

Origin of Nonradiative Recombination Centers in AlGaInP Grown by MOVPE

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Nonradiative recombination centers associated with midgap deep levels significantly degrade the radiative efficiency of AlGaInP heterostructures used in visible laser diodes (LDs) and light-emitting diodes (LEDs) in the 600-nm wavelength region^{1, 2}. We report the first direct evidence that such nonradiative recombination centers in AlGaInP are introduced by oxygen. We quantitatively demonstrate advantages of higher temperature growth and substrate misorientation for reducing the oxygen and, consequently, nonradiative recombination centers. We propose a model for oxygen incorporation mechanisms and defect configurations.

We investigated how oxygen is incorporated and affects deep level formation, using secondary ion mass spectroscopy (SIMS) and isothermal capacitance transient spectroscopy (ICTS) for $(\text{Al}_{0.7}\text{Ga}_{0.3})_{0.5}\text{In}_{0.5}\text{P}$ intentionally doped with $^{16}\text{O}_2$. Epitaxial layers were grown by metalorganic vapor phase epitaxy (MOVPE). The $^{16}\text{O}_2$ concentration in the vapor phase was varied from 0.004 to 0.04 ppm. We obtained a very low SIMS ^{16}O background (1 to $3 \times 10^{16}\text{cm}^{-3}$) by careful measurement precautions. We studied photoluminescence (PL) intensity for AlGaInP(O_2 -doped)/GaInP(undoped, $0.02\text{ }\mu\text{m}$) doublehetero (DH) structures.

We found that:

1. O_2 -doped layers contain three deep levels D1, D2, and D3 which we previously found in MOVPE-grown undoped AlGaInP¹ (Fig. 1 and Table 1).
2. The D3 and D2 concentrations increase linearly with increasing ^{16}O concentration in epilayers (Fig. 1).
3. The D3/D2 concentration ratio is almost constant: 0.4 to 0.6 (Fig. 1 and Fig. 3).
4. The ^{16}O concentration decreases as the growth temperature increases with an activation energy of $-5.0 \pm 0.7\text{ eV}$. This activation energy agrees with that for D3 concentration variations for undoped layers previously reported¹ (Fig. 2).
5. The $^{16}\text{O}_2$, D3, and D2 concentrations on the (h11)A-face ($h \geq 3$) are about one order of magnitude less than that on (100), in contrast to the (h11)B face ($h \geq 3$), where concentrations are identical or slightly increase (Fig. 3). This is similar to a universal tendency for the orientation dependence of group-VI donor (Se, S, Te) incorporation³.
6. The room temperature PL intensity for DH structures is improved, according to the oxygen and D3 concentration variation (shaded lines in Fig. 1 to Fig. 3).

We propose that oxygen is transported by a volatile alkoxide, $(\text{CH}_3)_2\text{AlOCH}_3$, formed by TMAI and O_2 reaction⁴, then incorporated near the group-V site, resulting in multiple deep levels. The activation energy for oxygen incorporation is close to the bond dissociation energy for Al-O ($5.3 \pm 0.1\text{ eV}$)⁵, indicating an oxygen incorporation configuration of $\text{Al}_{\text{III}}\text{-O}$ introduced by the alkoxide. A close analogy in the orientation dependence for oxygen and group-VI donor incorporation, in conjunction with a recent report of lower oxygen incorporation at higher group-V partial pressure⁴, strongly suggests that oxygen can reside on or near the group-V substitutional site, competing to group-V elements. The almost constant D3/D2 ratio implies that D3 and D2 are a pair of charge-state-dependent multiple levels due to an "off-center substitutional" oxygen ($\text{V}_{\text{P}}\text{-O}$) defect, as in GaAs^{6, 7}. Lower oxygen incorporation at higher growth temperature can be attributed to enhanced oxygen desorption, and that on the (h11)A face can be explained assuming that this face provides weak adsorption sites for oxygen as for group-VI impurities³.

