Effects of confined donor states on the optical and transport properties of ordered $GaInP_2$ alloys

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We report properties of long-range-ordered $GaInP_2$ alloys as a function of temperature by a combination of photoreflectance (PR), photoluminescence (PL), and Hall–van der Pauw measurements. Below $T=200$ K the optical and transport properties are strongly influenced by a donor state, which, owing to confinement in the ordered domains, has a large binding energy of 36 meV. Evidence for strong localization was obtained for $T<30$ K: the PR spectra showed a pronounced first-derivative line shape at the same energy where PL emission occurs, the conductivity was dominated by hopping (ϵ_3) conduction, and the temperature dependence of the PL intensity was consistent with localized states. Between 30 and 70 K the dominating conduction mechanism was identified as ϵ_2 conduction via negatively charged donors: the D^- band. At 70 K, Hall data showed a changeover from ϵ_2 to band conduction. It is proposed that the origin of the inverted-S shape of PL energy as a function of temperature is connected with thermal population of the D^- band. In the entire T interval between 30 and 200 K, the PR spectra showed a complex line shape owing to the absence of carriers in the disordered regions. Above $T=200$ K pronounced effects of cluster scattering are observed in the Hall mobility. Supported by data from PR and PL, this shows that carriers are then present in both ordered and disordered regions of the epilayer.

I. INTRODUCTION

The ternary semiconductor $Ga_xIn_{1-x}P$ forms an attractive alternative to $Al_xGa_{1-x}As$ in optoelectronic devices, such as $Ga_xIn_{1-x}P$/GaAs tandem junction solar cells, which exhibit amongst the highest energy conversion efficiencies reported so far,[1] and (Al,Ga,In)P laser diodes in which $Ga_xIn_{1-x}P$ is used as the active layer.[2–5] Reasons for using $Ga_xIn_{1-x}P$ are, first, that a direct-band-gap value as high as 2.2 eV can be obtained with $Ga_xIn_{1-x}P$, whereas for $Al_xGa_{1-x}As$ this value is 1.9 eV at the direct-to-indirect crossover. Second, the surface recombination velocity of the $Ga_xIn_{1-x}P$/GaAs interface is 1.5 cm/s,[6] some two orders of magnitude lower than for a typical $Al_xGa_{1-x}As$/GaAs interface. Third, the carrier-trapping DX center is not occupied in $Ga_{0.52}In_{0.48}P$ (hereafter abbreviated as $GaInP_2$), which is the composition at which lattice matching with GaAs is achieved. For $Al_xGa_{1-x}As$ the DX center is already occupied above $x=0.22$, where it leads to a decrease of the free-carrier concentration.[7]

In spite of its successful application, various fundamental material properties of $GaInP_2$ are not well understood. The reason for this is that optical and transport properties of the equimolar $GaInP_2$ are complicated by the occurrence of regions of spontaneous long-range order of the CuPt type, namely as monolayer $(GaP)_1(InP)_1$ superlattices in the [111] direction. As a consequence of this ordering the symmetry of the crystal is lowered in these regions, which leads to a splitting of the valence band and a decrease of the band gap.[8] For an infinitely large, ordered $GaInP_2$ crystal a reduction of 260 meV was calculated[9] whereas values around 100 meV (Refs. 10–12) and recently even 190 meV (Ref. 13) have been found experimentally. The degree of ordering—size, shape, homogeneity, and density of the ordered domains—depends on growth kinetics, particularly on surface mobility of group-III adatoms.[14] This surface mobility is, in turn, determined by growth conditions such as temperature of growth, V/III ratio, and substrate orientation. Growth of $GaInP_2$ epilayers without ordering has also been achieved.[15,16] The optical properties of ordered $GaInP_2$ show several anomalies: the so-called inverted-S shaped behavior of photoluminescence (PL) energy as a function of temperature;[17,18] the strong shift of the dominant PL peak towards higher energy upon increasing the excitation density P; and the long carrier lifetimes, which also depend strongly on P.[19] DeLong *et al.*[19] concluded from the last two properties that spatially indirect recombination took place in the alloy.

In this paper we present variable-temperature photoreflectance (PR), photoluminescence (PL) and Hall–van der Pauw measurements on long-range-ordered $GaInP_2$. We show that optical and transport properties are greatly influenced by localization on relatively deep donor states that are confined in the ordered domains.

