Properties of Al_2O_3 optical coatings on GaAs produced by oxidation of epitaxial AlAs/GaAs films

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Auger analysis of oxidized AlAs epitaxial layers grown by molecular-beam epitaxy reveals that the composition of the films is stoichiometric Al_2O_3. High optical quality of the films is demonstrated by optical reflection and transmission measurements. A reflectivity of 6% is measured for an antireflection coating on GaAs. Leakage currents in the nA range and resistivities $>5\times10^{11}\ \Omega$ cm are deduced from current-voltage measurements. Capacitance-voltage measurements on metal-oxide-semiconductor structures using the Al_2O_3 films obtained by oxidizing AlAs, reveal a significant reduction of the interface state density as compared to conventional, electron beam evaporated Al_2O_3.

High-reflectivity (HR) and antireflection (AR) coatings are used for many applications in semiconductor optoelectronics. Of particular importance are optical coatings on high power 980 nm lasers used for the excitation of Er ions in fiber amplifiers. Optical amplification using Er-doped fibers pumped by semiconductor lasers will be the backbone of future communication systems. A phenomenon called *catastrophic optical damage* (COD) of the facets of 980 nm lasers[1] is a severe obstacle toward improving the reliability of such lasers. Although several different mechanisms have been proposed to cause COD,[1–4] there is a general agreement that nonradiative energy-dissipating processes at the cleaved ⟨011⟩ semiconductor facet must be reduced as much as possible. The effect of such nonradiative dissipative processes mediated by states within the forbidden gap at the interface between the semiconductor and the optical HR and AR coating is shown in Fig. 1. The dissipative processes at the semiconductor laser facet [Fig. 1(a)] are the non-radiative recombination of electron-hole pairs as well as the absorption of photons via interface states as illustrated in Fig. 1(b). In the GaAs material system, the state density in the gap is large and the lifetime associated with these states is very short, typically in the picosecond range. As a consequence of the dissipative processes, the laser facet temperature increases as schematically shown in Fig. 1(c). A measurement of the temperature distribution along the active region near the facet of a 980 nm pump laser operated at 140 mA is shown in Fig. 1(d). A high-resolution infrared camera was employed for this measurement.[5] It is the purpose of this letter to demonstrate that epitaxial AlAs films oxidized in an oxygen containing ambient, which were demonstrated by Tsang *et al.*,[6] are stoichiometric Al_2O_3, have high-quality optical and dielectric properties, and are therefore suitable for antireflection coatings on semiconductors.

The coatings were fabricated by molecular beam epitaxial (MBE) growth of AlAs on an epitaxial ⟨001⟩ GaAs layer and by the subsequent oxidation of the AlAs. Visual inspection of the films using Nomarski microscopy reveals mirror-like surfaces of the oxidized AlAs and the absence of any extended defects such as cracks. The chemical composition of the oxidized AlAs was analyzed by Auger electron spectroscopy. A depth profile is shown in Fig. 2 The profile reveals that the 4000-Å-thick oxidized AlAs film is homogeneous without any significant change in composition along the depth. The profile further reveals that the top film (i) contains Al and O in a ratio of 2 to 3.2 and (ii) does not contain significant concentrations of As or Ga. We conclude from the measurements that, within the experimental error (relative error $\cong\pm5\%$) of the Auger electron spectroscopy, the oxidized AlAs films are stoichiometric Al_2O_3 and refer to the oxidized AlAs as Al_2O_3 throughout this publication. However, we note that Auger spectroscopy revealed traces of arsenic of $\leqslant4$ atomic percent in the films.

Ellipsometry, reflectance, and transmittance measurements were performed to characterize the optical properties of the Al_2O_3 films. Ellipsometry measurements at $\lambda=830$ nm revealed a refractive index of $n=1.56$ for the film which is within the range of indexes reported for electron beam evaporated Al_2O_3.[7] The refractive index of Al_2O_3 is slightly smaller than the ideal index for optical AR coatings on

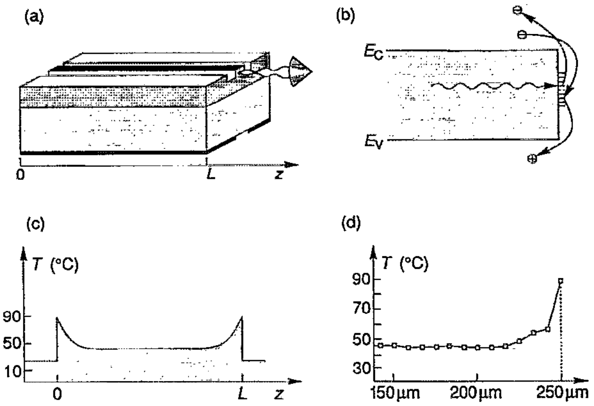

FIG. 1. (a) Schematic illustration of a semiconductor laser with an optical window at the bottom side to view far-infrared radiation from active region. (b) Band diagram at surface with surface states mediating recombination and absorption processes. (c) Schematic temperature distribution in active area of semiconductor laser. (d) Measured temperature distribution in a 980 nm laser at a cw drive current of 140 mA.

