

Properties of atomic-layer-deposited ultra-thin AlN films on GaAs surfaces



P. Mattila^{a,*}, M. Bosund^{a,b}, H. Jussila^a, A. Aierken^a, J. Riikonen^a, T. Huhtio^a, H. Lipsanen^a, M. Sopanen^a

^a Department of Micro and Nanosciences, Aalto University, P.O. Box 13500, FI-00076 Aalto, Finland

^b Beneq Oy, P.O. Box 262, FI-01511 Vantaa, Finland

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ABSTRACT

Properties and passivation effect of ultra-thin AlN films fabricated on InGaAs/GaAs near-surface quantum wells by plasma-enhanced atomic layer deposition are investigated. The role of the coating on the surface is studied by examining the electric field build-up by photoreflectance. Photoluminescence confirms the passivation effect with ultra-thin layers and the reduced electric fields with thicker AlN layers. Atomic force microscopy shows that an ultra-thin AlN layer does not substantially alter the surface morphology.

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1. Introduction

GaAs based metal-oxide-semiconductor field-effect transistors (MOSFET) have been proposed as high-speed alternatives for the widely used silicon based MOSFETs. However, due to the lack of proper native oxide on GaAs, materials such as Al₂O₃ [1] and HfO₂ [2,3] have to be used as dielectrics. In the GaAs/dielectric oxide interface the surface states and Fermi level pinning have, nevertheless, been a source of problems [4]. Many solutions towards improved interface such as thermal nitridation [5] and sputtered AlN [3] have been proposed. Aluminum nitride fabricated by plasma-enhanced atomic layer deposition (PEALD) can replace the sputtered AlN as a passivation layer prior to HfO₂ deposition. In PEALD AlN, the passivation layer is deposited *ex situ* at lower temperatures (at around 200 °C) instead of the high temperatures typically used in many *in situ* metalorganic vapor phase epitaxy (MOVPE) techniques (typically above 500 °C) [6]. Therefore, this method is suitable for passivation of structures that cannot tolerate high-temperature post-growth processing. In addition, the thermal expansion coefficient of AlN is close to that of GaAs [7], PEALD AlN does not require any pre-processing prior to AlN deposition, and the conformality of PEALD AlN enables the passivation of complex surface structures.

A drawback related to using plasma assisted processes to fabricate surface passivation layers is that they have been shown to induce damage on near-surface structures [8–11]. Although the nature and extent of the damage has been characterized using both photoreflectance (PR) and photoluminescence (PL) methods, only PR has proven effective in estimating plasma induced defect densities and resulting electric fields in the near surface region [8]. On the other hand, PL properties are very important from an application point of view. So far, there are very few studies on surface passivation by PEALD AlN [12,13], and they have concentrated on techniques other than PR.

In this paper, we study ultra-thin PEALD AlN layers on InGaAs/GaAs quantum well structures by investigating the surface electric fields and photoluminescence intensities using PR and PL, respectively. The electric field strength decreases with increasing AlN layer thickness up to about 0.5 nm, which is due to the passivating effect of the plasma treatment in the process. This is also seen in the photoluminescence results. Atomic force microscope images verify that the morphology of the GaAs surface is not substantially altered by an ultra-thin layer of AlN. Finally, it is shown that it is possible to use layers even thicker than 5 nm without detrimental effects on optical properties as long as the capping layer thickness is in a suitable range.

2. Theoretical background

Photoreflectance analysis usually presents the ratio of the change in reflectance due to modulation and the dc reflectance,

* Corresponding author.

E-mail address: paivi.mattila@aalto.fi (P. Mattila).

$\Delta R/R$, as a function of photon energy. A typical spectrum exhibits Franz–Keldysh oscillations (FKO) that can be used in determining the internal electric field. The FKOs obey the equation

$$m\pi = \left(\frac{\pi}{2}\right)(d-1) + \frac{4}{3} \left(\frac{E_m - E_g}{\hbar\theta}\right)^{3/2}, \quad (1)$$

where m is the index of the m th extremum of the FKOs, E_m is the energy of the m th extremum, E_g is the band gap of the semiconductor and d is the critical point dimension [14,15]. Electro-optical energy, $\hbar\theta$, can be expressed as

$$\hbar\theta = \left(\frac{e^2 \hbar^2 F^2}{2\mu}\right)^{1/3}, \quad (2)$$

where e is the unit charge, F the electric field, and μ the electron–hole reduced effective mass. In the case of GaAs, the reduced mass is $0.056m_0$, where m_0 is the free electron mass.

From Eq. (1) and Eq. (2), the internal electric field F can be solved by calculating $(4/3\pi)(E_m - E_g)^{3/2}$ for each m . Subsequently, from the slope of a linear fit, the field F can be determined using Eq. (2). The band gap energy E_g of GaAs in Eq. (1) can be approximated by Varshni equation [16]

$$E_g(T) = 1.519 \text{ eV} - \frac{\alpha T^2}{T + \beta}, \quad (3)$$

where T is temperature, $\alpha = 5.405 \times 10^{-4}$ eV/K, and $\beta = 204$ K [17]. The measured PL energies agree well with the energies calculated by Varshni equation.

