In-Situ Ga$_2$O$_3$ Process for GaAs Inversion/Accumulation Device and Surface Passivation Applications

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Abstract

In-situ deposition of Ga$_2$O$_3$ films on clean, atomically ordered (100) GaAs surfaces has been investigated. Unique Ga$_2$O$_3$-GaAs interface properties including an interface state density in the mid $10^{10}$ cm$^{-2}$ eV$^{-1}$ range and an interface recombination velocity of 4500 cm/s have been demonstrated. The formation of inversion layers in both n- and p-type GaAs has been clearly established. The Ga$_2$O$_3$-GaAs interface is characterized by thermodynamic and photochemical stability.

I. Introduction

Since the emergence of GaAs technology, the development of GaAs electronic and optoelectronic devices has been hampered by the lack of dielectric films providing low interface state density [1]. Recent efforts have been focused on a variety of dry and wet surface treatments prior to deposition of dielectric films [2] - [5]. Interface state densities inferred from capacitance-voltage measurements are still high, typically around $10^{12}$ cm$^{-2}$ eV$^{-1}$ or above. Apparently, these techniques inadequately address major sources of interface states such as surface exposure and defects [6] - [9], surface nonstoichiometry [10], thermodynamic instability [11], and intrinsic Fermi level pinning [12].

II. Sample Fabrication

Ga$_2$O$_3$ films have been deposited in-situ on clean, atomically ordered (100) GaAs surfaces grown by molecular beam epitaxy using a multiple-chamber ultra high vacuum system (Fig. 1). Prior to oxide deposition, (i) the surface stoichiometry is maintained as observed by reflection high energy electron diffraction (RHEED), and (ii) extremely low GaAs surface exposure (predominantly oxygen) of typically less than 10 Langmuirs (1 L = 10$^{-6}$ Torr sec) has been accomplished (Fig. 2). Based on typical initial sticking coefficients for oxygen [1], [13], the GaAs surface impurity coverage is estimated at $10^{-2}$ to $10^{-3}$% of a monolayer or $10^8$ to $10^9$ surface impurities/cm$^2$ prior to deposition. Ga$_2$O$_3$ deposition comprises electron-beam evaporation of a single-crystal Gd$_2$Ga$_5$O$_{12}$ source at GaAs substrate temperatures ranging from 0 °C to 620 °C [14].
26 nm thick Ga$_2$O$_3$ film deposited at 360 °C. Partial ordering in a completely disordered amorphous state is observed for increased deposition temperature as indicated by the development of sharp edges in the diffuse diffraction halo [15]. Fig. 4 shows the measured and simulated RBS spectrum of a 52.5 nm thick Ga$_2$O$_3$ film deposited at 360 °C. Gd incorporation is enhanced with increasing film thickness reaching a maximum of 1.5 at. % at the film surface. The Gd concentration, however, is more than three orders of magnitude smaller in the near interface region as revealed by secondary ion mass spectroscopy. Fig. 5 shows typical Ga and As 3d core levels of in-situ fabricated Ga$_2$O$_3$-GaAs structures using a (2x4) As stabilized GaAs surface prior to deposition. The chemical shift of the interfacial As 3d core level acquired by XPS depth profiling is clearly correlated to As surface coverage prior to deposition and thus, to surface reconstruction [12]. Chemical reaction products, in particular As$_2$O$_3$ (44.6 eV) and As$_2$O$_5$ (45.7 eV) are not detectable at in-situ fabricated oxide-GaAs interfaces. Consequently, thermodynamic stability is obtained as predicted by thermochemical phase diagrams [11]. Stability aspects will be further discussed in Sec. V.

