These characteristics make InP a promising alternative material which should be studied for future low-power logic applications.

For Si-based technology, HfO₂ has been widely studied as an alternative gate oxide material to attain further scaling down.^{13,14} In addition, there have been some attempts to adopt HfO₂ on III-V semiconductor compounds.^{1,2,6,11} However, very little work has been performed on gate oxide scaling down below equivalent oxide thickness (EOT) of 20 Å on III-V MOSFETs. The ALD provides an *ex situ* technique with which a high quality, thermodynamically stable oxide

can be directly placed on III-V substrate,^{6,10,15} and favors the scaling of gate oxides. While ALD Al₂O₃ with κ value of 8–10 shows good compatibility with III-V substrate, ALD HfO₂ with κ value of more than 20, which is of course more promising for scaling of gate oxide, always has higher interface state density than ALD Al₂O₃ with III-V materials.^{6,11,16} In this paper, a thin layer of HfAlO_x nanolaminates was used between HfO₂ and InP to reduce the interface state density, the capacitance-voltage (*C-V*) and current-voltage (*I-V*) characteristics of MOS capacitors (MOSCAPs) were investigated and the well-behaved MOSFETs with EOT of 12 Å were realized.

The MOSCAPs were fabricated on *n*-type InP (100) wafer doped with sulfur ($5 \times 10^{17}/\text{cm}^3$). The surface oxides were removed with the 1% HF solution, followed by 20% (NH₄)₂S_x dip.¹⁷ For sample (a), 35 Å HfO₂ was deposited by ALD at 200 °C using tetrakis(dimethyl-amino) hafnium [Hf(NMe₂)₄] and H₂O as the precursors. For sample (b), HfAlO_x nanolaminates were used as gate dielectric. The nanolaminates structure consisted of one cycle of hafnium oxide growth and one cycle of aluminum oxide growth (trimethylaluminum and H₂O as the precursors). This stack was repeated for 15 times to form 30 Å HfAlO_x at 200 °C. For sample (c), 6 Å HfAlO_x was deposited at the bottom followed by 25 Å HfO₂ on the top. For sample (d), 10 Å HfAlO_x was deposited followed by 25 Å HfO₂. Physical vapor deposited (PVD) TaN was used for gate electrode and e-beam evaporated AuGe/Ni/Au alloy for the backside contact. The *n*-channel MOSFETs were fabricated on semi-insulating (SI)-InP (100) substrate with a ring-type structure¹ by gate-last process. The surface treatment was performed on SI-InP same as MOSCAPs, then 100 Å Al₂O₃ (dummy gate oxides) was deposited by ALD at 250 °C. After 35 keV, $5 \times 10^{14}/\text{cm}^2$ Si ion implantation at the source and drain regions, samples were annealed at 750 °C for 15 s. The Al₂O₃ layer was then removed by buffered oxide etchant (BOE). After the same surface treatment on these InP samples, 35 Å HfO₂ [sample (a)], or 6 Å HfAlO_x/25 Å HfO₂ stacked dielectric [sample (c)], or 10 Å HfAlO_x/25 Å HfO₂ stacked

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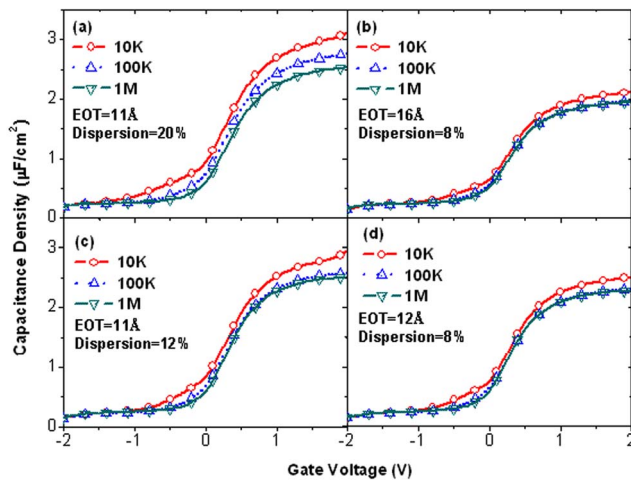


FIG. 1. (Color online) Typical C - V characteristics from 10 KHz to 1 MHz for InP MOSCAPs with different gate dielectrics: (a) 35 Å HfO_2 [sample (a)], (b) 30 Å HfAlO_x [sample (b)], (c) stacked 6 Å $\text{HfAlO}_x/25$ Å HfO_2 [sample (c)], (d) Stacked 10 Å $\text{HfAlO}_x/25$ Å HfO_2 [sample (d)]. Frequency dispersion was calculated between 1 MHz and 10 KHz at a gate voltage of 1.5 V.

dielectric [sample (d)] was deposited on separate samples. The TaN gate electrode was deposited by PVD and AuGe/Ni/Au by e-beam evaporation for source and drain Ohmic contact.

