In situ fabricated Ga_2O_3–GaAs structures with low interface recombination velocity

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Amorphous Ga_2O_3 films have been deposited *in situ* on (100) GaAs layers grown by molecular beam epitaxy in ultrahigh vacuum. The Ga_2O_3–GaAs interface is stable during photoexcitation and the photoluminescence (PL) intensity, measured at 514.5 nm excitation wavelength, is enhanced drastically by a factor of 420 as compared to a corresponding bare GaAs surface. The Ga_2O_3–GaAs interface recombination velocity derived from a modified dead layer model is below 10^4 cm/s. Furthermore, the PL intensity of Ga_2O_3–GaAs structures approaches that of a very low interface state density (2×10^9 eV^{-1} cm^{-2}) AlGaAs–GaAs reference structure. © *1995 American Institute of Physics.*

The lack of stable dielectric films providing a low interface state density has been a drawback of III–V semiconductors. In the case of GaAs, surface states are attributed to defects or excess As, although some aspects of the origin of surface states are still controversial.[1,2] Thermal, anodic, and plasma surface oxidation techniques produced high resistivity films but could not prevent the formation of excess As at the dielectric–semiconductor interface.[3] Deposition of different dielectric materials including Si_3N_4, SiO_x, Al_2O_3, and Ga_2O_x has been used in combination with dry, liquid, and photochemical semiconductor surface treatments.[4] Recently, Aydil *et al.*[5,6] achieved passivation of surface states during a NH_3 or H_2 plasma treatment at room temperature by removal of excess As and As_2O_3 and subsequent formation of a Ga_2O_3 film (a few monolayers thick) on a GaAs surface.

This letter reports on a completely new approach encompassing *in situ* deposition of thermochemically stable,[7] native Ga_2O_3 on a pristine GaAs surface grown by molecular beam epitaxy (MBE) in ultrahigh vacuum (UHV). The entire *in situ* processing system is described in Ref. 8. The system components utilized for fabrication of Ga_2O_3–GaAs structures with low interface recombination velocity are (i) a semiconductor MBE growth chamber (solid-source III–V chamber, 2×10^{-11} Torr) and (ii) a dielectric film deposition chamber (1×10^{-10} Torr), both linked together by transfer modules with a background pressure of 6×10^{-11} Torr. The sample fabrication comprised a 1.5 μm thick GaAs *n*-type (2×10^{16} cm^{-3}) layer grown by MBE on an n^+ doped (100) GaAs substrate. Subsequently, the wafer was transferred from the MBE growth chamber into the dielectric film deposition chamber. Finally, Ga_2O_3 films were deposited by electron-beam evaporation from a single-crystal $Gd_3Ga_5O_{12}$ source[9,10] at substrate temperatures ranging from 0 to 500 °C.

The Ga_2O_3 films were characterized by transmission electron microscopy (TEM), Rutherford backscattering spectroscopy (RBS), and by secondary ion mass spectroscopy (SIMS) for microstructure, atomic composition, and depth profile, respectively. Figure 1 shows plan-view TEM micrographs and corresponding electron diffraction patterns of Ga_2O_3 films deposited at (a) 0 °C and (b) 500 °C. The film deposited at 0 °C shows a typical electron diffraction pattern of an amorphous material. It consists of a diffuse halo surrounded by weak halos with a rapid decrease in intensity. The intensity distribution of the diffuse halos gradually sharpens up with increasing deposition temperature (500 °C), indicating a change from a completely disordered state into a weakly ordered amorphous state. Further increase in deposition temperature would result in distinct edges around the diffuse rings, which eventually develop into a sharp ring pattern observed in polycrystalline films. RBS measurements indicated an atomic composition of 55.5% O, 43% Ga, and 1.5% Gd for Ga_2O_3 films deposited at 0 and 300 °C. Earlier x-ray photoelectron spectroscopy measurements revealed a mixture of Ga_2O_3 and elemental Ga.[10] Furthermore, SIMS measurements indicated a strong confinement of Gd to the oxide surface region.

The *in situ* prepared Ga_2O_3–GaAs interface was investigated by PL measurements using an argon ion laser ($\lambda=514.5$ nm) and a HeNe ($\lambda=632.8$ nm) laser both operated at optical power densities between 0.1 and 10 W/cm^2. The PL signal was detected by a SPEX 1681 spectrometer and a Princeton 5301 A lock-in amplifier. Figure 2 shows as-measured PL intensity spectra for Ga_2O_3–GaAs and AlGaAs–GaAs structures as well as for a corresponding bare surface. The excitation wavelength is (a) 514.5 nm and (b) 632.8 nm and the excitation power density is 0.5 W/cm^2. The integrated PL intensity of the Ga_2O_3–GaAs structure is higher by a factor of 420 ($\lambda_{ex}=514.5$) and 56 ($\lambda_{ex}=632.8$ nm) as compared to a corresponding bare GaAs surface. Furthermore, the Ga_2O_3–GaAs interface was found to be stable during photoexcitation.