II. EXPERIMENTAL DETAILS

A. Experimental techniques

Variable temperature ($4.2<T<450$ K) Hall–van der Pauw measurements were performed using a clover-leaf sample shape. The Hall factor (the ratio of Hall mobility and drift mobility) was taken as unity. Details on the PL experiment were described in Ref. 20 except that an Ar^+ laser at 514 nm was used for excitation. The PR technique has been described previously in the literature.[21] Here, an Ar^+ laser (again 514 nm) was used for modulating the built-in surface field of the sample that was mounted in a variable temperature optical flow cryostat.

During PR, typical values of excitation density of the modulating source were 0.1–100 mW over a 0.5-cm^2 spotsize. Because the laser light did not pass the monochromator, there was an energy-independent background of additionally modulated PL signal. Special care was taken to minimize temperature variations, so that during each PR measurement the integrated PL background was constant and could be subtracted from the signal.

B. Samples and their degree of ordering

The experiments were carried out on $GaInP_2$ epilayers grown by metal organic vapor phase epitaxy at a pressure of 20 mbar. The 2.1-μm-thick epilayers were grown lattice matched on a (100) 2° off towards a (110) semi-insulating GaAs substrate at $T=700$ °C and V/III ratios of 400 (sample 1) and 870 (sample 2). The epilayers were nominally undoped and showed n-type conductivity. At room temperature the values for carrier concentration and mobility were 4.2×10^{15} cm^{-3} and 2500 cm^2/V s for sample 1, and 3.4×10^{15} cm^{-3} and 2250 cm^2/V s for sample 2. The aforementioned growth conditions are known to produce samples with long-range regions of monolayer superlattice ordering; the degree of ordering being larger for sample 2.[10,16,22,23]

The existence of the ordered structure in these samples was confirmed by transmission electron microscopy (TEM) which showed extra diffraction spots for the $(\bar{1}11)$ and $(1\bar{1}1)$ directions corresponding to long-range ordering of the CuPt type. The TEM diffraction patterns also showed diffused streaks in the $\langle 001 \rangle$ directions, which provides evidence for the quasi-two-dimensionality of the ordered domains: thin in the directions of ordering and extended in the directions perpendicular thereto. Furthermore, qualitative measures of the degree of ordering of $GaInP_2$ epilayers are the values for both the anomalously strong shift of PL energy as a function of excitation density P (the so-called "moving emission"[10,11,19,24]) and for the carrier lifetime, which is extremely long ($\sim\mu$s–ms) (Ref. 19) compared with random alloys ($\sim$ns). The moving components of the 4-K PL spectra of samples 1 and 2 increased 4.7 and 6.1 meV per order of magnitude increase in excitation density; values which, under the given growth conditions, are in good agreement with other published data.[10] A qualitative measure of the long carrier lifetimes τ can be obtained by determining the decrease of the PL intensity upon increasing the PL chopping frequency ν_{chop}.[19] The decrease starts as soon as this modulation frequency ν_{chop} is of the order of the inverse lifetime τ^{-1} because then a phase difference occurs between the PL and the reference signal. For samples 1 and 2 roll-off frequencies of approximately 12.1 and 8.8 kHz were measured at an excitation density of 2.6×10^{-2} W cm^{-2}; this implies lifetimes ($1/e$ time constant) of 80 and 110 μs, respectively. A time-resolved PL experiment on sample 1 confirmed the long lifetimes: $\tau=200$ μs at $T=4.2$ K (the higher τ is a result of a slightly lower excitation density). These results are also in good agreement with those reported in literature for samples grown under the same conditions. Hence, although strongly dependent on growth conditions, $GaInP_2$ epilayers with a specific degree of ordering can be grown reproducibly. Almost all measurements we performed gave comparable results on both samples, so we report the results of only sample 1.

III. RESULTS AND DISCUSSION

A. Photoreflectance

PR spectra recorded at various temperatures are shown in Fig. 1. In those recorded at 240 and 293 K, a third-derivative line shape (TDLS) is observed. For semiconductors with a homogeneous intrinsic field distribution this TDLS occurs for low values of the modulation field,[25] such as it is the case under our experimental conditions. In the temperature interval 40–190 K the spectra show a markedly different PR line shape from those at higher T. This complex line shape corresponds nearly to that observed in the high-field limit;[25,26] the low-energy side of the line shape may be affected by impurities. Because the value of the modulating field was not increased while lowering T,[27] the high-field line shape can possibly be explained by field inhomogeneities in the sample. These inhomogeneities are presumably caused by confinement of electrons in the ordered domains, which have lower band gaps.