Figures 1(a)–1(d) illustrate the typical C - V characteristics of InP MOSCAP for samples (a)–(d), respectively. The EOT was calculated with consideration to the quantum mechanism.¹⁸ Single HfO_2 dielectric on InP [Fig. 1(a)] shows a frequency dispersion as large as 20% from 1 MHz to 10 KHz, while the HfAlO_x nanolaminates have much better interface with InP, illustrated by a much smaller frequency dispersion of 8% [Fig. 1(b)]. The κ value of the nanolaminates is about 12, calculated from EOT of HfAlO_x with different physical thicknesses (data not shown). This value is still not high enough for further scaling down. Thus a thin HfAlO_x at the bottom and another HfO_2 layer on the top were used to obtain a small EOT while maintaining good interface at the same time. C - V of MOSCAPs using 6 or 10 Å HfAlO_x at the bottom and 25 Å HfO_2 on the top are shown in Figs. 1(c) and 1(d). It has been found that frequency dispersion is reduced with thicker HfAlO_x , achieving the same amount as the single HfAlO_x gate dielectric (8%)

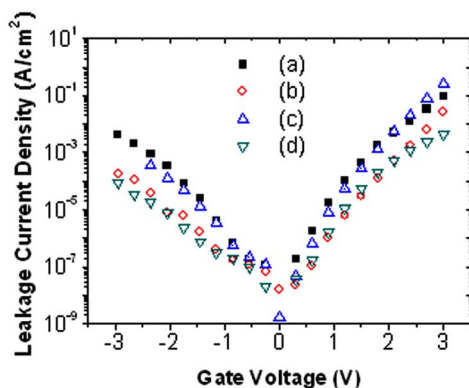


FIG. 2. (Color online) Gate leakage current density (J_g) versus gate voltage of InP MOSCAPs with different gate dielectrics for sample (a) to sample (d).

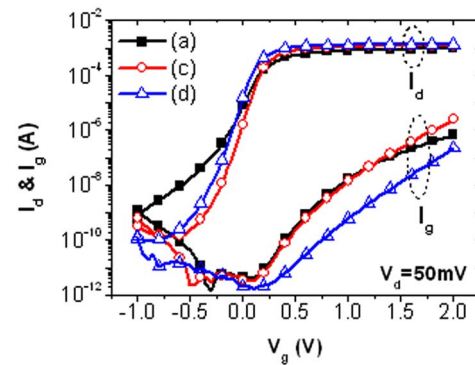


FIG. 3. (Color online) Log-scale drive current I_d and gate leakage current I_g versus gate voltage V_g at $V_d=50$ mV for InP MOSFETs with 35 Å HfO_2 (a), or 6 Å $\text{HfAlO}_x/25$ Å HfO_2 (c), or 10 Å $\text{HfAlO}_x/25$ Å HfO_2 (d) as gate dielectric ($W/L=600\mu\text{m}/5\mu\text{m}$).

when HfAlO_x is 10 Å thick. The EOT of this gate stack structure is 12 Å, which is close to that of 35 Å single HfO_2 dielectric. The C - V hysteresis of samples (a)–(d) are 340, 230, 270, and 280 mV, respectively, measured from -2 to 2 V, and the flatband voltage is about 0.31 V for all four kinds of samples. The leakage current density versus gate voltage of sample (a)–(d) is shown in Fig. 2, the leakage current density of 30 Å HfAlO_x or 10 Å $\text{HfAlO}_x/25$ Å HfO_2 as the gate dielectric is similar, which is about 2×10^{-5} A/cm² at $V_g=V_{fb}+1$ V. This value is one order lower than the leakage current density of 35 Å HfO_2 or 6 Å $\text{HfAlO}_x/25$ Å HfO_2 .

We compared the characteristics of MOSFETs with the same gate dielectrics as MOSCAPs sample (a), (c), and (d) in Figs. 3–5, which have similar EOT of 11–12 Å (Fig. 1). Figure 3 shows the log-scale driver current (I_d) and gate leakage current (I_g) versus gate voltage (V_g) at $V_d=50$ mV, where a gate width (W) is 600 μm and gate length (L) is 5 μm . For single 35 Å HfO_2 , the subthreshold swing is 126 mV/decade, and this value reduces to 83 mV/decade for $\text{HfAlO}_x/\text{HfO}_2$ stacked dielectric with 6 Å HfAlO_x or 10 Å HfAlO_x . The gate leakage current is about 8×10^{-10} A for the 10 Å $\text{HfAlO}_x/25$ Å HfO_2 stacked dielectric and 2×10^{-8} A for single HfO_2 dielectric or 6 Å $\text{HfAlO}_x/25$ Å HfO_2 gate stacks at $V_g=1$ V. We also compared the extrinsic transconductance (g_m) at $V_d=50$ mV of these MOSFETs in Fig. 4(a). The maximum transconductance of 10 Å $\text{HfAlO}_x/25$ Å HfO_2 stacked gate dielectric is two times of the single HfO_2 gate dielectric, and 20% higher than 6 Å $\text{HfAlO}_x/25$ Å HfO_2 stacked gate dielectric. Figure 4(b) plot-

