Recombination velocity at oxide–GaAs interfaces fabricated by in situ molecular beam epitaxy

M. Passlack,a) M. Hong, J. P. Mannaerts, J. R. Kwo, and L. W. Tu
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974

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The recombination velocity at oxide–GaAs interfaces fabricated by in situ multiple-chamber molecular beam epitaxy has been investigated. Ga2O3, Al2O3, SiO2, and MgO films have been deposited on clean, atomically ordered n- and p-type (100) GaAs surfaces using molecular beams of Ga–, Al–, Si–, and Mg oxide, respectively. Based on the internal quantum efficiency measured for incident light power densities 1 ≈ P0 ≈ 104 W/cm2, the interface recombination velocity S has been inferred using a self-consistent numerical heterostructure device model. While Al2O3–, SiO2–, and MgO–GaAs structures are characterized by an interface recombination velocity which is comparable to that of a bare GaAs surface (≈ 107 cm/s), S observed at Ga2O3–GaAs interfaces is as low as 4000–5000 cm/s. The excellent Ga2O3–GaAs interface recombination velocity is consistent with the previously reported low interface state density in the mid 1010 cm–2 eV–1 range.

The fabrication of thermodynamically stable insulator-GaAs interfaces with low interface recombination velocity and defect density has remained one of the key challenges in compound semiconductors during the last three decades.1 Pivotal aspects include an extremely low GaAs surface exposure to impurity gases (<10–100 Langmuirs, 1 L = 10–6 Torr s) and the preservation of GaAs bulk and surface stoichiometry,2 the complete exclusion of GaAs surface oxidation,3,4 and the specific chemical bonding associated with the interfacial atoms of GaAs and the insulating species.5 Previous efforts including a variety of dry and wet surface treatments prior to deposition of dielectric films,6,7 photowashing,8–10 oxidation of GaAs11 or Ga,12 and vacuum exposure to impurity gases13,14 inadequately addressed the above-mentioned requirements. Consequently, only limited improvements of electronic interface properties were demonstrated and commercial device applications have not yet been reported. We have recently demonstrated that thermodynamically stable,15 low interface state density Dit,16 insulator-GaAs interfaces can be fabricated when specific molecules are deposited on clean, atomically ordered (100) GaAs surfaces under ultrahigh vacuum (UHV) conditions. This letter investigates the interface recombination velocities S measured at our in situ fabricated oxide-GaAs interfaces with emphasis on the unique feature of low S at Ga2O3–GaAs interfaces.

The 2 in. wafers have been fabricated using a multiple-chamber UHV system.17 The fabrication was comprised of 1.5–μm thick n-type (donor concentration N D = 1.6×1016 cm–3) or p-type (acceptor concentration N A = 4.4×1016 cm–3) GaAs layers grown by solid source molecular beam epitaxy (MBE) on heavily Si or Zn doped (100) GaAs substrates, respectively. Subsequently, the freshly grown film with an As-stabilized (2×4) surface was transferred under a vacuum of 6×10–11 Torr from the III–V MBE chamber (background pressure of 2×10–11 Torr) to another chamber (1×10–10 Torr) for oxide deposition. Prior to oxide deposition, (i) the surface stoichiometry and atomic order are preserved as observed by reflection high-energy electron diffraction,5 and (ii) extremely low GaAs surface exposure (predominantly oxygen) of typically less than 10 L has been accomplished.5 The surface exposure prior to opening the shutter for oxide deposition was caused by vaporization and thermal dissociation of the oxide target during electron-beam heating. Based on typical initial sticking coefficients for oxygen1,18 the GaAs surface impurity coverage is estimated at 10–5%–10–3% of a monolayer or at 105–106 surface impurities/cm2 prior to deposition. Finally Ga2O3, Al2O3, SiO2, or MgO films were deposited on a clean, atomically ordered (100) GaAs surface at substrate temperatures T s ranging from 0 to 620 °C using a molecular beam of Ga–, Al–, Si–, or Mg oxide, respectively. The oxide molecules were supplied by electron-beam evaporation of a single-crystal Gd3Ga5O12 (see Ref. 19). The fabricated oxide–GaAs interfaces,5 Reference samples with identical GaAs epitaxial structure and substrate were also fabricated in the same solid-source III–V chamber using (i) no oxide deposition (bare samples) and (ii) Al0.45Ga0.55As–GaAs interfaces.

The fabricated structures have been investigated by standard steady-state photoluminescence (PL) measurements using an argon ion laser (λ0 = 514.5 nm). First, PL measurements at high injection level have been used to qualitatively characterize the Ga2O3–, SiO2–, Al2O3–, MgO–, and Al0.45Ga0.55As–GaAs interface as well as the bare sample surface. At high injection level (ρ > N), radiative recombination dominates for low nonradiative contributions (internal quantum efficiency η ≈ 1), however, quantum efficiencies close to that of a bare sample (η ≈ 1) are measured for high surface recombination velocity S > 106 cm/s.20 Here, ρ and N are the injected carrier density and the doping concentration, respectively. Figure 1 shows typical PL spectra obtained
from oxide– and Al$_{0.45}$Ga$_{0.55}$As–GaAs interfaces as well as from the bare sample surface ($n$ type). The excitation density $P_0$ is 1100 W/cm$^2$. Clearly, the results shown in Fig. 1 reveal two distinctively different classes of interfaces where the first group includes Ga$_2$O$_3$– and Al$_{0.45}$Ga$_{0.55}$As–GaAs and the second comprises the other oxides. The latter group exhibits a surface recombination velocity $S$ comparable to that of a bare surface ($\approx 10^7$ cm/s) and a Fermi level pinned at the interface as demonstrated by C–V measurements (not shown). Evidently, the fundamentally different electronic interface properties observed at various in situ fabricated oxide–GaAs interfaces are due to the specific chemical bonding associated with the interfacial atoms of GaAs and the deposited oxide molecules. Therefore, we have chosen the term intrinsic pinning for our observation of Fermi-level pinning in situ fabricated SiO$_2$–, Al$_2$O$_3$–, and MgO–GaAs interfaces.