The interface recombination velocity *s* can be evaluated using a modified dead layer model,[11–13] which accounts for carrier diffusion and surface minority carrier recombination. Assuming flatband surface potential, the PL intensity I_{fb} of the Ga_2O_3–GaAs sample is given by

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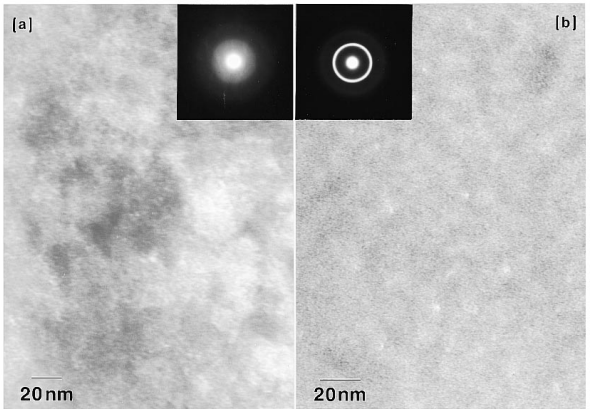

FIG. 1. Plan-view TEM micrographs and corresponding electron diffraction patterns of Ga_2O_3 films *in situ* deposited on GaAs substrate at temperatures of (a) 0 °C and (b) 500 °C.

$$I_{\rm fb}=\frac{\kappa I_0}{1-\alpha^2L^2}\left(1-\alpha L\,\frac{\alpha L+S}{1+S}\right), \tag{1}$$

where κ is the semiconductor radiative recombination yield, I_0 the light intensity entering the semiconductor, α the semiconductor absorption coefficient at the excitation wavelength,[14] $L=\sqrt{D\tau}$ the minority carrier diffusion length, and $S=sL/D$ the reduced interface recombination velocity. Using a minority carrier diffusion coefficient D of 7.5 cm^2/s and a radiative lifetime for holes $\tau=64$ ns[15] for a doping concentration $N_D=2\times10^{16}$ cm^{-3}, we get $L=6.9$ μm. In order to compare the PL intensities of the Ga_2O_3–GaAs sample and a corresponding bare GaAs surface, a hypothetical flatband PL intensity $\mathscr{I}_{\rm fb}$ of the bare sample accounting for the dead layer (depletion layer) effect has to be determined

$$\mathscr{I}_{\rm fb}=\mathscr{I}e^{\alpha W}, \tag{2}$$

where $\mathscr{I}$ is the measured bare sample PL intensity and W is the semiconductor depletion layer width. Since $S\gg\alpha L$ for a bare GaAs surface, the PL ratio β between the measured PL intensity of the Ga_2O_3–GaAs sample and the hypothetical flatband PL signal derived from Eq. (2) of a bare surface predicted by the modified dead layer model is

$$\beta=\frac{I_{\rm fb}}{\mathscr{I}_{\rm fb}}=\frac{1}{1-\alpha L}\left(1-\alpha L\,\frac{\alpha L+S}{1+S}\right). \tag{3}$$

The PL ratio β has been inferred from the measured integrated PL intensities $I_{\rm fb}$ and $\mathscr{I}$ taking into account the change in sample reflectivity after Ga_2O_3 film deposition and assuming a Fermi level which is pinned 0.8 eV below the conduction band edge on the bare GaAs surface, respectively. Rearranging Eq. (3) gives the reduced interface recombination velocity

$$S=\frac{1+\alpha L-\beta}{\beta-1}\,. \tag{4}$$

Using Eq. (4), Ga_2O_3–GaAs interface recombination velocities s of 9400 and 12 500 cm/s were obtained from the integrated PL intensity ratios β measured at 623.8 and 514.5 nm, respectively. The quantification of the PL data using the modified dead layer model gives an upper limit for the Ga_2O_3–GaAs interface recombination velocity due to uncertainties associated with the actual band bending in the investigated structures. The consideration of a residual band bending in the Ga_2O_3–GaAs samples as well as of a band bending less than 0.8 eV at the bare GaAs surface under illumination would provide larger values of β resulting in an even lower Ga_2O_3–GaAs interface recombination velocity as predicted by the modified dead layer model. The presence of a residual band bending at the interface of our Ga_2O_3–GaAs samples is discussed in the following.