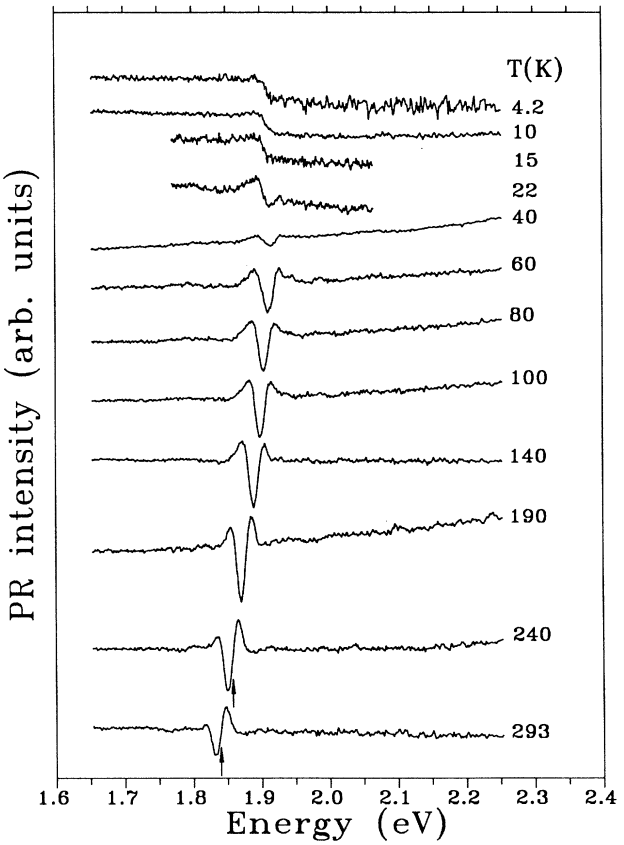

FIG. 1. Photoreflectance spectra as a function of temperature. The arrows in the spectra with a third-derivative line shape correspond to the energy of the band gap.

A second interesting change in PR line shape is observed in spectra recorded at temperatures between 4.2 and 22 K: the spectra then show a stepped line shape. Recently, the effects of electric-field modulation on the PR line shapes of isolated confined systems, such as quantum wells and superlattices, have been calculated by Glembocki and Shanabrook,[28,29] and by Enderlein, Jiang, and Tang.[30,31] In all cases a first-derivative line shape (FDLS) was found resulting from the Stark effect of minibands and sublevels for superlattices and quantum wells, respectively. In the case of superlattices, tunneling through its barriers resulted in an additional TDLS, which is characteristic for the Franz-Keldysh effect.[31] If our line shapes at $T<22$ K are interpreted as first-derivative line spectra, this shows that at low T the Stark effect is operative and that, therefore, the carriers are strongly localized.[32]

From the PR line shapes the band gap was calculated using the three-point method of Aspnes and Rowe.[25] For TDLS these energies are shown by the arrows in the lower spectra of Fig. 1; they will be discussed below in conjunction with results from PL.

B. Hall–van der Pauw measurements

Figure 2 shows the Hall mobility μ_H as a function of T. Below $T=100$ K, $\mu_H \propto T^{1.5}$, which is characteristic of the dominance of ionized impurity scattering; between 150–200 K, $\mu_H \propto T^{-0.3}$, showing that scattering of electrons by optical phonons through the polar interaction plays an important role.[33,34] Above $T=200$ K μ_H depends only little on T, which shows that a third scattering mechanism predominates. By treating spherically ordered domains as clusters, Friedman, Kibbler, and Olson[35] calculated that scattering at ordered clusters in $GaInP_2$ strongly affected μ_H. Their model predicts that, for samples with large cluster radius r_c, μ_H should even increase with increasing T. However, experimental verification of the effect of cluster scattering on μ_H at high T could not be made from their measurements on ordered $Ga_xIn_{1-x}P$ samples; they could only conclude that $r_c<20$ Å. We believe that the behavior of μ_H above $T=200$ K, shown in Fig. 2, is the first experimental observation of the pronounced effect that cluster scattering can have on the mobility of $GaInP_2$ samples. The temperature at which electrons in the disordered regions show pronounced scattering at ordered domains corresponds with the temperature above which PR spectra show a uniform carrier distribution in the entire sample. According to the model of Ref. 35, the influence of cluster scattering should become more pronounced if r_c is larger. For sample 2, which has a larger degree of ordering, larger effects of cluster scattering were indeed observed: the mobility decreased only by 15% upon increasing T from 200 to 450 K. This result and further data obtained from magnetotransport measurements will be published separately.[36]

