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# ELECTRICAL PROPERTIES OF InAlP NATIVE OXIDES FOR GaAs-BASED MOS APPLICATIONS

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Data on the leakage current, breakdown voltage, dielectric constant and interface trap density of InAlP native oxides in both InAlP/GaAs and InAlP/InGaP/GaAs heterostructures are presented and compared with the electrical properties of AlGaAs native oxides. Both InAlP samples, when properly oxidized and tested under illumination, show the formation of an inversion layer. Over-oxidized or partially oxidized samples show lesser degrees of inversion. Cross-sectional TEM images show higher disorder at the oxide/InGaP interface suggesting that the inversion layer may form at the smoother InGaP/GaAs interface.

Past explorations of native oxides in the GaAs material system have failed to produce an adequate insulator possessing low leakage currents, high breakdown fields, and low interface trap densities as required for metal-oxide-semiconductor (MOS) device applications. Recent studies on in-situ deposition of $Ga_2O_3(Gd_2O_3)$ from $Gd_3Ga_5O_{12}$ have yielded promising results [1]. Native oxides formed via wet thermal oxidation of AlGaAs have thus far shown unacceptably high leakage currents and Fermi-level pinning due to residual As [2,3]. We report here our observations of the significantly better electrical characteristics of wet-thermal native oxides of the As-free material, $In_{0.485}Al_{0.515}P$ (lattice-matched to GaAs).

All samples were grown by metalorganic chemical vapor deposition (MOCVD) in a modified Emcore GS32000 UTM reactor. GaAs substrates were epi-ready with a thin passive oxide layer that was baked-out in arsine in the MOCVD chamber. Immediately after bake out, a GaAs buffer layer of a thickness of at least 500 nm was grown to insure smoothness and cleanliness of subsequent epitaxial layers. InAlP films (~63 nm thick) on GaAs are surface-oxidized in water vapor for 60 min at 500 ¡C.

As shown in Table I, leakage current densities for all the native oxides of InAlP are in the $10^{-10}$ A/cm$^2$ range (at 5 V), 3 to 4 orders of magnitude smaller than our average leakage result for surface-oxidized $Al_{0.98}Ga_{0.02}As$ films. Figure 1 shows typical current-voltage (IV) characteristics. Breakdown fields for InAlP native oxides are approximately 7 MV/cm -- about 2 times higher than values for our AlGaAs oxides, and similar to those reported for $Ga_2O_3(Gd_2O_3)$ [1]. Typical breakdown curves are shown in Fig. 2.

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Table 1. Average values for electrical data of studied structures after wet-thermal oxidation.

| Original Structure | $J_{Leakage}$ @ 5V ($A/cm^2$) | $E_{Breakdown}$ (MV/cm) | $\varepsilon_r$ | $D_{it}$ at midgap ($10^{12}/cm^2/eV$) |
|---|---|---|---|---|
| 500 $Al_{0.98}Ga_{0.02}As$ | 6.0e-6 | 3.75 | 4.66 | 2.3 |
| 630 $In_{0.485}Al_{0.515}P$ | 6.2e-10 | 6.35 | 6.57 | 1.1 |
| 630 $In_{0.485}Al_{0.515}P$/ 100 $In_{0.485}Ga_{0.515}P$ | 2.2e-10 | 6.33 | 5.77 | 1.3 |

