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# Photoluminescence of modulation-doped ordered–disordered $GaInP_2$ homojunctions: Intrinsic versus extrinsic emissions

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Photoluminescence (PL) measurements are reported on modulation-doped ordered-$GaInP_2$/disordered-$GaInP_2$ homojunctions. These junctions exhibit extremely high carrier densities of the two-dimensional (2D) electron gas. A luminescence peak that involves recombination of these intrinsic 2D electrons and photoexcited holes shows a very large redshift as a result of the spatially separated carriers. However, no inverted S shaped behavior of PL energy is observed for this signal upon increasing temperature. This result affirms that the inverted S PL behavior of bulk ordered $GaInP_2$ has an extrinsic nature. © *1995 American Institute of Physics.*

The concept of spatially separating a conducting layer of electrons from their parental donors by using the conduction band discontinuity $\Delta E_c$ in heteroepitaxy as a barrier was first verified by Dingle *et al.*[1] In such modulation-doped heterojunctions, electrons propagate with strongly reduced probability of being scattered by ionized impurities which results in higher mobilities. We recently extended this concept to homoepitaxy of alloys of the same composition: $Ga_{0.52}In_{0.48}P$ (hereafter: $GaInP_2$).[2] The required $\Delta E_c$ of approximately 100 meV was achieved by using the low and high band-gap states of the alloy. The former is a $LI_1$ ordered variant [i.e., domains of spontaneously ordered $(GaP)_1(InP)_1$ monolayer superlattices in the $\langle 111 \rangle$ directions] and the latter is the random alloy (the so-called disordered state). This homoepitaxy has the advantage of a reduced density of interface states. The absence of occupied *DX* centers and the strongly reduced density of oxygen- and water-related deep centers are further advantages of the use of $GaInP_2$ instead of $Al_xGa_{1-x}As$, which is commonly used in heteroepitaxy of III-V compounds. The two-dimensional electron gas (2DEG) in the ordered–disordered $(o-d)$ $GaInP_2$ junction exhibited unprecedently high values of sheet carrier density and room-temperature channel conductivity: $3.6\times10^{13}$ $cm^{-2}$ and $3.2\times10^{-3}$ $\Omega^{-1}$, respectively.

In this letter we present photoluminescence (PL) data on the aforementioned homojunction and on one in which the 2DEG was provided by a planar-doped Si layer ($\delta$ doping) in the high band-gap layer. Differences between optical properties of the 2DEG and those of the bulk $o$-$GaInP_2$ epilayers will be emphasized.

Details on the growth and structure of junction (1) can be found in Ref. 2. The high band-gap layer of this junction was undoped for 5 nm and uniformly $n$-doped for the next 100 nm. Junction (2) differed only from (1) in that the high band-gap layer was undoped except for one monolayer that contained $2\times10^{12}$ Si atoms $cm^{-2}$ at a spacer thickness of 5 nm from the homointerface. PL measurements were performed with the sample mounted either in an optical flow cryostat or in a He-bath cryostat. Optical excitation was provided either by an $Ar^+$ laser or by a tunable standing-wave dye laser, which contained DCM as dye. The luminescence was dispersed by a 0.6 m double monochromator with 1200 lines/mm gratings and detected by a cooled photomultiplier with a GaAs photocathode.

Figure 1 shows the band structure of the two junctions and their capacitance-voltage $(C$-$V)$ profiles, along with a schematic of the PL transitions that are treated below. The $C$-$V$ profile of junction (1) was treated before in Ref. 2; it shows a strongly confined 2DEG at the $o-d$ interface and absence of parallel conduction in the high-band-gap $d$ layer. That of junction (2) shows that first the $\delta$-doped layer has to be depleted before depletion of the 2DEG at the interface starts. Hence, the $d$-$GaInP_2$ of junction (2) is not entirely depleted but possesses a parallel conducting channel,[3] which is deleterious for the interpretation of transport properties. The reason that we also report on junction (2) is that some optical features are more clearly observed in it.