Similar results have been measured for $p$-type Ga$_2$O$_3$– and Al$_{0.45}$Ga$_{0.55}$As–GaAs structures (Fig. 2). In the following, we will focus on the unique electronic interface properties of in situ fabricated Ga$_2$O$_3$–GaAs interfaces.

The interface recombination velocity $S$ has been inferred from thorough studies of the internal quantum efficiency $\eta$ over a wide range of incident light densities ($1 \leq P_0 \leq 10^4$ W/cm$^2$). This technique is based on the relative weight of the nonradiative recombination rate $R_{SRH}$ (Shockley–Read–Hall recombination) given here for a single defect level located at the intrinsic level $E_i$.

$$R_{SRH} = \frac{pn - n_i^2}{\tau_p(n + n_i) + \tau_n(p + n_i)}$$

and the radiative recombination $R_{rad} = B(n_p - n_i^2)$ as a function of $P_0$. Here, $p$, $n$, $\tau_p$, $\tau_n$, $n_i$, and $B$ are the hole and the electron density, the hole and electron lifetime, the intrinsic carrier density, and the radiative band–to–band recombination coefficient, respectively. For interface nonradiative recombination, $\tau_{pln} = 1/S_{pln}$, where $S_p$ and $S_n$ are the interface recombination velocities for holes and electrons, respectively. At intermediate and high injection levels, $R_{SRH}$ decreases relative to the radiative recombination rate resulting in a unique curve shape of $\eta$ vs $P_0$ for a specific $S$. This is demonstrated in Fig. 3 which shows the measured (symbols) and simulated (dashed lines) efficiency $\eta$ vs $P_0^*$ of Ga$_2$O$_3$–GaAs structures and, for comparison purposes, that of an Al$_{0.45}$Ga$_{0.55}$As–GaAs interface ($n$ type) with $S = S_p = S_n$ as a parameter. The simulation results have been obtained from calculated PL depth profiles to be discussed later. Note that the analysis has been performed from low to very high injection levels.

![Measured PL spectra of n-type oxide– and Al$_{0.45}$Ga$_{0.55}$As–GaAs structures as well as of a corresponding bare surface. The deposition temperatures for Ga$_2$O$_3$ are 620, 360, and 550 °C from the highest to the lowest measured spectrum, respectively. The other results were typically obtained for $T_s = 660$ °C (Al$_{0.45}$Ga$_{0.55}$As), and 0 °C $\leq T_s \leq 500$ °C (Al$_2$O$_3$, SiO$_2$, and MgO).](image1)

![Measured PL spectra of p-type Ga$_2$O$_3$– and Al$_{0.45}$Ga$_{0.55}$As–GaAs structures as well as of a corresponding bare surface. These results were typically obtained for $T_s = 690$ °C (Al$_{0.45}$Ga$_{0.55}$As) and 450 °C $\leq T_s \leq 600$ °C (Ga$_2$O$_3$).](image2)

![Measured (symbols) and calculated (lines) internal quantum efficiency $\eta$ as a function of $P_0^*$ for the samples. For Ga$_2$O$_3$, squares, diamonds, and circles represent results measured for $T_s = 360, 550$, and 620 °C, respectively.](image3)
projection levels since the carrier densities are $6.5 \times 10^{14}$ and $7.8 \times 10^{17}$ cm$^{-3}$ at the semiconductor surface for the lowest and highest excitation densities $P_0$ of 1 and $10^4$ W/cm$^2$, respectively. Since the PL intensity is not measured in absolute units, the measured curves are rigidly shifted to the calculated ones.$^{23}$ The best fit of the simulations to the measurement data has been attained for $S=4000$–5000 and 1000 cm/s for Ga$_2$O$_3$– and Al$_{0.45}$Ga$_{0.55}$As–GaAs structures and for a corresponding bare surface. The GaAs surface is located at a distance of 100 nm.

In summary, we have demonstrated very low recombination velocities at in situ fabricated Ga$_2$O$_3$–GaAs interfaces. This result is consistent with the previously reported low interface state density in the mid $10^{10}$ cm$^{-2}$ eV$^{-1}$ range.

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1 A review can be found in C. W. Wilmsen, *Physics and Chemistry of III-V Compound Semiconductor Interfaces* (Plenum, New York, 1985).


6 See, for example, J. S. Herman and F. L. Terry, Appl. Phys. Lett. 60, 716 (1992).