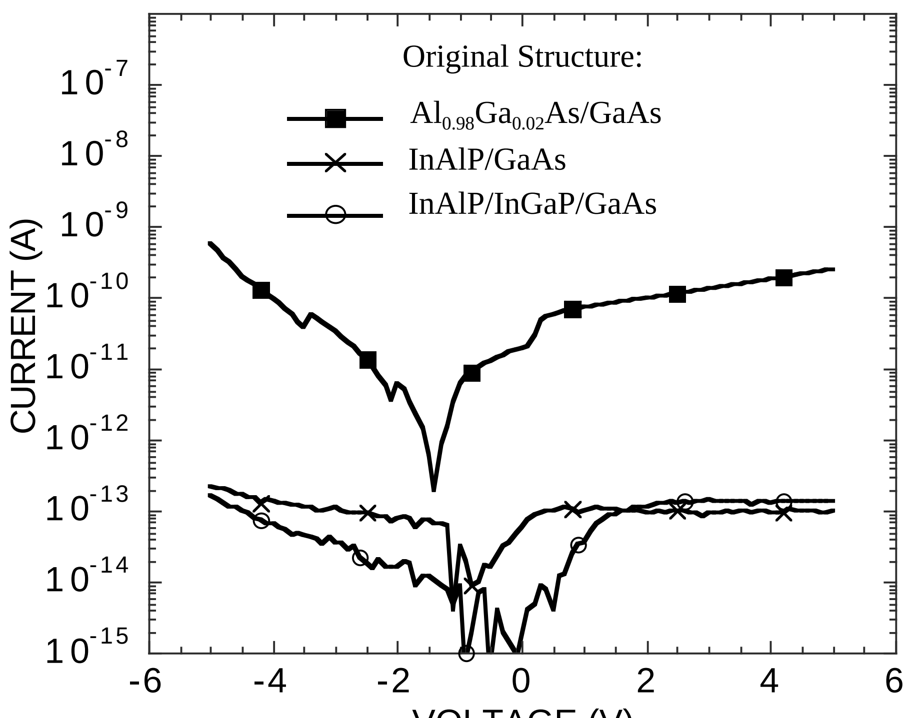


Figure 1. Typical IV curves for MOS capacitors (Area = $1.15 \times 10^{-3}$ $cm^2$) with native oxides of AlGaAs or InAlP (with and without InGaP oxidation barrier).

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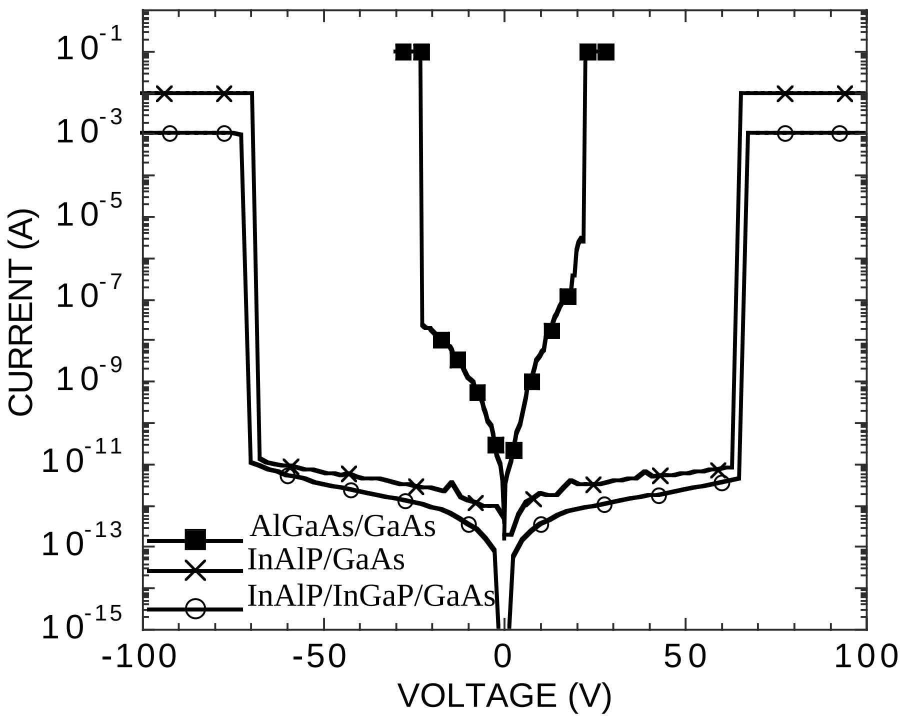


Figure 2. Typical breakdown curves for MOS capacitors (Area = $3.6x10^{-5}$ $cm^2$) with native oxides of AlGaAs or InAlP (with and without InGaP oxidation barrier). The native oxide thicknesses are ~ 450 (AlGaAs) and ~1100 ( InAlP).

High-frequency (1 MHz) and quasi-static capacitance-voltage (CV) measurements are performed on capacitors with areas ranging from 3600 to 115,200 $\mu m^2$. Figure 3 shows high-frequency (HF) CV measurements performed on samples mounted in a dark box. A CV scan that was performed with lights off until the most negative part of the negative-going scan (circular empty makers) shows a deep-depletion characteristic. After momentarily illuminating the sample (before the positive going scan, to generate electron-hole pairs), a flatter inversion region is obtained, suggesting the presence of an inversion layer. The steep jump in capacitance is attributed to the presence of a large number of interface traps. Figure 3 also shows an HF CV scan performed with lights on where a flat inversion region again suggests the formation of an inversion layer.

