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Temperature dependence of photoluminescence from Mg-doped In₀.₅Ga₀.₅P grown by liquid-phase epitaxy

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The temperature dependence of photoluminescence from the Mg-doped In₀.₅Ga₀.₅P layers on (100) GaAs substrates grown by liquid-phase epitaxy has been studied. At low temperature, the spectra show only two major emission peaks involving intrinsic recombination and conduction-band-to-acceptor transition. The intrinsic recombination dominates in the doping concentration range studied (1.0 x 10¹⁴ - 7.0 x 10¹⁸ cm⁻³) above 60 K. Below 50 K, these two peaks merged with each other when the doping concentration is higher than 1 x 10¹⁸ cm⁻³. The temperature dependence of band gap in In₀.₅Ga₀.₅P layers determined from the photoluminescence peak energy varies as 1.976 - [7.5 x 10⁻⁴ T²/(T + 500)] eV. For the moderately doped concentration (p < 1.4 x 10¹⁸ cm⁻³), the Mg acceptor ionization energy obtained from 50-K photoluminescent spectra is in the range from 37 to 40 meV.

I. INTRODUCTION

In₁₋ₓGaₓP ternary compound offers the possibility of direct recombination luminescence up to photon energy of approximately 2.2 eV at 300 K and was predicted to be a highly efficient luminescence material, providing an opportunity for the fabrication of visible light-emitting devices. Especially, with x = 0.3, it can be lattice matched to GaAs, and thus has attracted much attention for the fabrication of red light-emitting devices. Mg and Zn are well known p-type dopants in GaAs and AlGaAs layers grown by liquid-phase epitaxy (LPE). Mg is expected to be more attractive than Zn as a p-type dopant in GaAs related III-V compounds because the diffusion coefficient of Mg is about 10³ times lower than that of Zn in GaAs. Zn has been shown to migrate in AlGaAs at low temperature and produce compositional disorder at the AlGaAs-GaAs interface. Recently, remarkable improvement in Mg doping efficiency, compared with that for Zn, has been observed for (Al₁₋ₓGaₓ)₁₋ₓIn₀.₅P grown by metalorganic chemical vapor deposition (MOCVD), especially for a high aluminum composition layers. Suzuki et al. reported the low-temperature photoluminescence (PL) properties of Mg-doped In₀.₅Ga₀.₅P layers grown by MOCVD with different hole concentrations. Chang et al. reported the doping properties of Mg in In₀.₅Ga₀.₅P layers grown by LPE. But there is no detailed report on the temperature dependence of luminescence properties of Mg-doped InGaP material or devices.

II. EXPERIMENT

This article reports the temperature dependence of photoluminescence of Mg-doped In₀.₅Ga₀.₅P layers with various doping concentrations.

The Mg-doped In₀.₅Ga₀.₅P epitaxial layers used for this study were grown on undoped semi-insulating GaAs substrates with a horizontal sliding LPE system. The growth temperature, the initial supercooling, and the cooling rate were 785 °C, 12 °C, and 0.3 °C/min, respectively. The thickness of the layers during a growth period of 17 min was 8–10 μm. Details of the LPE growth were described in Ref. 5.

The PL measurements were made using argon laser excitation (4880-Å line) with an average power density of ~5 W/cm² and a spot size of ~1 mm in diameter. The emission spectra were analyzed by a 1-m spectrometer and detected with a silicon pin photodetector. The samples were mounted on a holder inside a cryostat and the temperature was varied and controlled by a thermal foil heater wound near the holder and detected by a Pt temperature sensor.

III. RESULTS AND DISCUSSIONS

Table I illustrates some of the electrical and optical properties at room temperature of the undoped and Mg-doped In₀.₅Ga₀.₅P samples used for this investigation. An undoped In₀.₅Ga₀.₅P sample with background concentration of 4 x 10¹⁸ cm⁻³ was used as a reference for the PL measurements. The fact that the room-temperature PL full width at half maximum (FWHM) of the four Mg-doped samples broadens as the carrier concentration increased is due to the evolution of the impurity levels into a band of states.

The PL spectra at 50 K of all the samples illustrated in Table I are shown in Fig. 1. These spectra are normalized to the same main peak intensity. Except for the undoped and most heavily doped samples No. 1 and No. 5, respectively, as shown in Figs. 1(a) and 1(e), all other samples exhibit three peaks denoted as A, B, and C. Peak A with the narrowest FWHM and the highest photon energy was 8–10 μm. Details of the LPE growth were described in Ref. 5.
peak A and moves closer to peak A with increasing hole concentration. Since the relative intensity of peak B to peak A increases with hole concentration, it confirms that peak B is definitely associated with the Mg acceptor level. The weak peak C located at ~50 meV below peak B is believed to be the phonon replica of peak B. As the hole concentration is higher than ~1×10^{18} \text{cm}^{-3}, these two peaks A and B merged with each other and is not distinguished even at 16 K. This is due to the evolution of acceptor impurity levels into a band and merging with the valence band.

