Intrinsic Doping: A New Approach for *n*-Type Modulation Doping in InP-Based Heterostructures

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A new approach for *n*-type modulation doping in InP-based heterostructures is proposed where intrinsic defects are utilized to provide charge carriers without an external shallow impurity doping source. The success of this approach is demonstrated by results from InGaAs/InP heterostructures, where doping is provided by P_{In} antisites, preferably introduced during off-stoichiometric growth of InP. The efficiency of electron transfer and quantum mobility of a two-dimensional electron gas formed near the heterointerface is shown to be much higher as compared to traditional extrinsic doping. [S0031-9007(96)01303-8]

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InP-based heterostructures, containing, e.g., InGaAs ternary compounds and InGaAsP quaternary compounds, are now well recognized as being among the most promising electronic material systems, owing to their superior performance in optoelectronic and ultrahigh speed electronic devices. They also provide an excellent playground for the understanding of fundamental physics in quantum structures and devices, which are now largely available and where the quantum regime can be rather easily achieved. One of the fundamental processes and essential steps in fabrication of these quantum systems is selective doping in certain regions of the structures. Such doping is traditionally done by incorporating shallow donor or acceptor dopants in the structures via diffusion or ion implantation, or *in situ* incorporation during growth of the host crystal. The electronic properties of these shallow dopants are well understood by the effective-mass theory. Despite the success of this standard doping mechanism, there are still many problems remaining, such as thermal instability, implantation damage, memory effects, configurational metastability, etc. [1–3]. These problems are and will be found to be unacceptable for certain devices, in particular, those modern devices of lower dimensionality and of submicron or nanometer size, where a high precision of doping and interface profiles is crucial. To resolve these problems, a substantial effort is required in seeking for both a better control of the existing doping processes and a better doping mechanism.

In this Letter, we propose a new approach for *n*-type modulation doping in InP-based heterostructures, where intrinsic defects are utilized to provide the required doping without an external doping source. The success of such an intrinsic doping concept is clearly demonstrated by the example case of InGaAs/InP heterostructures, designed to resemble high electron mobility transistor (HEMT) structures. Though all of the structures are intentionally undoped, *n*-type modulation doping in the InP barrier is readily realized by the presence of P_{In} antisites, preferably introduced during off-stoichiometric growth of InP at low temperatures (LT) by gas source molecular beam epitaxy (GS-MBE) [4–6]. The formation of a two-dimensional electron gas (2DEG) near the InGaAs/InP interface, due to electron transfer from the LT-InP barrier, is evident from studies of Shubnikov–de Haas (SdH) oscillations and photoluminescence (PL). Important advantages arising from unique physical properties of the new doping approach will be discussed.

The lattice-matched InGaAs/InP heterostructures (see Fig. 1) studied in this work were grown by GS-MBE, on semi-insulating Fe-doped InP substrates. They consist of a 5000-Å InP buffer layer, a 400-Å $In_{0.53}Ga_{0.47}As$ active layer, a 100-Å InP spacer, and finally a 500-Å InP layer. All structures were intentionally undoped and were grown

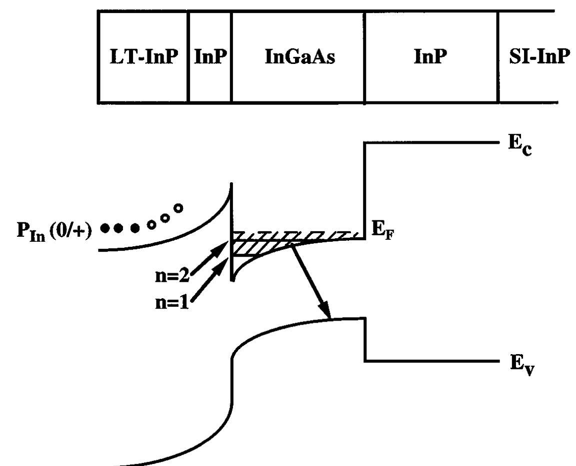

FIG. 1. Schematic pictures of the InGaAs/LT-InP structures and the energy band diagram. For simplicity only two subbands of the 2DEG are drawn in the figure. The filling of the 2DEG is depicted by the shaded region. The arrow across the InGaAs band gap indicates the PL transition between the 2DEG and photoexcited holes upon optical excitation.