Low frequency (quasi-static) CV studies, useful for observation of inversion layer formation, have not been feasible in earlier investigations of AlGaAs or other III-V native oxides because of their high leakage currents [3]. With the much lower leakage levels obtained from the InAlP native oxides, quasi-static CV measurements can be performed. Under dark-box measurement conditions, none of our InAlP oxide samples show evidence of an inversion layer. With electron-hole pair (EHP) generation via the illumination of a microscope lamp, many of our InAlP oxide samples show clear signs of an inversion layer, characteristic of a relatively clean interface and possibly unpinned

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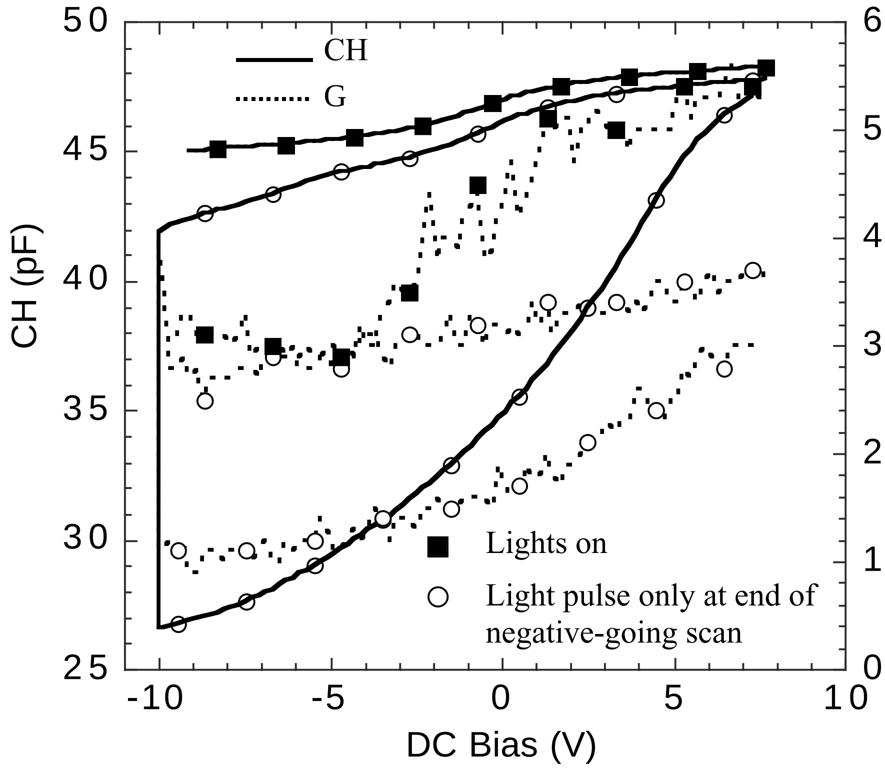


Figure 3. HF curves of InAlP native oxide samples with an InGaP oxidation barrier. The light-pulse scan starts at positive bias with lights off, a light pulse is applied at the most negative part of the scan, and the scan continues to positive bias with lights off. The device area is 115,200 $\mu m^2$ and the sample was oxidized at 500 ¡C for 60 min.

Fermi level. Figure 4 shows a strong reverse bias increase in capacitance, corresponding to hole accumulation and inversion layer formation, for one such InAlP/GaAs sample oxidized for 60 min at 500 ¡C. Similar results are obtained for samples with the InGaP layer. The need for optical generation of electron-hole pairs does not itself necessarily imply the presence of traps, as the thermal generation rates are quite low here due to the larger energy gap of GaAs. It is not uncommon in other wide-bandgap systems (e.g., in GaN MOS research) [4] to require light for carrier generation. The dashed curve of Fig. 4 shows that leakage (Q/t data) measured during the quasi-static CV scan is negligibly small, indicating that thermal equilibrium is maintained throughout the measurement.

In addition, comparative quasi-static CV studies indicate that the apparent inversion layer formation is dependent on oxidation time, $t_{ox}$ (data not shown). With incomplete InAlP oxidation at $t_{ox}$=30 min, only partial inversion is observed, presumably because of the lower optical generation rate of EHPs with our illumination source in the higher energy gap of $In_{0.485}Al_{0.515}P$ ($E_g$=2.33 eV). For full oxidation, near $t_{ox}$=60 min

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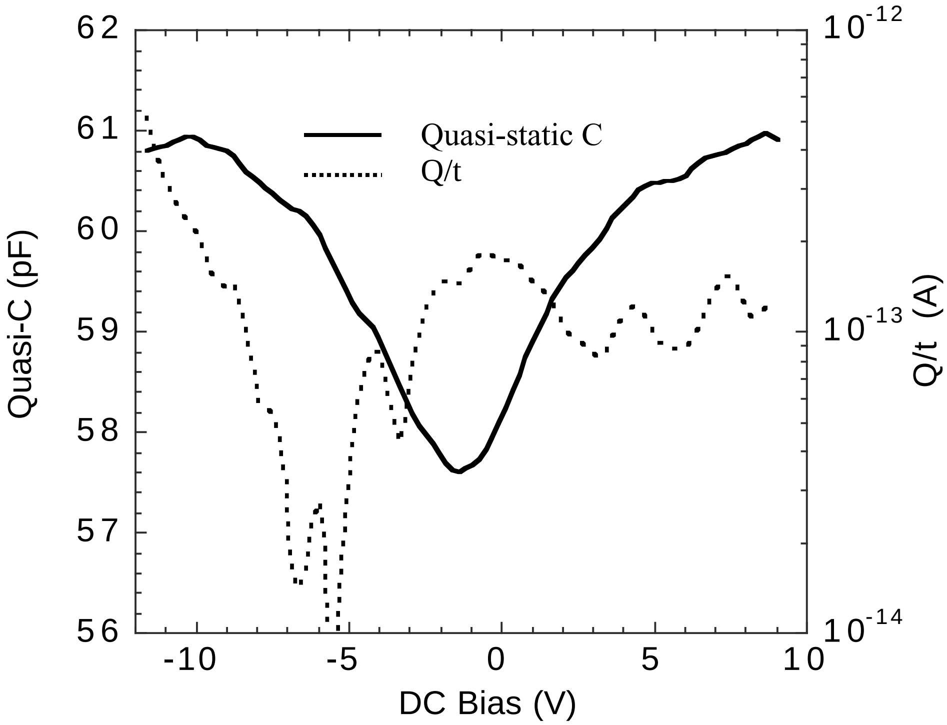