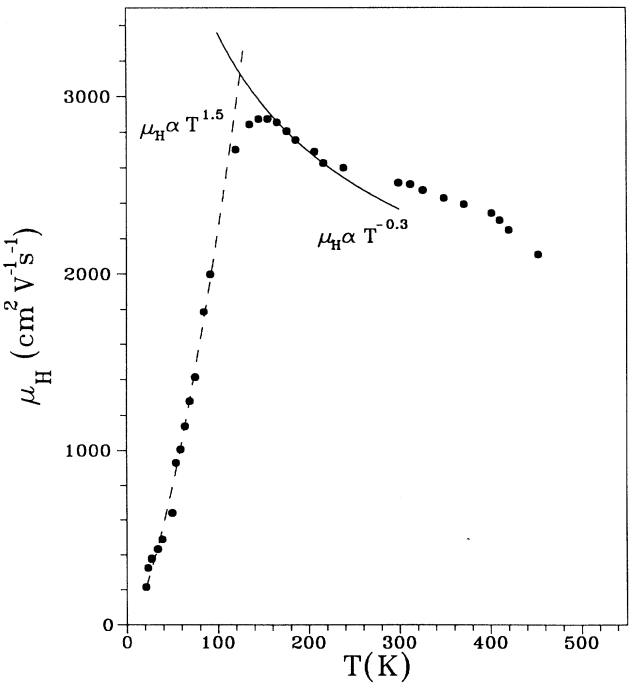

FIG. 2. Temperature dependence of the dc Hall mobility.

Before proceeding, a brief reminder will be given on impurity conduction in semiconductors, valid for not too high temperatures; n-type terminology is used. The dc conductivity can be expressed as a sum of three terms,[37,38]

$$\sigma(T)=\sigma_1 e^{-\epsilon_1/kT}+\sigma_2 e^{-\epsilon_2/kT}+\sigma_3 e^{-\epsilon_3/kT}, \quad (1)$$

where ϵ_1 is the donor ionization energy, which can always be observed provided the donor concentration n_D does not give rise to metallic conduction ($n_D<10^{18}$ cm^{-3} for $GaInP_2$). The second term in the conductivity can only be observed at intermediate concentrations in a certain temperature range intermediate between the high-T regime where ϵ_1 conduction dominates, and the low-T regime where ϵ_3 conduction dominates.[39] This ϵ_2 conduction is associated with conduction in an impurity band that is believed to arise from a resonance between negatively charged donors, the D^- ions. The D^- band is intermediate between the bottom of the conduction band and the donor level. The activation energy ϵ_2 is known to be half of the energy gap from the donor ground state to the bottom of the D^- band.[40] Owing to the great spatial extent of these D^- states,[40] the interaction between them is strong, which results in a large D^--band width. Upon increasing n_D this width increases and ϵ_2 is consequently reduced. The third term in the conductivity is observed most prominently in the low impurity concentration region and dominates at the lowest temperatures. Charge transport is explained in terms of hopping conduction: phonon-induced tunneling of electrons from occupied to unoccupied donor states.[37,41,42] Its small activation energy ϵ_3 is attributed to the potential difference between impurity sites owing to Coulomb fields of compensating impurity ions.

Changes in the dominant conductivity mechanism can be observed by a maximum in the relationship between

the Hall coefficient $R_H=[n(T)e]^{-1}$ and T^{-1}, where $n(T)$ is the carrier concentration and e the electron charge.[43] Figure 3 shows such a plot for sample 1 above $T=25$ K; the clear maximum shows that the dominant conduction mechanism changes at $T\approx 70$ K. A maximum was found for sample 2 at $T\approx 85$ K. In order to determine whether ϵ_3 conduction or ϵ_2 conduction occurs below the transition point, we performed magnetotransport measurements on sample 2 in the High-Field Magnet Laboratory, Nijmegen. From the behavior of activation energies in a magnetic field we found ϵ_2 conduction for temperatures in the range 30–70 K and ϵ_3 conduction below 30 K; the results from these measurements will be published separately.[36] Because neutral donors are required for both impurity conduction mechanisms, the remarkably high temperatures at which the changes in conduction mechanisms occurred suggest a large donor binding energy. From the T region where carrier freezeout determined the resistivity in the magnetotransport measurements, a donor binding energy ϵ_1 of 36 meV was found.[36] This value is large compared with the ionization energy E_D of a hydrogenlike donor in $GaInP_2$. On the basis of effective-mass theory this energy is expected to be 11.1 meV because $E_D=(m_0^*/\varepsilon_r^2)$ Ry, where $m_0^*=0.108$ is the effective electron mass in units of the free-electron mass,[44] $\varepsilon_r=11.49$ is the dielectric constant,[45] and Ry=13.6 eV is the Rydberg energy. The ordered domains are, at least in the direction of ordering, expected to be smaller than the effective Bohr radius of the hydrogenlike donor. By analogy with quantum wells, the conduction-band offset between the ordered (well) and disordered (barrier) alloy then acts as a potential barrier and constricts the donor wave function to the ordered domains, which results in a large overlap with the donor core. An accompanying enhancement of E_D by up to a factor of 4 was calculated for quantum wells.[46]