The structures typically used in FKO measurements to study Fermi level pinning at the surface have an undoped layer on a buried n^+ (p^+) buffer layer, which is fabricated on a n^+ (p^+) substrate. These structures are often called s - i - n^+ (surface-intrinsic- n^+)

or s - i - p^+ , respectively [15,18,19]. Nevertheless, the PR technique can also be used to characterize electric fields in undoped structures [20]. Many studies involving both undoped and doped structures have been conducted throughout the last decades [21–25].

The typical doping level for an undoped GaAs layer fabricated by MOVPE is in the order of 10^{15} cm^{-3} , which is high enough for FKOs [15,26]. The background doping in this range affects only slightly the obtained internal electric fields in undoped structures [27] and, therefore, special care was taken that the samples for this study were fabricated in comparable growth conditions.

It has been demonstrated that the InGaAs/GaAs interfaces are relatively free of interface trap states. In addition, the internal electric field is induced by charges trapped in the surface states of GaAs (1 0 0) [28]. Therefore, when the InGaAs/GaAs structures are fabricated in similar growth conditions, it can be assumed that the differences in the electric fields F are originating from the differences in the surface states of the GaAs capping layer. Thus, a weaker internal electric field in a passivated sample compared to an unpassivated one implicates a lower surface state density.

3. Experiment

$\text{In}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ near-surface quantum well (NSQW) structures were fabricated on a semi-insulating GaAs ($100 \pm 0.1^\circ$) substrate by MOVPE at 650°C . Trimethylindium, trimethylgallium, and tertiary-butylarsine were used as precursors and hydrogen as the carrier gas. The V/III ratio was 30 and 27 for GaAs and InGaAs, respectively. The nominal indium content x in the $\text{In}_x\text{Ga}_{1-x}\text{As}$ quantum wells (QW) was 0.21, and the QWs were sandwiched between a GaAs buffer and a GaAs capping layer. The nominal layer thicknesses of the buffer layer, the QW and the capping layer were 125 nm, 4 nm, and 6 nm, respectively. After the MOVPE growth, the

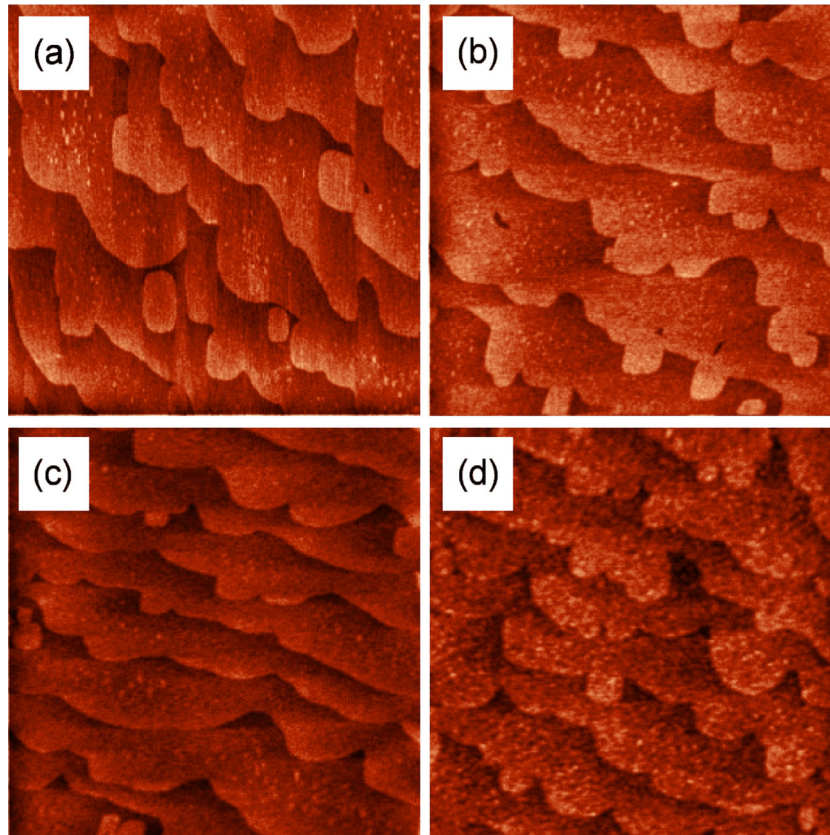


Fig. 1. AFM images of (a) unpassivated and (b)–(d) passivated InGaAs/GaAs NSQW samples. The AlN layer thickness is (b) 0.3 nm, (c) 1.0 nm, and (d) 4.8 nm. The scan size and height scale are $3 \mu\text{m} \times 3 \mu\text{m}$ and 1.2 nm, respectively.

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