In summary, we have shown that oxygen incorporation causes nonradiative recombination centers in MOVPE-grown AlGaInP. We quantitatively demonstrated the effectiveness of higher temperature growth and substrate misorientation to improve the radiative efficiency of AlGaInP heterostructures. These results should provide significance in fabricating high-power or high-brightness AlGaInP visible LDs and LEDs.

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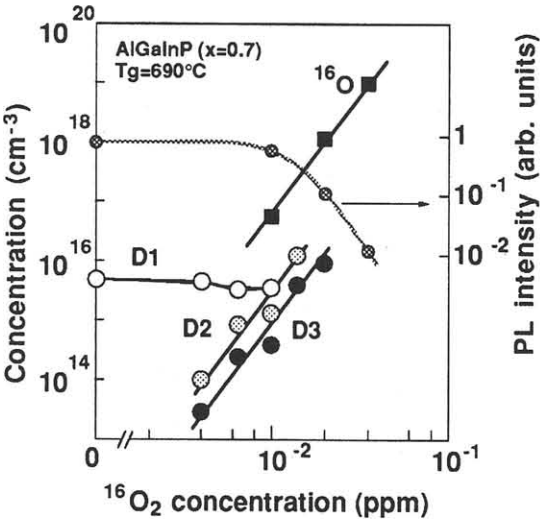


Fig. 1. Oxygen and deep level concentration versus O₂ concentration in the vapor phase. PL intensity for AlGaInP (O₂-doped)/GaInP DH structures is shown by a shaded line. See Table 1 for deep level parameters for D1, D2, and D3.

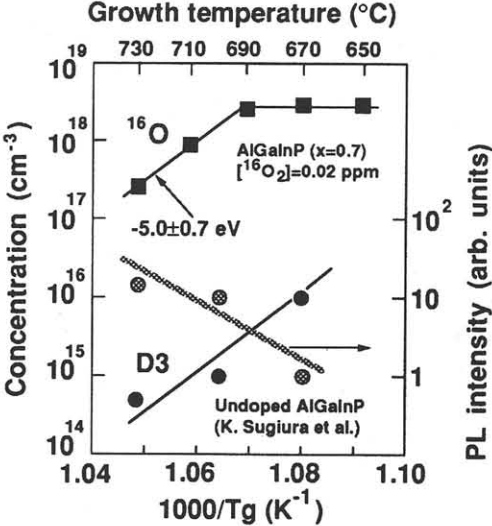


Fig. 2. Growth temperature dependence of oxygen concentration for O₂-doped AlGaInP. D3 concentration and PL intensity dependence for undoped AlGaInP¹ are also shown.

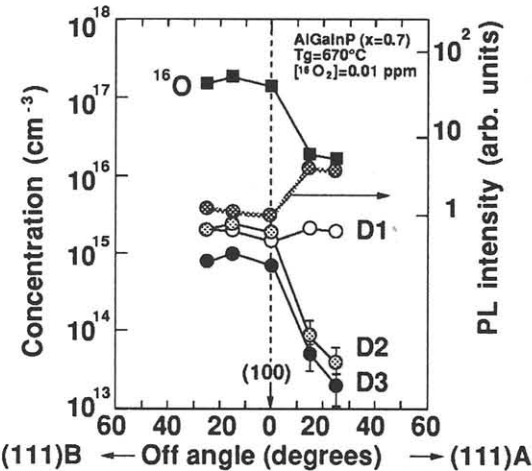


Fig. 3. Substrate orientation dependence of oxygen and deep level concentration. PL intensity dependence for DH structures is included.

Table 1. Parameters for deep levels in AlGaInP¹.

	D1	D2	D3 (nonradiative)
Thermal activation energy: E _T (eV)	0.43	0.6 to 0.7	1.3
Capture cross section for electrons: σ _n (cm ²)	6 × 10 ⁻¹³	1 × 10 ⁻¹⁵	2 × 10 ⁻¹⁰
Capture cross section for holes: σ _p (cm ²)	<1 × 10 ⁻¹⁸	<1 × 10 ⁻¹⁹	1 × 10 ⁻¹⁵