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at a normal temperature of 480 °C except the top InP layer which was grown at 265 °C. These samples will be referred to below as InGaAs/LT-InP or intrinsically doped structures. A reference sample was also grown with an identical structure, except that the top InP layer was in this case grown at 480 °C. For comparison an extrinsically doped structure was grown with an identical design of the structure, except that the n-type doping was done by traditional shallow Si donors with $[\mathrm{Si}] = 1 \times 10^{18}\ \mathrm{cm}^{-3}$. Studies of SdH oscillations and PL were performed with the aid of a 5 T magneto-optical system. Lithographically defined Hall bars with six In Ohmic contacts were fabricated on the samples for electrical SdH measurements. Hall effect measurements were done at 0.2 T, with the Van der Pauw geometry. PL, excited at 2 mW by the 6328-Å line of a He-Ne laser, was spectrally dispersed by a grating monochromator and was collected by a cooled Ge detector.

In Fig. 1 we show schematic pictures of the InGaAs/LT-InP structures and the corresponding energy band diagram. As a direct consequence of electron transfer from the LT-InP barrier to the InGaAs active layer, a notch potential is formed near the heterointerface where the 2DEG is confined. For simplicity only two subbands of the 2DEG are drawn in the figure. The filling of the 2DEG is depicted by the shaded region. The arrow across the InGaAs band gap indicates the PL transition between the 2DEG and photoexcited holes upon optical excitation.

Figure 2(a) shows the SdH oscillation spectrum taken at 1.5 K from the InGaAs/LT-InP structure, with the external magnetic field normal to the heterointerface plane. It can clearly be seen that there is more than one period of the magnetoresistance oscillations vs reciprocal magnetic field. PL spectra obtained from the same sample are shown in Fig. 3, at 0 and 5 T. Identical SdH oscillations were observed by detecting this PL emission at the highest photon energy, indicating that the PL emission originates from the same free carriers which give rise to the electrical SdH oscillations. The splittings of the PL emission in the magnetic field (Fig. 3) therefore represent the Landau level splittings of the monitored carriers. The SdH spectrum from the reference sample, taken under the same experimental conditions, is shown in Fig. 2(b) for comparison. It contains a single and much larger period of the magnetoresistance oscillations, meaning a much lower carrier concentration (due to the residual doping). This is because the period $\Delta(1/B) = 2e/hn_i$, assuming an ideal 2D system. (Here n_i denotes the sheet concentration of free carriers for the ith subband, e is the electron charge, and h is the Planck's constant.) This experimental fact clearly shows that the much higher concentration of free carriers giving rise to the SdH oscillations in Fig. 2(a) is directly related to the modulation doping by the LT-InP, since the growth temperature of the InP barrier is the only difference between the two samples.

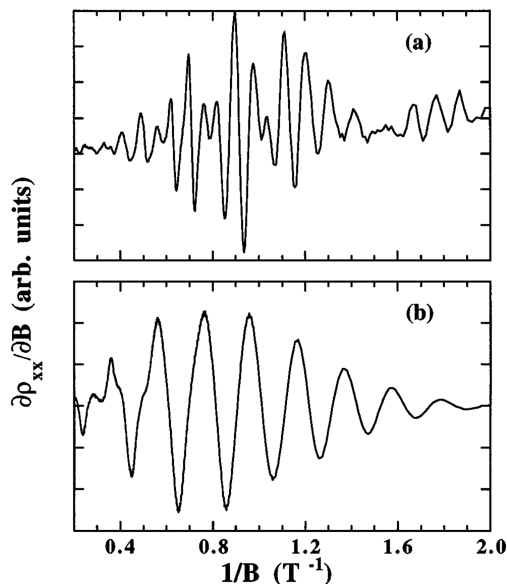

FIG. 2. SdH oscillation spectra taken at 1.5 K in dark from (a) the InGaAs/LT-InP structure and (b) the reference sample, with the external magnetic field normal to the heterointerface plane. The additional structure at low reciprocal magnetic fields is due to spin splittings.

Below we will provide unambiguous experimental evidence that the SdH oscillations in Fig. 2(a) are due to a dense 2DEG formed in the InGaAs active layer near the heterointerface as a result of electron transfer from the LT-InP. First of all, an angular dependence study of the SdH oscillations clearly elucidates the 2D character of the free carriers, where the period of the SdH oscillations obeys a cosine relation of the relative angle between the magnetic field and the direction normal to the conducting layer.