From this BA transition of peak B, the ionization energy of the Mg acceptor, \( E_A \), can be estimated from the photon energy of peak B, \( h\nu_B \), and \( E_g \) using Eagles equation:  
\[
E_A = E_g - h\nu_B + \frac{1}{2}kT,
\]
where \( E_g \) is the band-gap energy of In_{0.5}Ga_{0.5}P and \( h\nu_B \) is the peak energy of the Mg acceptor. The thermal-energy correction term \( \frac{1}{2}kT \) adds about 2 meV to the term of \( (E_g - h\nu_B) \) at 50 K. The ionization energy of Mg acceptor in the lightly doped In_{0.5}Ga_{0.5}P is thus calculated as 37-40 meV at 50 K.

Figure 2 (a) presents the temperature dependence (\( T=16\text{--}300 \text{K} \)) of the emission peak of sample No. 2 with a hole concentration of 1×10^{17} \text{cm}^{-3}. Peak B is the dominant recombination process at temperature below 60 K. As the temperature is increased, the intensity of this peak gradually decreased while that of peak A gradually increased. Above 130 K, the emission of peak B becomes negligibly weak. The decreasing of relative intensity of peak B with increasing temperature is due to the thermal release of holes from acceptor sites.

The PL spectra of sample No. 4 with a hole concentration of 1.4×10^{18} \text{cm}^{-3} is shown in Fig. 2(b). At 16 K, only peaks B and C are observed and it can be explained as the increase of transition probability due to higher hole population in the acceptor level. It is relevant to note in Table I that the PL intensity at 300 K reaches its maximum in the range from 5×10^{17} to 1.4×10^{18} \text{cm}^{-3} and then drops quickly as the hole concentration is further increased. There may be relatively deep centers formed at high Mg-doped concentrations to lower the radiative efficiency as in the case of heavily Zn-doped In_{0.5}Ga_{0.5}P layers.\(^{13-15}\)

Figure 3 shows the variation of the photon energies of the peaks A and B as a function of temperature for sample No. 2 with PL spectra shown in Fig. 2(a). The temperature dependence of the band gap in this figure can be expressed as the Varshni equation:  
\[
E_g(T) = E_g(0) - \alpha T^2/(T + \beta),
\]

\[\alpha \text{ and } \beta \text{ are constants.}\]

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>( n ) or ( p ) (×10^{17} \text{ cm}^{-3})</th>
<th>Mobility (cm²/V s)</th>
<th>PL peak energy (eV)</th>
<th>PL FWHM (meV)</th>
<th>PL intensity (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>undoped</td>
<td>1300</td>
<td>1.890</td>
<td>36.5</td>
<td>1.8</td>
</tr>
<tr>
<td>2</td>
<td>1.0 (p)</td>
<td>63</td>
<td>1.889</td>
<td>41.2</td>
<td>2.1</td>
</tr>
<tr>
<td>3</td>
<td>5.1 (p)</td>
<td>52</td>
<td>1.890</td>
<td>45.0</td>
<td>4.5</td>
</tr>
<tr>
<td>4</td>
<td>14 (p)</td>
<td>41</td>
<td>1.880</td>
<td>59.5</td>
<td>3.8</td>
</tr>
<tr>
<td>5</td>
<td>70 (p)</td>
<td>29</td>
<td>1.885</td>
<td>75.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>

TABLE I. 300-K electrical and optical properties of the Mg-doped In_{0.5}Ga_{0.5}P samples used in this study.
FIG. 2. Photoluminescence spectra of the Mg-doped In$_{0.5}$Ga$_{0.5}$P layers with (a) $p = 1.0 \times 10^{17}$ cm$^{-3}$ and (b) $p = 1.4 \times 10^{18}$ cm$^{-3}$ at various temperatures between 16 and 300 K showing the gradual evolution of the peaks. The spectra are normalized to the same main peak intensity.

FIG. 3. Variation of the photon energies of the peaks A and B as a function of temperature for sample No. 2 with PL spectra as shown in Fig. 2 (a).
where $E_g(0)$ is the energy gap at 0 K, $\alpha$ and $\beta$ are material constants. The calculated $E_g(0)$, $\alpha$, and $\beta$ by least-square method are 1.976 eV, $7.5 \times 10^{-4}$ eV/K, and 500 K, respectively. Temperature dependence of the FWHM of peak $A$ is also shown in Fig. 3. The experimental value agrees well with the theoretical value of $1.85 kT$ (Ref. 17) as shown in Fig. 3, where $k$ is the Boltzmann constant. The slightly smaller FWHM than the theoretical value at 300 K seems to be due to reabsorption of emitted photons with energies higher than the peak energy by the epitaxial layer, while the somewhat larger FWHM at the temperatures lower than 100 K may be due to the existence of another radiative transition process such as (residual) donor-to-valence-band recombination very near to the band-to-band transition peak.

**IV. CONCLUSIONS**

We have demonstrated the temperature dependence of photoluminescence of Mg-doped $\text{In}_{0.5}\text{Ga}_{0.5}\text{P}$ material with carrier concentrations of $1.0 \times 10^{17}$–$7.0 \times 10^{18}$ cm$^{-3}$. The relationship between the temperature and PL relative intensities of the two major peaks termed the intrinsic transition and band-to-acceptor recombination has been investigated in detail. At temperature above 60 K, the intrinsic recombination dominates in the doping range studied. The temperature dependence of band gap in $\text{In}_{0.5}\text{Ga}_{0.5}\text{P}$ layers determined from PL peak energy varies as $1.976 - [7.5 \times 10^{-4} T^2/(T + 500)]$ eV.

**ACKNOWLEDGMENTS**

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