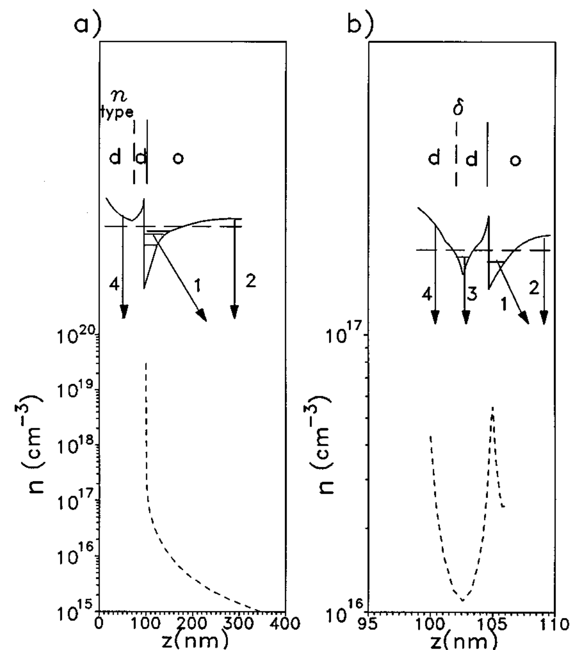


FIG. 1. Schematics of conduction bands and growth schemes of (a) junction (1) and (b) junction (2) along with their capacitance-voltage profiles (dashed traces). The arrows represent the luminescence transitions treated below.

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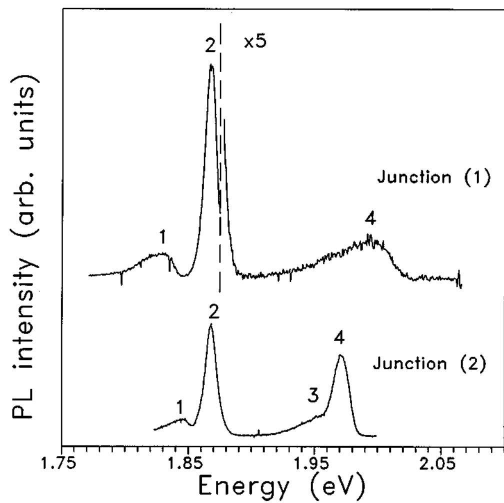


FIG. 2. 4 K PL spectra of the two junctions; the relative gain used to record the high-energy part of junction (1) is 5.

Figure 2 shows the 4 K PL spectra of both junctions recorded with the 514 nm (2.409 eV) line of an $Ar^+$ laser. The intensities of features 1, 3, and 4 decreased markedly when 600 nm (2.066 eV) laser light with a larger penetration depth was used. These relative decreases do not originate from the corresponding lower excitation density as follows from Fig. 3 and, therefore, this indicates that these three emissions originate from the top of the junction. Peak (2) is attributed to PL from the "bulk" ordered layer. This peak exhibits the characteristic properties of that PL as shown below and peak (4) is attributed to PL from the disordered top layer. Its lower energy in junction (2) is caused by exciton formation in the undoped top layer which, because of screening, is not possible in the $n$-doped top layer of junction (1). Furthermore, excitons have a larger optical cross section than band-to-band transitions which explains the higher intensity of peak (4) in junction (2). The relatively large energy difference between the exciton and the band edge (Stokes shift) is due to clustering:[4] free excitons are mobile and recombine at sites with the narrowest band gap.

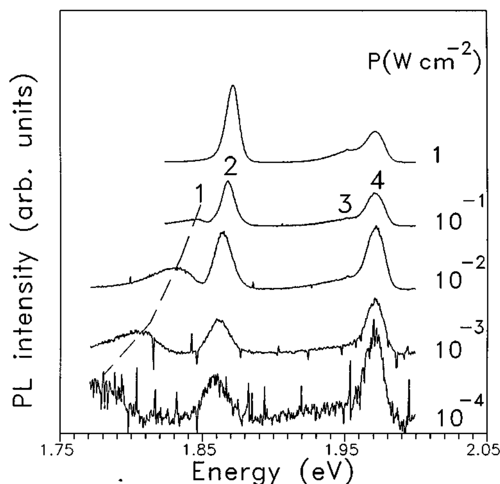


FIG. 3. Dependence of the PL spectra of junction (2) on excitation density.

