

## Photoluminescence excitation spectroscopy on InP:Yb

J. Wagner

*Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, 7000 Stuttgart 80,  
Federal Republic of Germany*

J. Windscheif and H. Ennen

*Fraunhofer-Institut für Angewandte Festkörperphysik, Eckerstrasse 4,  
7800 Freiburg, Federal Republic of Germany*

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Photoluminescence excitation measurements were performed on InP:Yb, using a tunable LiF:F<sub>2</sub><sup>+</sup> color-center laser. The excitation spectra show that only one dominant Yb<sup>3+</sup> (4f<sup>13</sup>) center is responsible for the complex set of emission lines observed in the 1.0- $\mu$ m spectral range. With the combination of the present results with data obtained by photoluminescence experiments the observed emission lines can be ordered into a level scheme with a twofold-split initial (<sup>2</sup>F<sub>5/2</sub>) and a threefold-split (<sup>2</sup>F<sub>7/2</sub>) ground state.

The emission of rare-earth (4f) ions in III-V compound semiconductors has been discovered recently.<sup>1-6</sup> Doping of InP with Yb gives rise to a complex set of luminescence lines in the 1.0- $\mu$ m spectral range.<sup>1,5</sup> The radiative transitions occur between the spin-orbit terms <sup>2</sup>F<sub>5/2</sub> and <sup>2</sup>F<sub>7/2</sub> of Yb<sup>3+</sup> (4f<sup>13</sup>). By a crystal field of cubic symmetry these terms are split into two and three levels for the <sup>2</sup>F<sub>5/2</sub> and the <sup>2</sup>F<sub>7/2</sub> terms, respectively. From conventional luminescence data, however, it is not possible to decide which luminescence transition terminates at the lowest level of the <sup>2</sup>F<sub>7/2</sub> term. Therefore, it is also not possible to order the observed emission lines in a level scheme. Furthermore, it cannot be ruled out that more than one optical center contribute to the observed emission spectrum.

To clarify these points, we have performed photoluminescence excitation (PLE) spectroscopy on Yb<sup>3+</sup> in InP. For excitation we used a tunable LiF:F<sub>2</sub><sup>+</sup> color-center laser.<sup>7</sup> The typical output power at 1.0  $\mu$ m was 300 mW at a width of the laser line of 0.6 Å. A detailed description of the experimental setup is given in Ref. 8. The InP:Yb samples used were prepared by ion implantation into different starting materials. For details see Ref. 5.

A typical low-temperature photoluminescence (PL) spectrum of a sample implanted with Yb for above band-gap excitation (647-nm Kr<sup>+</sup> laser line) is shown in Fig. 1 (upper spectrum). The spectrum consists of one strong and relatively sharp line at 1001 nm (line 4 in the notation of Ref. 5) and a broader double peak at 1008 nm (lines 7 and 8). At the high-energy side of line 4 a rather weak emission is observed at 998 nm (line 3). Raising the sample temperature a thermally activated emission line at 993 nm (line 2) appears, which is not seen in Fig. 1. The lower spectrum shown in Fig. 1 was recorded for resonant excitation into line 2. The emission lines 4, 7, and 8 are observed as for above band-gap excitation. The weak emission line 3 at 998 nm is not resolved due to the background from scattered laser light. The two additional peaks at  $\approx$ 1025 and  $\approx$ 1030 nm arise from Raman scattering by optic zone-center phonons of InP. Comparing the PL spectra recorded with above band-gap and resonant excitations, we conclude that the whole set of emission lines 2-8 originates from one optical center only.

Further support for that conclusion is found in the PLE

spectra (Fig. 2). At low temperature ( $T \approx 5$  K) two resonances, corresponding to lines 2 and 3 in the emission spectrum, are observed.<sup>9</sup> The emission at 1008 nm (line 8) was used to monitor the absorption of the optical center. When recording the PLE spectrum at a somewhat higher temperature of the sample ( $T \geq 10$  K), an absorption peak appears also at 1001 nm (line 4). This shows that the emission transitions 2 and 3 terminate at the lowest level of the <sup>2</sup>F<sub>7/2</sub> term. Line 4, however, has its final state in one of the two upper <sup>2</sup>F<sub>7/2</sub> levels and becomes only visible in absorption (PLE) when this level is thermally populated. From the PL