Although all nominally undoped $Ga_xIn_{1-x}P$ samples grown in our group were n type at 10^{15}–10^{16} cm^{-3} (at room temperature), ϵ_2 and ϵ_3 conduction from deep donors in the ordered domains was only observed in those samples with long-range ordering; this implies large film-like domains. Clearly, interdomain distances are relatively small in these epilayers otherwise it would not be possible to measure conduction through the ordered domains.

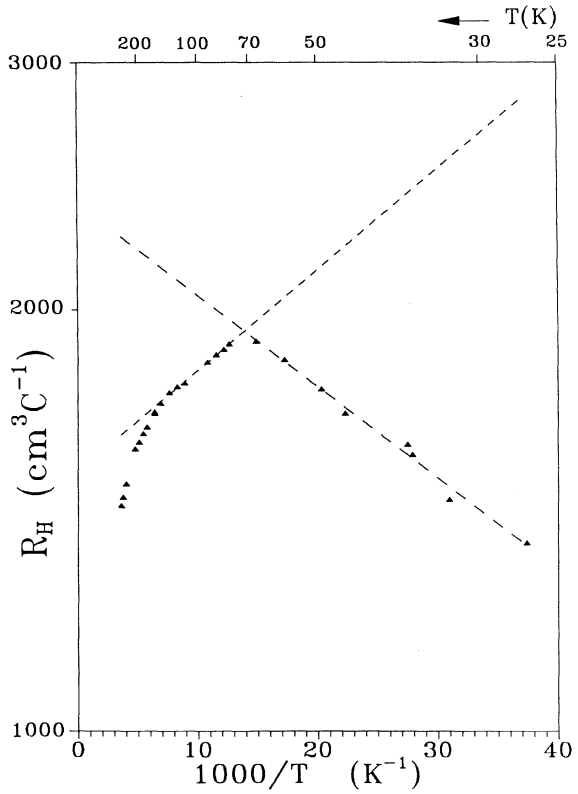

FIG. 3. Hall coefficient R_H vs T^{-1}.

C. Photoluminescence

The low excitation density PL and PR spectra at $T=4.2$ K are compared in Fig. 4. The dominant PL peak is accompanied by a low-energy shoulder that increased sublinearly with increasing excitation density. This shoulder is probably acceptor related or results from intrinsic recombination with large spatial separation and small recombination probability. The most important feature of Fig. 4 is that the dominant PL signal is emitted at the same energy as the step in the PR signal. This is a remarkable result because PR more strongly reflects the band structure and PL comes preferentially from impurity states in the band gap. Therefore, the absence of Franz-Keldysh oscillations and the clear first-derivative line shape at the impurity edge shows that the PR line shape is entirely determined by electron localization at these impurities in our samples. On the basis of Hall data and the long lifetimes, we attribute the low-T PL to spa-

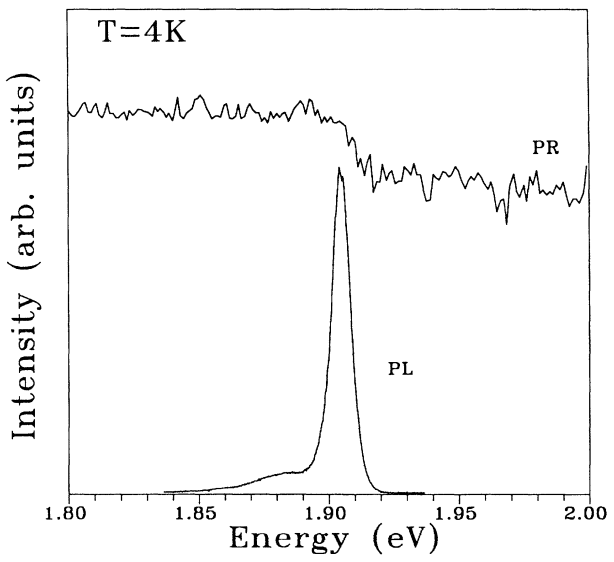

FIG. 4. Photoreflectance and photoluminescence spectra at $T=4.2$ K.

tially separated recombination between electrons at donors in the ordered regions and photoexcited holes, i.e., (D^0_{ord},h).