In principle, there are two parallel conducting channels, i.e., the LT-InP barrier and the InGaAs active layer, which can possibly contribute to the magnetotransport measurements. A possible contribution from the LT-InP

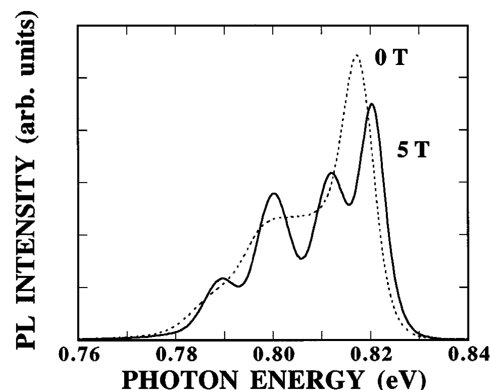

FIG. 3. PL spectra at 1.5 K obtained from the InGaAs/LT-InP structure, at zero magnetic field (the dashed curve) and 5 T (the solid curve).

layer can, however, be safely ruled out based on the following experimental facts. First, the electron mass value $m_e^* \approx 0.05 m_0$, determined from the Landau level splitting observed in the PL experiments (Fig. 3), differs from the electron mass value $m_e^* \approx 0.07 m_0$ in InP but lies well within the range $m_e^* \approx (0.04\text{–}0.06) m_0$ of the electron effective mass determined for $In_{0.53}Ga_{0.47}As$ [7]. Second, the electron mobility $\mu_e \approx 1.3 \times 10^4$ cm^2/V s obtained by the Hall measurements is much higher than $\mu_e \approx 5 \times 10^2$ cm^2/V s determined independently for the LT-InP layer grown at the same temperature (i.e., 265 °C). Moreover, the photon energy (~0.8 eV) of the PL emission (Fig. 3) is consistent with the band gap of $In_{0.53}Ga_{0.47}As$. The PL spectrum resembles that observed in similar InGaAs/InP and InGaAs/AlInAs HEMT structures [8,9], where the conventional shallow donors were employed to achieve n-type modulation doping, and was attributed to the recombination between the 2DEG and the photoexcited holes in the InGaAs layer (see Fig. 1). A detailed account of the PL emission is beyond the scope of this Letter and will not be discussed further.

Consequently, the only plausible candidate responsible for the SdH oscillations in Fig. 2(a) is a 2DEG in the InGaAs active layer, formed as a result of electron transfer from the LT-InP barrier. A detailed analysis of the SdH oscillations reveals that two subbands of the 2DEG are readily occupied. The sheet concentrations of the first and second subbands of the 2DEG are determined to be $n_1 = 6.75 \times 10^{11}$ cm^{-2} and $n_2 = 4.75 \times 10^{11}$ cm^{-2}, respectively, yielding a total sheet concentration of 1.15×10^{12} cm^{-2}. This is about an order of magnitude higher than the concentration (2.37×10^{11} cm^{-2}) in the reference sample, where only one subband is partially occupied by a 2DEG due to residual doping.

The success of the intrinsic doping approach has further been confirmed by our results from an additional InGaAs/LT-InP sample with an identical structural design except that the spacer thickness is reduced to 50 Å. The mechanism responsible for the n-type modulation doping by using LT-InP is attributed to an abundant presence of P_{In} antisites, deep double donors in InP, preferably introduced during off-stoichiometric growth of LT-InP. The high electron concentration is provided by the autoionization of the P_{In} antisites via its first ionization stage, i.e., the (0/+) level, which is located at $E_c + 0.12$ eV resonant with the conduction band [4–6]. We note that not-intentional modulation doping was observed in InAs/AlSb quantum wells and was attributed to the presence of surface [10] or interface donors (suggested to be antisite defects [11]). The exact nature as to, e.g., the chemical identity of these donors is, however, still unknown.