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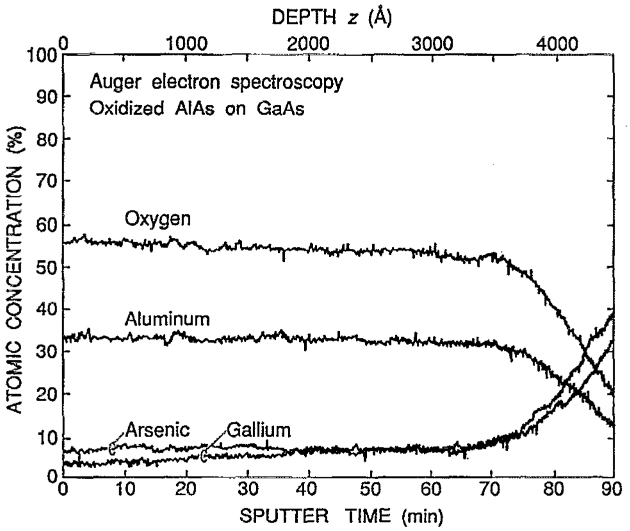

FIG. 2. Auger electron spectroscopy profile of oxidized AlAs on GaAs using 2 keV Ar ions.

GaAs, which is $n_{\text{ideal}}=\sqrt{D_{\text{GaAs}}}=1.8$. The reflectivity of a 4100 Å-thick Al_2O_3 coating on epitaxial GaAs is shown in Fig. 3 for wavelengths ranging from 0.6 to 1.8 μm. The minimum reflectivity of the film occurs at $\lambda=0.86$ μm and has a value of $R=6\%\pm2\%$. The calculated reflectivity of an abrupt transition from a medium with index n_1 to a second medium with index n_3 separated by an AR coating with $\lambda/4$, $3\lambda/4$,... thickness and an index n_2 is given by[8]

$$R=\left(\frac{n_1n_3-n_2^2}{n_1n_3+n_2^2}\right)^2 . \tag{1}$$

For $n_1=1$, $n_2=1.56$, and $n_3=3.45$, one obtains a theoretical value of $R=3\%$.

For transmittance measurements, the Al_2O_3 films were mounted on sapphire with an index-matched epoxy. The absorbing GaAs substrates were chemically removed. The measured transmittance shown in Fig. 3 has a magnitude of $96\%-97\%\pm2\%$. We have performed the same measurement on conventional Al_2O_3 films and have found, within the experimental error, the same transmittance indicating the high quality of the new optical coating.

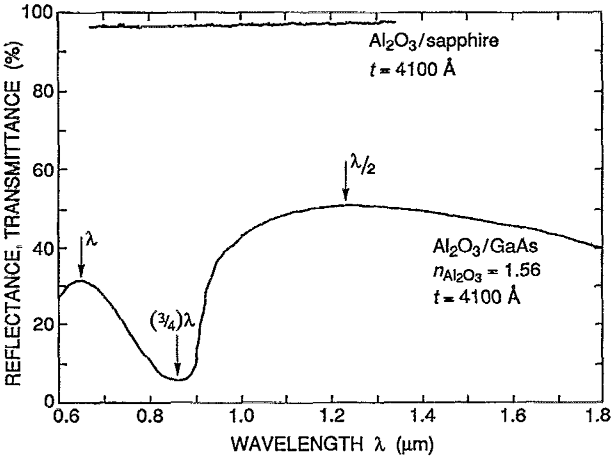

FIG. 3. Reflectivity spectrum of a 4100-Å-thick Al_2O_3 film on GaAs fabricated by oxidizing AlAs. Also shown in the transmittance through the Al_2O_3 film mounted on sapphire.

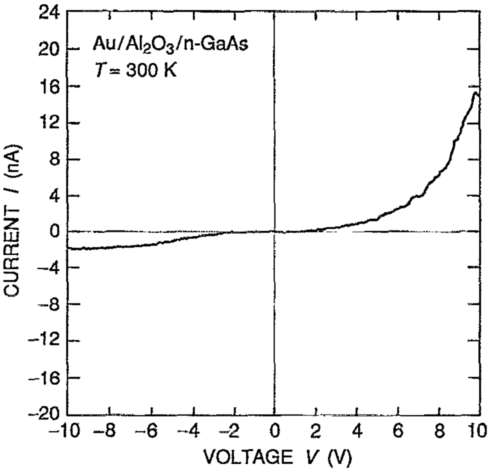

FIG. 4. Current-voltage characteristic of 500-μm-diameter Au contacts on an Al_2O_3/GaAs structure.