Figure 5 shows PL spectra for temperatures below 45 K recorded at $P=1$ W cm^{-2}. A second low-energy shoulder is now observed in the lowest-T spectra separated 47 meV from the dominant PL (labeled A). On the basis of the energy difference we attribute this shoulder to an LO-phonon replica, for which an energy separation of 46.8 meV was reported.[47] According to selection rules for scattering of excitons by LO phonons, the first LO replica is forbidden owing to momentum conservation.[48] However, this selection rule is relaxed in cases of strong spatial localization, for which the uncertainty in momentum is comparable with the phonon momentum. Our observation of an LO-phonon replica below $T=25$ K is therefore further evidence for the strong localization that appears in $GaInP_2$ alloys at low temperatures. At the high-energy side a second shoulder (labeled B) is present, which dominates the spectrum above $T>25$ K. Peak B is not accompanied by a phonon replica, indicating a nonlocalized nature of that PL.

Table I summarizes the rate of emission shift dE/dP and the dependence of PL intensity I upon P for peaks A and B at various temperatures. The I of peak A depends virtually linearly on P. This behavior is in accordance with the expected behavior of (D^0_{ord},h): I proportional to the hole density $[h]$, which in turn depends linearly on P.

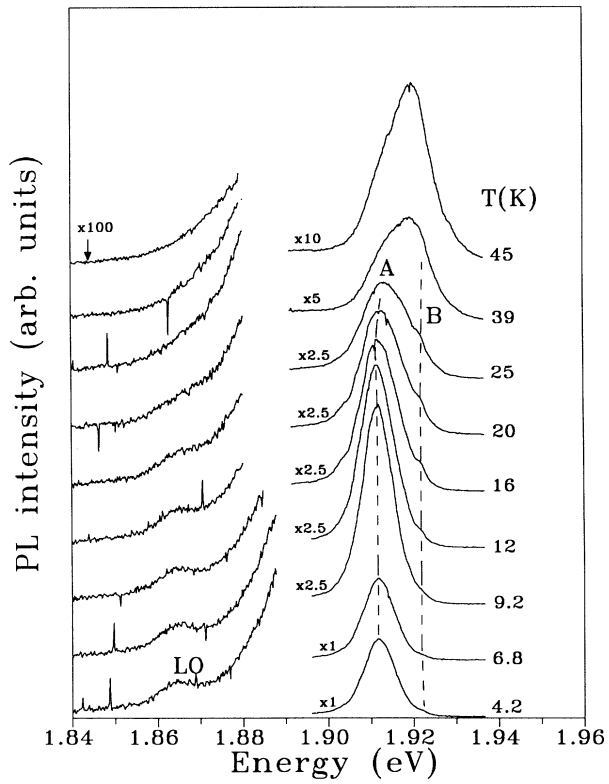

FIG. 5. Temperature dependence of the photoluminescence spectra from 4.2–45 K.

TABLE I. Rates of emission shift dE/dP and exponents x in $I \propto P^x$ for peaks A and B at different temperatures.

	Peak A		Peak B	
T (K)	dE/dP	x	dE/dP	x
4.2	4.7	0.98	[a]	[a]
25	5.2	1.01	0	1.45
40	7.2	1.08	0	1.49
70	[a]	[a]	0	1.61

[a]Not observable.

The I of peak B depends superlinearly on P. An exponent between 1 and 2 is typical for PL processes in which both electrons and holes are photocreated (e.g., bound excitons, free excitons, and band-to-band recombination), and in which parallel radiationless processes participate. The dE/dP was found to be zero for peak B which shows that electrons and holes are not spatially separated. The rate at which the PL energy of peak A shifts is seen to increase if peak B increases. This can be rationalized by assuming that peak B has a short lifetime, which results in a reduction of the valence-band filling. The accompanying reduction in band flattening will then cause a larger dE/dP.