Figure 4. Quasi-static capacitance and leakage vs. DC bias for oxidized InAlP/GaAs. Oxidation was carried out in water vapor at 500 ¡C for 60 min. Scans were performed at speeds of 0.2-0.8 mV/sec.

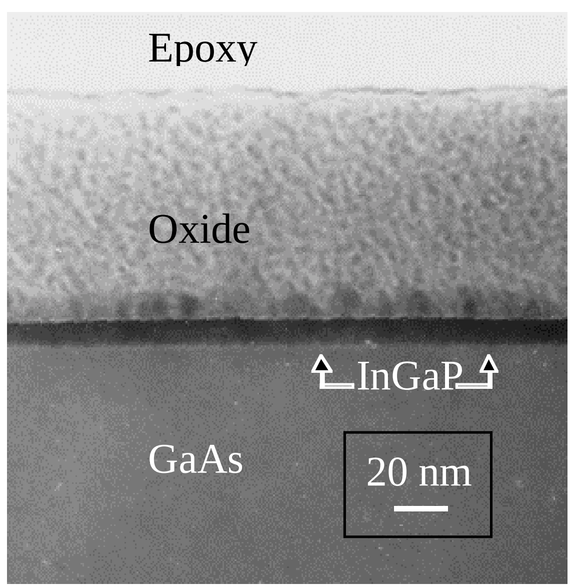


Figure 5. Bright-field TEM image of an oxidized InAlP/InGaP/GaAs sample.

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(data of Fig. 4), the inversion effect is the strongest. At $t_{ox}$=90 min, the degree of inversion is reduced and, at $t_{ox}$=120 min, the inversion layer does not develop at all, which we attribute to excessive over-oxidation into the GaAs substrate. High frequency CV measurements are consistent with quasi-static behavior, as a flat inversion region occurs with illumination for samples oxidized for 60 min. For other times, sloping inversion regions indicate varying degrees of deep depletion. Samples containing a 10 nm InGaP oxidation barrier layer below the InAlP exhibit similar behavior, but with less reduction of inversion at $t_{ox}$=90 min than observed in samples without the barrier.

Transmission electron microscopy (TEM) studies and variable-angle spectroscopic ellipsometry (VASE) measurements are employed to further elucidate precisely where the inversion layer is occurring within the oxidized InAlP/GaAs and InAlP/InGaP/GaAs heterostructures. These measurements indicate thicknesses of ~1100 for the InAlP native oxide and 100 for the InGaP buried layer, indicating a high oxidation rate selectivity between InAlP and InGaP, making the latter effective at stopping the progressing oxidation front. The TEM picture of Fig. 5 shows an amorphous oxide above a darker contrast, crystalline layer (the InGaP barrier), consistent with the VASE data. From these measurements, an expansion of approximately 75% is observed for the InAlP layer after oxidation. This measurement is notably larger than the 29% expansion reported by Mathes, et al [5] for similarly oxidized InAlP films. In Fig. 5, a darker contrast region just above the oxide/InGaP interface is thought to be due to denser materials in the form of In or InP [5]. This region is most likely not a suitable host for an inversion layer due to the large amount of disordering and interface states that these byproducts could introduce. On the other hand, the InGaP/GaAs interface is quite clean and smooth and could be readily inverted as revealed by CV measurements. Studies are continuing to determine the location of the inverted interface in samples without the InGaP oxidation barrier layer.

In conclusion, we report on the much better electrical characteristics of InAlP native oxides as compared to AlGaAs native oxides. An inversion layer is observed when the samples are illuminated with a microscope light, and its formation depends on oxidation conditions. TEM studies reveal precipitates at the oxide/InGaP interface while the InGaP/GaAs interface remains uniform and epitaxial.

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