IV. Electrical Film and Interface Properties

The fabricated samples have been characterized by current-voltage (I-V), quasi-static and high frequency capacitance-voltage (C-V), and photoluminescence (PL) measurements. Fig. 6 shows I-V characteristics of n- and p-type samples with a 46.2 and 59.4 nm thick Ga$_2$O$_3$ film, respectively. The spe-
cific resistivity inferred from the slope at low voltage is in excess of $10^{15}$ $\Omega$ cm. Fig. 7 and Fig. 8 show typical quasi-static and high frequency characteristics measured for n- and p-type samples, respectively. Excellent uniformity has been achieved over the two inch wafers. The formation of inversion layers is clearly established in both n- and p-type samples. The frequency dispersion observed in accumulation for $f \leq 10$ kHz is attributed to varying oxide composition with film depth. The interface state density $D_i$ shown in Fig. 9 has been inferred using the quasi-static/high frequency technique [16]. An excellent midgap interface state density $< 5 \times 10^{10}$ cm$^{-2}$ eV$^{-1}$ has been obtained. The interface states are characterized by large time constants in excess of 0.1 - 10 s almost independent of surface Fermi level position. Charge trapping in the oxide was revealed as the dominant trapping mechanism [17].

The interface recombination velocity $S$ has been derived from steady state PL measurements at power densities between 20 and 5000 W/cm$^2$. The best fit of the measured data to a model solving Poisson's and current continuity equations self-consistently, has been obtained for $4500 < S < 7000$ cm/s (Fig. 10). The capture cross section acquired from both $D_i$ and $S$ is of the order of $10^{-15}$ cm$^2$ [18]. Using the same technique, the interface recombination velocity of an AlGaAs-GaAs structure using identical GaAs epitaxial layers and substrate is determined to 800 cm/s.

![Fig. 7. Quasi-static and high frequency capacitance as a function of voltage measured on Ga$_2$O$_3$-GaAs n-type samples. The oxide thickness $t_{ox}$ is 46.2, the oxide deposition temperature $T_d$ was 620 $^0$C. The oxide relative dielectric constant is 14.2.](image1)

![Fig. 8. Quasi-static capacitance and high frequency capacitance as a function of voltage measured on Ga$_2$O$_3$-GaAs p-type samples. The oxide thickness $t_{ox}$ is 59.4 nm, the oxide deposition temperature $T_d$ was 590$^0$C.](image2)

![Fig. 9. Interface state density of in-situ fabricated Ga$_2$O$_3$-GaAs interfaces inferred using the quasi-static/high frequency method.](image3)

![Fig. 10. Measured peak PL (circle, triangle, and diamond represent results for $T_d$ = 360, 550, and 620 $^0$C, respectively) normalized to PL of a corresponding bare surface (measured at $P$ = 580 W/cm$^2$). The solid and dashed lines are obtained by simulations.](image4)
V. Thermodynamic and Photochemical Stability

Thermodynamic and photochemical stability have been investigated by exposure to temperature and laser excitation, respectively. Degradation of PL intensity has not been observed after temperature exposure of 800 °C indicating completely preserved interface properties (Fig. 11). No chemical interface reaction could be detected even after temperature exposure of 1000 °C. Ga and As 3d core levels are virtually identical to levels of as deposited structures (s. Fig. 5) and As₂O₃ are not detectable [19].

In-situ fabricated Ga₂O₃-GaAs interfaces show excellent photochemical stability (Fig. 12). No degradation of PL intensity is observed after 22 hours of laser excitation using a power density of 580 W/cm² implying preservation of excellent interface properties. This is in sharp contrast to typical results based on an optimized (NH₄)₂S treatment and subsequent electron cyclotron resonance plasma deposition of Si₃N₄. Note that the considerably lower PL obtained by using the latter approach indicates $S = 10^3$ cm/s at zero time (s. Fig. 10).

VI. Conclusions

Unique structural and electrical interface properties have been obtained by in-situ deposition of Ga₂O₃ films on clean, atomically ordered (100) GaAs surfaces. This approach may pave the way for new device concepts on GaAs and will significantly improve existing GaAs device technologies. Field effect device applications will require further improvements of bulk oxide properties, in particular a reduction of trap density.

References