The anomalous behavior of photon energy as a function of temperature in ordered $GaInP_2$ (Refs. 17 and 18) is shown in Fig. 6 for sample 1; where possible, energies of the moving and nonmoving components are shown separately. The dashed curve visualizes the energy of the PL maximum. With increasing temperature (4–20 K) an initial small decrease in energy was observed, followed by an increase in energy (T from 20–45 K) and finally a decrease again: the so-called inverted-S shape.[49] The energies of the band-gap E_0 as deduced from PR are also

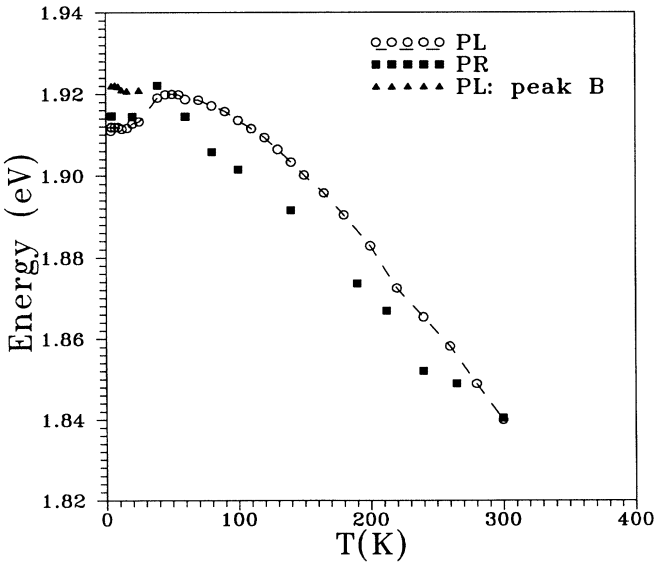

FIG. 6. Energy of photoluminescence emissions as a function of T. The dashed line (inverted S) shows the maximum of PL intensity. The values of the band gap as determined by photoreflectance are shown by triangles.

shown in Fig. 6 by the triangles. At the highest temperatures these energies could be precisely determined using the formalism of Aspnes and Rowe.[25] The more complex line shape between $T=40$ and 190 K hindered the precise determination of E_0. The E_0 determined using Ref. 25 corresponded virtually to the energies of the dips in the spectra for $40<T<190$ K and merged with the FDLS at lower temperatures. At $T=293$ K E_0 coincides with the energy of the PL emission, from which the PL process at $T=293$ K is identified as band-to-band recombination. For $40<T<190$ K E_0 is of lower energy than that of the PL emissions. Kondow *et al.*[17] also reported lower E_0 values obtained from the dips in their PR spectra (recorded below 150 K) for $GaInP_2$ epilayers with a smaller degree of ordering (V/III ratio of 160 and growth temperature of 700 K). They attributed this effect to an inhomogeneous band-gap distribution in their sample. However, our data points at 300 K and below 22 K show that PR and PL features appear at the same energy. Therefore, we believe that the energy of the dip in the PR spectrum gives an unreliable value for the band gap for such a complex PR line shape.

A similar inverted *S*-shaped temperature dependence of PL energy E was also reported recently in so-called disordered superlattices, i.e., those in which disorder is introduced by random variations of the well and/or barrier widths.[50] It was also observed for $Al_xIn_{1-x}As$ epilayers.[51] For both the disordered superlattices[52,53] and $Al_xIn_{1-x}As$, strong carrier localization was reported. Therefore, it appears that the inverted-*S* shaped behavior occurs only together with carrier localization. For our sample the anomalous increase of PL energy starts if T exceeds 25 K, which is virtually the same temperature below which the PR spectra showed evidence for strong localization through FDLS. Furthermore, the conduction mechanism changed from ϵ_3 conduction to ϵ_2 conduction at this temperature. The origin of the inverted-*S* shaped dependence of photon energy on temperature may therefore be the following. At low temperature confined donor-to-band transitions occur (peak *A*). Because the gap between the bottom of the D^- band and the donor states is small, the lowest-lying states in the D^- band can be occupied at relatively low temperature and this wide band will then be filled. The observed increase in PL energy upon increasing temperature may therefore be due to PL from the D^- band, which in the spectra of Fig. 5 is observed as peak *B* (note its consistent superlinear relationship between *I* and *P*). The additional, usual band-gap reduction[54] upon increasing temperature leads to a decrease in PL energy at higher temperatures.