The intrinsic doping proposed in this work exhibits interesting and unique physical properties providing many advantages over the conventional doping by shallow dopants. First of all, no external doping source is needed to be installed in the growth chamber, which implies a reduced risk of contamination and memory effects. In addition, deep resonant donor levels such as the (0/+) level of the P_{In} antisites lie well above the bottom of the conduction band, in contrast to the usual case when the shallow donor level is slightly below the bottom of the conduction band. This leads to a higher efficiency in the electron transfer from the doped region to the active 2D channel, which is supported by the experimental fact that the total sheet concentration, $n_s = 1.15 \times 10^{12}$ cm^{-2}, of the 2DEG in the intrinsically doped structure is higher than $n_s = 8.4 \times 10^{11}$ cm^{-2} in the extrinsically doped structure. This is in full agreement with our self-consistent theoretical calculations on such heterostructures by the coupled Poisson-Schrödinger model, where the 2DEG concentration is shown (Fig. 4) to increase by approximately a factor of 2 when the donor level raises from the typical value ($\sim E_c - 0.007$ eV) of shallow dopants to the (0/+) level of the P_{In} antisites at $\sim E_c + 0.12$ eV. Furthermore, the quantum mobility for each occupied subband of the 2DEG in the intrinsically doped structure is about a factor of 1.5–2 higher than that in the extrinsically doped structure, from an analysis of fast Fourier transformation of the SdH oscillations [12]. Since both alloy and interface scattering should be nearly identical for both structures, an enhanced quantum mobility can only be due to a reduced scattering of the 2DEG by remote dopants in the intrinsically doped structure. This can be attributed to a different scattering potential of the *deep* P_{In} antisites, and also to a stronger screening of the defect potential by a degenerate electron gas present in the LT-InP barrier. The latter results from autoionization of the P_{In} antisites and is revealed by Hall measurements. It should also be pointed out

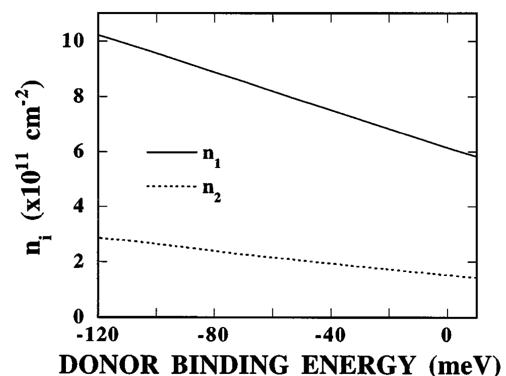

FIG. 4. Subband populations (n_i) of a 2DEG as a function of donor binding energy in modulation doped InGaAs/InP heterostructures, from self-consistent theoretical calculations based on the coupled Poisson-Schrödinger model. The same design parameters as the structures experimentally studied in this work are used in the calculations. The value of the donor binding energy is shown with respect to the bottom of the conduction band E_c in the InP barrier, and a negative value corresponds to a donor level lying above E_c.

that the doping concentration of the intrinsically doped InP-based heterostructures can be conveniently controlled by varying the growth temperature of LT-InP, where a monotonic increase in electron concentration is found with decreasing growth temperatures [4–6]. At 265 °C a saturation electron concentration of $\sim 3 \times 10^{18}$ cm^{-3} in LT-InP thin films is reached due to the Fermi level pinning at the $(0/+)$ donor level of the P_{In} antisites, when the LT-InP exhibits a metallic n-type conduction. The actual concentration of the P_{In} antisites can in fact be higher, which will lead to a higher doping level when LT-InP is incorporated in modulation doped InP-based heterostructures as more additional states are now available in the adjacent 2D channel.

In summary, we have proposed a novel modulation doping approach in InP-based heterostructures by employing intrinsic defects such as the P_{In} antisites, without invoking an external doping source. The success of this approach is clearly demonstrated by our results from the InGaAs/LT-InP heterostructures, where the required n-type doping in the InP barriers is efficiently provided by the P_{In} antisites preferably introduced during off-stoichiometric growth of LT-InP by GS-MBE. Unambiguous experimental evidence on the formation of a dense two-dimensional electron gas (as high as 1.15×10^{12} cm^{-2}) near the InGaAs/InP heterointerface, as a direct consequence of electron transfer from the intrinsically doped InP barrier, is provided from studies of SdH oscillations and PL. This work concludes that the intrinsically modulation doped InGaAs/InP structure provides a higher density of the 2DEG (due to a more efficient charge transfer) as well as a higher quantum mobility (due to a reduced scattering), as compared to the extrinsically doped structure. Though it has only been demonstrated for InGaAs/InP heterostructures, the principle of the intrinsic doping concept is in fact rather general and can be extended to applications in other electronic material systems. This work is thus expected, e.g., to contribute to a better understanding and a possible follow-up application of the recently intensively studied autodoping phenomenon GaN And ZnSe [13,14], where intrinsic defects are largely suspected to be responsible but no definite identification has so far been made.

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