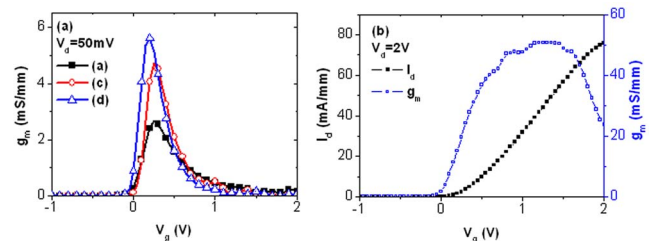


FIG. 4. (Color online) Extrinsic transconductance g_m versus V_g at $V_d=50$ mV for InP MOSFETs with 35 Å HfO_2 (a), or 6 Å $\text{HfAlO}_x/25$ Å HfO_2 (c), or 10 Å $\text{HfAlO}_x/25$ Å HfO_2 (d) as gate dielectric. (b) I_d - V_g and g_m versus V_g for InP MOSFETs with 10 Å $\text{HfAlO}_x/25$ Å HfO_2 (d) as gate dielectric at $V_d=2$ V ($W/L=600\mu\text{m}/5\mu\text{m}$).

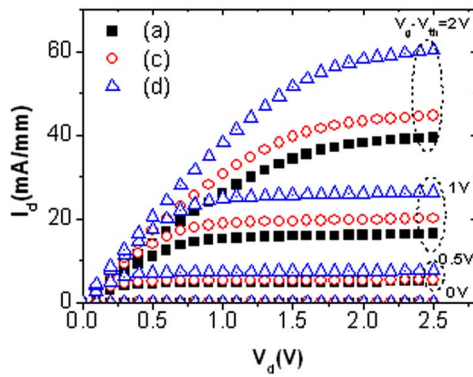


FIG. 5. (Color online) I_d - V_d as a function of V_g at $V_g - V_{th} = 0, 0.5, 1, 2$ V for InP MOSFETs with 35 \AA HfO₂ (a), or 6 \AA HfAlO_x/ 25 \AA HfO₂ (c), or 10 \AA HfAlO_x/ 25 \AA HfO₂ (d) as gate dielectric ($W/L = 600 \mu\text{m}/5 \mu\text{m}$).

ted the $I_d - V_g$ and $g_m - V_g$ at $V_d = 2$ V for MOSFETs with 10 \AA HfAlO_x/ 25 \AA HfO₂ stacked gate dielectric. It shows V_{th} of about 0.1 V and maximum extrinsic transconductance of 51 mS/mm.

Figure 5 illustrates the $I_d - V_d$ curves of MOSFETs with different gate stacks at $V_g = V_{th}, V_{th} + 0.5$ V, $V_{th} + 1$ V, and $V_{th} + 2$ V. The MOSFETs with 10 \AA HfAlO_x/ 25 \AA HfO₂ stacked dielectric show much higher current driver capability than other types. The driver current density is 60.6, 44.8, and 39.5 mA/mm for 10 \AA HfAlO_x/ 25 \AA HfO₂, 6 \AA HfAlO_x/ 25 \AA HfO₂, and 35 \AA HfO₂ gate dielectrics at $V_g = V_{th} + 2$ V and $V_d = 2.5$ V, respectively.

In conclusion, MOSCAPs and MOSFETs have been fabricated on InP using various gate stacks deposited by ALD. The MOSCAPs with 10 \AA HfAlO_x/ 25 \AA HfO₂ stacked gate dielectric exhibit EOT of 12 \AA , and they also show much better interface with InP substrate than a single 35 \AA HfO₂ gate dielectric, demonstrated by 12% less frequency dispersion and one order lower leakage current density. The characteristics of the transistors are also compared; two times higher transconductance, 53% higher drive current density, and 42 mV/decade smaller subthreshold swing are obtained

by MOSFETs with 10 \AA HfAlO_x/ 25 \AA HfO₂ gate stack than the ones with single 35 \AA HfO₂ gate dielectric. These results suggest that HfAlO_x/HfO₂ stacked structure holds promise for attaining further scaling down of III-V MOSFETs.

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