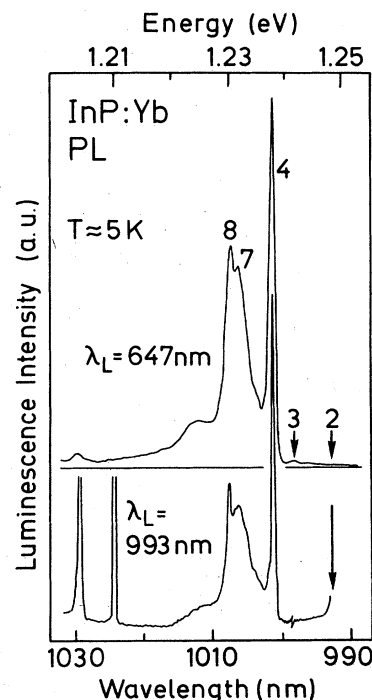


FIG. 1. Photoluminescence (PL) spectra of Yb implanted InP recorded with above band-gap excitation (upper trace) and resonant excitation (lower trace).  $\lambda_L$  denotes the exciting laser wavelength.

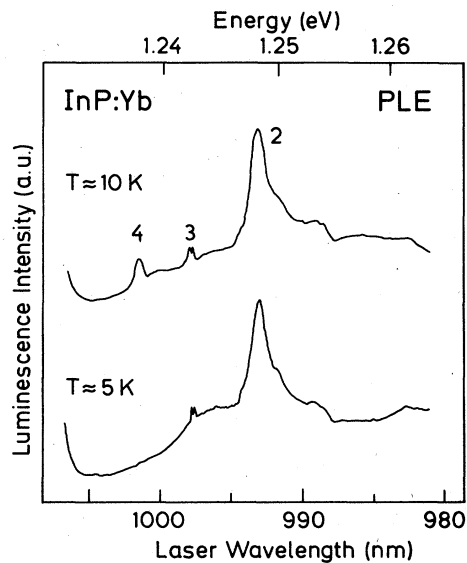


FIG. 2. Excitation (PLE) spectra of InP:Yb taken at two different sample temperatures. The 1008-nm emission (line 8) was taken as the monitor transition.

experiments it is known that line 2 is thermally activated.<sup>5</sup> Therefore, its initial state has to be the upper  $^2F_{5/2}$  level. The relative PL intensities of all the emission lines 3, 4, and 8 are temperature independent, indicating that they all have the lower  $^2F_{5/2}$  level as their initial state.

Combining the results of the PL and PLE experiments the following level scheme can be constructed (Fig. 3). The  $^2F_{5/2}$  term is split into two levels by 5.9 meV. The  $^2F_{7/2}$  term is split threefold with the two higher-lying levels 4.3 and 12.0 meV above the lowest one. Emission line 2 connects the upper  $^2F_{5/2}$  level with the lowest  $^2F_{7/2}$  level. Lines

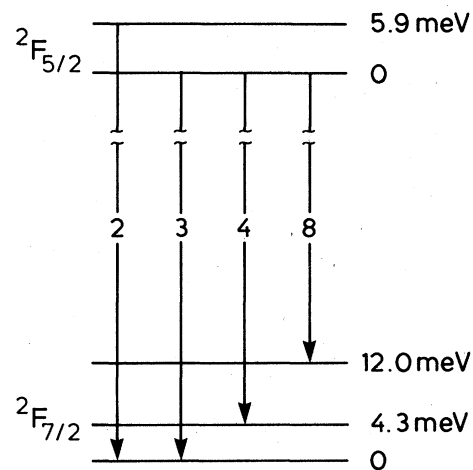


FIG. 3. Level scheme of  $\text{Yb}^{3+}$  in InP based on emission (PL) and absorption (PLE) data.

3, 4, and 8 have all the lower  $^2F_{5/2}$  level as its initial state and terminate in the lowest, the 4.3- and 12-meV  $^2F_{7/2}$  levels, respectively.

Performing PLE spectroscopy and PL experiments with selective excitation, we have shown that the emission lines 2–8 of  $\text{Yb}^{3+}$  in InP, which are observed in the 1.0- $\mu\text{m}$  range, arise all from one optical center. In addition, we have identified the emission at 998 nm (line 3) as the transition between the lowest levels of the  $^2F_{5/2}$  and  $^2F_{7/2}$  terms. All other transitions observed have an excited initial (line 2) or final state (line 4 and 8).

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<sup>9</sup>A feature, which is not yet understood, is the dip in the 998-nm (line 3) absorption peak. This dip was observed in all samples studied.