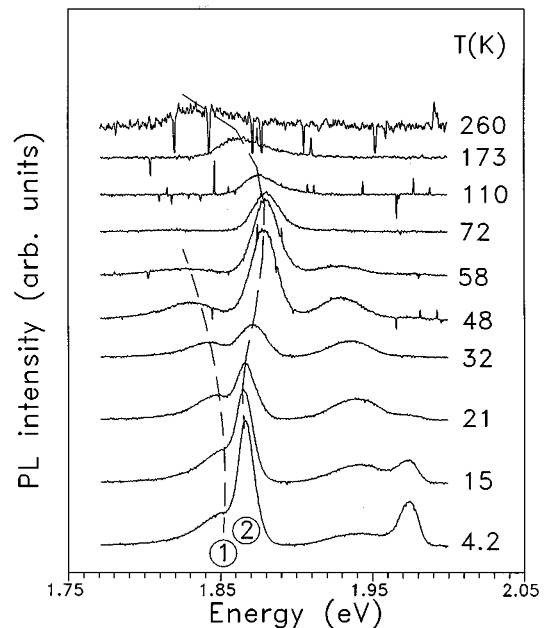


FIG. 4. Dependence of the PL spectra of junction (2) on temperature: peak (1) does not show inverted-S behavior.

Because peak (3) is only observed for junction (2), we tentatively ascribe it to PL from electrons in the confining well of the $\delta$ layer. Presently, we turn to the most important feature of the spectra: peak (1) has never been observed by us in single epilayers of either ordered or disordered material, and has the remarkable property that it shifts to lower energy by as much as 20–25 meV upon decreasing the excitation density $P$ by a factor of 10. Figure 3 shows this effect for junction (2): a total shift of 90 meV is readily achieved. This redshift is much higher than that of PL of the bulk ordered region [peak (2)], which shifts approximately 4 meV per order of magnitude of $P$. In general, such moving emissions are characteristic for recombination processes between spatially separated carriers, because an increase in $P$ neutralizes the impurities in space-charge regions.[5] It is well established that in $o$-$GaInP_2$ carriers are spatially separated.[6] The large shift of peak (1) implies a strong internal depletion field, which agrees with the high sheet-carrier density. From this we conclude that this peak originates from 2D electrons and photoexcited holes, which are spatially separated in the ordered layer, as shown in the inset of Fig. 1.

With this in mind, we turn to the behavior of the PL spectrum versus temperature. As shown in Fig. 4, the energy of peak (2) shows its characteristic inverted-$S$ shaped dependence upon increasing temperature,[7] whereas that of peak (1) shows a monotonous decrease according to the Varshni equation,[8] which describes the decrease of the band gap. In other words: of two spatially separated recombination processes in $o$-$GaInP_2$ one, which is an intrinsic process, behaves similarly to the band gap, whereas the other shows its inverted-S fingerprint. This observation agrees with our previous findings that the inverted-S behavior of bulk ordered $GaInP_2$ has an extrinsic nature.[9] We attributed it to thermal population of a broad donor related band.

In conclusion, we have identified a radiative recombina-



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tion involving a 2DEG at the $o-d$ interface and spatially separated photoexcited holes, in modulation doped $o-d$ $GaInP_2$ homojunctions. The PL properties of this extrinsic recombination showed a very large redshift and, in contrast to bulk recombination in ordered $GaInP_2$, no inverted-S shaped dependence of PL energy upon increasing temperature.

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*Note added in proof:* Recent experiments[11,12] strongly indicate that the $o$-$d$ interface exhibits a staggered band alignment. In that case the nature of peak 1 would remain indirect in real space albeit the holes are localized at the $d$ side of the interface. This does not change the interpretation of the PL properties.


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