Current-voltage measurements were performed to establish the dielectric properties of the Al_2O_3 films. The current-voltage trace of a metal-oxide-semiconductor (Au/Al_2O_3/n-GaAs) structure is shown in Fig. 4. The evaluation of the resistance of the structure at $V=0$ yields a specific resistivity of the Al_2O_3 of $>5\times10^{11}$ Ω cm which is comparable to the resistivity of conventional Al_2O_3.[9]

The interface state density of the Au/Al_2O_3/GaAs MOS system can be assessed by capacitance-voltage (C-V) measurements. We have performed such measurements using a frequency of 1 MHz at room temperature on structures with conventional, electron-beam evaporated Al_2O_3, and on the Al_2O_3 fabricated by oxidizing epitaxial AlAs. The measurements on the conventional Al_2O_3 exhibit a nearly constant capacitance which is independent of the dc bias. Such a constant capacitance is found for organic (acetone, methanol) as well as inorganic (hydrochloric and sulfuric acid) cleaning procedures which we employed prior to evaporation of the Al_2O_3. The constant capacitance indicates that the Fermi level at the GaAs/Al_2O_3 interface is completely pinned by a very high density of interface states.

The C-V curve on the Al_2O_3 obtained by oxidation of MBE grown AlAs is shown in Fig. 5 for a 500-μm-diam contact. The C-V curve displays saturation of the capacitance for positive and for large negative voltages. Such a behavior has been observed previously by Tsang *et al.*[6] The values of the maximum capacitance (accumulation) and of the minimum capacitance (inversion) per unit area are given by

$$C_{\text{acc}}=\frac{\epsilon_{\text{ox}}}{t_{\text{ox}}}, \quad C_{\text{inv}}=\left(\frac{t_{\text{ox}}}{\epsilon_{\text{ox}}}+\frac{W_{\text{dep}}}{\epsilon_s}\right)^{-1}, \tag{2}$$

where $W_{\text{dep}}=(2\epsilon_sE_g/e^2N_D)^{1/2}$ and ϵ_{ox} and ϵ_s are the permit-

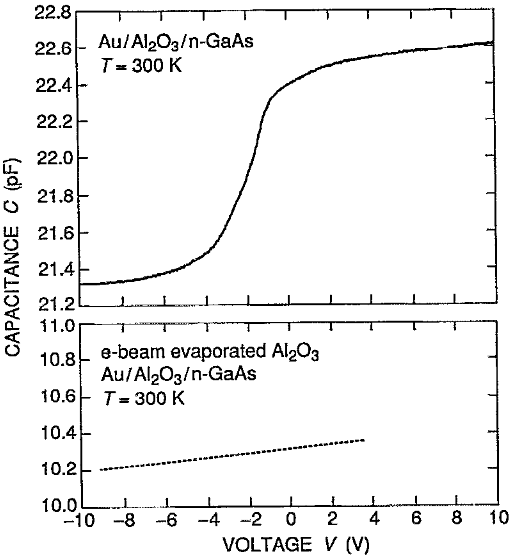

FIG. 5. Capacitance-voltage characteristic of an $Au/Al_2O_3/GaAs$ MOS structure at room temperature ($\phi=500$ μm, $t_{ox}=4100$ Å). Also shown is the C-V characteristic of an e beam evaporated $Au/Al_2O_3/GaAs$ structure ($\phi=200$ μm, $t_{ox}=1900$ Å).

tivity of the oxide and of the semiconductor, t_{ox} is the thickness of the Al_2O_3, and W_D is the width of the depletion region of the semiconductor at the onset of inversion. The theoretical capacitances agree with those calculated from Eq. 2, if we assume $t_{ox}=4100$ Å, $\epsilon_{ox}=5.3\epsilon_0$, $\epsilon_s=13.1\epsilon_0$, and a doping concentration of 5×10^{17} cm^{-3}. The value chosen for ϵ_{ox} falls within the range of dielectric constants reported for Al_2O_3.[9] The agreement between the measured and the calculated capacitance demonstrates the low interface state density of the coatings and confirms results reported previously.[6] Also shown in Fig. 5 is the C-V curve measured on an electron beam evaporated Al_2O_3 film. The capacitance does not change significantly over the entire voltage range indicating that the Fermi level is pinned.

We finally point out that the process used to fabricate the Al_2O_3 coating is a very clean process since the GaAs surface is never exposed to air. Chemical impurities other than the elements of GaAs and Al_2O_3 are not expected at the interface. This is in contrast to electron beam evaporated Al_2O_3, where chemical impurities are likely to contaminate the interface.

In conclusion, we have demonstrated a novel optical coating on GaAs which is fabricated by oxidizing epitaxially grown AlAs. Auger measurements demonstrate that the films are stoichiometric Al_2O_3. The films have an optically smooth surface morphology and a reflectivity of 6% when used as an antireflection coating on GaAs. Absorption in the Al_2O_3 films is comparable to electron beam evaporated Al_2O_3 films. A specific resistivity of $>5\times10^{11}$ Ω cm was determined from current-voltage measurements. The capacitance-voltage measurements reveal a reduced interface state density when compared to electron beam evaporated Al_2O_3.

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