Yamamoto *et al.*[53] also reported PL intensity as a function of temperature for their disordered superlattices $(AlAs)_m(GaAs)_n$ (m and n randomly chosen between one and three with an average value of two), and found that their behavior was strongly determined by the presence of localized states. In comparison with ordered superlattices and a random $Al_{0.5}Ga_{0.5}As$ alloy, which both also contained 50% of Al for the group-III component, the PL intensity of the disordered superlattices showed a more gradual reduction upon increasing temperature.[50,53] It appeared that the data could be well fitted to a relationship valid for amorphous semiconductors because of the existence of localized states therein:[55]

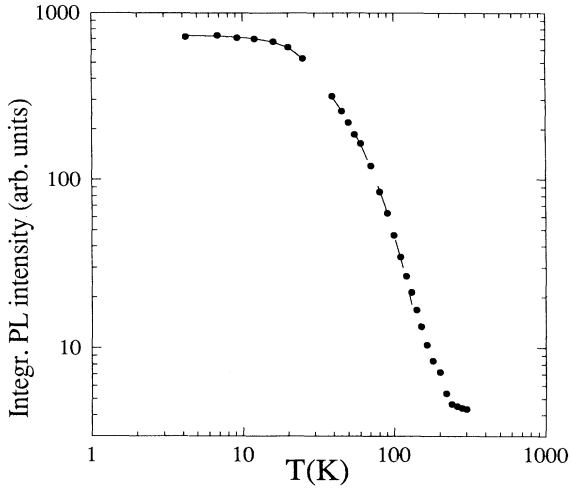

FIG. 7. Numerically integrated photoluminescence intensity vs T. The solid and broken curves are computer-calculated best fits described in the text.

$$I_{PL}(T)=\frac{I_0}{1+A\exp(T/T_0)}\ , \tag{2}$$

where I_{PL} is the PL intensity, T is the measured temperature, T_0 is a characteristic temperature corresponding to the energy depth of localized states, A is the tunneling factor, and I_0 scales the PL intensity at the low-temperature limit.

In Fig. 7 we show the numerically integrated PL intensity of the $GaInP_2$ PL as a function of temperature. A discontinuity is seen around 200 K. Above this temperature, PR data indicated a homogeneous electron distribution and Hall data showed cluster scattering. Therefore, the discontinuity in the PL intensity will most likely be caused by the onset of luminescence from the disordered regions above 200 K. Below this discontinuity two regions can be distinguished in Fig. 7. The data could be well described by Eq. (2) for $T<30$ K; the solid curve represents a best fit yielding $T_0=7.5$ K, $A=0.01$, and $I_0=753.1$. The fit became less good if data points above $T=30$ K were added showing that these data were not consistent with Eq. (2). However, an Arrhenius equation $I_{PL}(T)=I_0\exp(-T/T_0)$, with $T_0=32.0$ K, described these data perfectly, as shown by the broken curve in Fig. 7.

IV. CONCLUSIONS

We have performed PR, PL, and Hall–van der Pauw measurements as a function of temperature on long-range-ordered $Ga_xIn_{1-x}P$ obtained by metal organic vapor phase epitaxy. The data provide information on the origin of the "anomalous" optical and transport properties of the ordered alloy.

Below $T=200$ K we found that optical and transport properties were strongly influenced by a donor state

which, owing to confinement in the ordered domains, had a high binding energy of 36 meV. Evidence for strong localization was obtained for $T<30$ K: the PR spectra showed a pronounced first-derivative line shape, the conductivity was dominated by ϵ_3 conduction (hopping), the relationship between PL intensity and temperature could be well fitted assuming localized states, and an LO-phonon replica was observed. Energies of the PL and PR features were found to be identical at these low temperatures. On the basis of transport data the low-T PL transition was attributed to recombination between a photoexcited hole and an electron that is localized on a donor in an ordered superlattice domain. Between 30 and 70 K the dominating conduction mechanism was identified as ϵ_2 conduction via negatively charged donors: the D^- band. At 70 K, the Hall data showed a changeover from ϵ_2 to band conduction. It is proposed that the origin of the inverted-S shape of PL energy as a function of temperature is connected with thermal population of the D^- band. In the temperature interval 30–200 K the PR showed a complex line shape owing to the absence of carriers in the disordered regions. Furthermore, the conduction mechanism changed at $T=70$ K from band conduction (ϵ_1) to ϵ_2 conduction via negatively charged donors.

Above $T\approx 200$ K the PR showed third-derivative line shapes, which indicates a uniform electric-field distribution. Hall-mobility data showed unprecedently strong effects of cluster scattering on ordered domains above $T=200$ K. These two observations show that a finite carrier concentration will then be present in the disordered regions of $GaInP_2$. The discontinuity in the PL intensity at 200 K therefore indicates that additional recombination from randomly alloyed regions occurs above this temperature.

ACKNOWLEDGMENTS

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