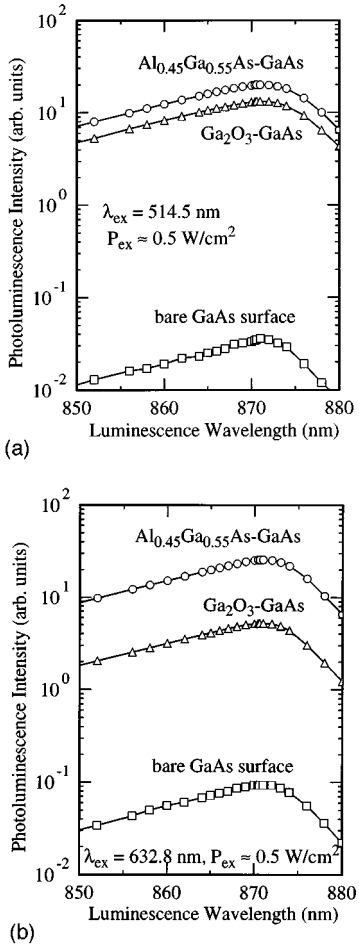

FIG. 2. PL intensity vs wavelength for Ga_2O_3–GaAs structures, AlGaAs–GaAs samples and for a corresponding bare GaAs surface. The 470 Å thick Ga_2O_3 film was deposited at a substrate temperature of 500 °C and the AlGaAs–GaAs sample was grown at 650 °C by MBE.

Figure 3 shows the peak PL intensity as a function of excitation power density for Ga_2O_3–GaAs and AlGaAs–GaAs structures as well as for a corresponding bare GaAs surface ($\lambda_{ex}=514.5$ nm). The PL intensities in Fig. 3 are corrected for the change in reflectivity after Ga_2O_3 film deposition and for the absorption of excitation light in the 1000 Å thick AlGaAs layer, respectively. According to Eqs. (1) and (2), a linear relation between PL intensity and excitation density is expected for constant interface recombination velocity and band bending. Such a linear dependence of the PL intensity on excitation power density is observed for the AlGaAs–GaAs sample and the bare GaAs surface. How-

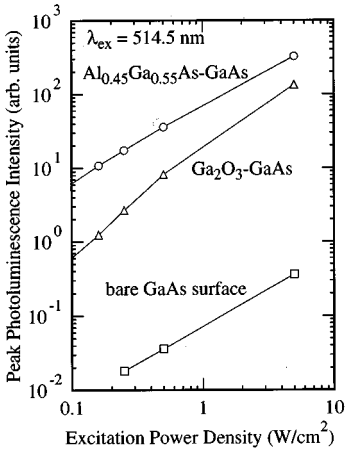

FIG. 3. Peak PL intensity as a function of excitation power density for Ga_2O_3–GaAs structures, AlGaAs–GaAs samples and for a corresponding bare GaAs surface (λ_{ex}=514.5 nm).

ever, a nonlinear relation between excitation power density and the PL signal was measured for the Ga_2O_3–GaAs sample. We found evidence of fixed oxide charges located near the Ga_2O_3–GaAs interface in our samples. It is therefore concluded, that band bending, which is reduced by increasing excitation power density and decreasing excitation wavelength, rather than saturation of interface recombination velocity is responsible for the observed nonlinear behavior.

Note that the PL intensity of the Ga_2O_3–GaAs structure approaches that of a AlGaAs–GaAs reference sample with increasing excitation power density (Fig. 3) and decreasing excitation wavelength (Fig. 2). Since the measured interface state density of this reference structure is 2×10^9 cm^{-2} eV^{-1} (Ref. 16), a small Ga_2O_3–GaAs interface state density can be concluded in agreement with the derived low interface recombination velocity. Furthermore, preliminary capacitance–voltage measurements on metal–Ga_2O_3–GaAs structures demonstrated both accumulation and inversion.

In summary, the first *in situ* deposited Ga_2O_3–GaAs structure has been fabricated in ultrahigh vacuum. A Ga_2O_3–GaAs interface recombination velocity as low as 10^4 cm/s has been obtained and a low interface state density has been concluded. This structure may find a wide range of applications from passivation of surface states in various types of electronic and optoelectronic devices to metal–insulator–semiconductor field-effect devices.

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