High-quality GaAs/$Ga_{0.49}In_{0.51}P$ superlattices grown on GaAs and silicon substrates by low-pressure metalorganic chemical vapor deposition

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We report the successful growth of $Ga_{0.49}In_{0.51}P$-GaAs superlattices on GaAs and Si substrates by low-pressure metalorganic chemical vapor deposition. The high quality of the structure grown on GaAs and silicon substrates has been evidenced by transmission electron microscopy photographs, that show very sharp interfaces between GaAs wells and $Ga_{0.49}In_{0.51}P$ barriers, with perfect control of thicknesses and compositions. Classical Hall measurements performed on the sample further demonstrated the presence of a two-dimensional electron gas with a mobility at $T = 4$ K, $\mu(4\text{ K}) = 50\,000\text{ cm}^2/\text{V/s}$, and a carrier concentration $n_{-}(4\text{ K}) = 2.9\times 10^{11}\text{ cm}^{-2}$. GaAs/$Ga_{0.49}In_{0.51}P$ superlattices have been used, as well as buffer layer in order to grow GaAs on silicon substrates. Mirrorlike single-crystal GaAs has thus been obtained. A GaInP/GaAs heterostructure with electron Hall mobility as high as 6000 $\text{cm}^2/\text{V/s}$ at 300 K and 80 000 $\text{cm}^2/\text{V/s}$ at 4 K has been grown, which is the highest mobility that has yet been reported for these materials.

I. INTRODUCTION

$Ga_{0.49}In_{0.51}P$ lattice matched to GaAs, with a band gap at room temperature of 1.9 eV, has been proven to be of much interest as a replacement for $Ga_xAl_{1-x}As$ in GaAs/$Ga_xAl_{1-x}As$ structures because of the tendency of aluminum to be oxidized. It has already been grown by many techniques.[1-4] We have recently reported[5] the observation of a two-dimensional electron gas at the $Ga_{0.49}In_{0.51}P$/GaAs modulation-doped single heterojunction. In this paper, we show that low-pressure metalorganic chemical vapor deposition (LP-MOCVD) is well adapted for the growth of GaAs/$Ga_{0.49}In_{0.51}P$ superlattices and multiquantum wells.

A. Growth and characterization of high quality GaAs/$Ga_{0.49}In_{0.51}P$ superlattices on GaAs substrate

Growth apparatus and processes using an induction-heated horizontal cool wall reactor, triethylindium (TEI) and triethylgallium (TEG) as In and Ga sources, and arsine (AsH_3) and phosphine (PH_3) as As and P sources, have already been reported in detail in a previous paper.[6] Carrier gases are hydrogen (H_2) and nitrogen (N_2) in a 50%/50% proportion. Growth is carried out at 76 Torr, at a substrate temperature of 550 °C. The growth conditions are listed in Table I. The GaAs substrate orientation (used in this study) was (100) exact.

Sample No. II-31 is a typical ten-period GaAs/$Ga_{0.49}In_{0.51}P$ superlattice. Its structure, deduced from growth rates of GaAs and $Ga_{0.49}In_{0.51}P$, is briefly described in Table II.

Figure 1 shows the simple diffraction pattern of the sample, performed using $K\alpha_1$ (1.54 Å) and $K\alpha_2$ (1.544 Å) of Cu as x-ray sources, in a classical (θ, 2θ) configuration. $K\alpha_1$ and $K\alpha_2$ components of the satellites, due to the superperiod $D = d_1 + d_2$ artificially introduced by the growth, can be seen up to order $n = \pm 3$. This fact is remarkable, especially using simple diffraction, and suggests that the thicknesses of the wells and barriers are perfectly controlled. We have shown with arrows the $K\alpha_1$ components of the satellites, together with their order n. The corresponding data are summarized in Table III.

A mean value of $2\delta\theta = 0.31°$, corresponding to the spacing between two satellites, is found. The superperiodicity $D = d_1 + d_2$ can then be deduced by the well-known relation

$$D = \lambda / (2\delta\theta \cos \theta_0), \tag{1}$$

where θ_0 represents the Bragg angle at which the (400) reflection of the GaAs occurs ($\theta_0 = 33.01°$). λ is the excitation wavelength, which is about 1.54 Å for the Cu$K\alpha_1$ ray.

We thus find $D = 340$ Å, which is in good agreement with the value obtained from the growth times and deposition rates (see Table II).

The morphology of this GaInP/GaAs superlattice sample was examined by cross-sectional transmission electron microscopy (TEM) on specimens prepared using the methods described in Ref. 7. A dark-field image of the complete superlattice is shown in Fig. 2(a). This image was taken using the 200 reflection, with GaInP appearing brighter than

TABLE I. Optimized growth parameters.

		GaAs	$Ga_{0.49}In_{0.51}P$
Growth temperature	°C	550	550
Total flowrate ($N_2 + H_2$)	l/min	4	4
N_2/TEI bubbler flow	cm^3/min	···	200
H_2/TEG bubbler flow	cm^3/min	120	120
PH_3 flow	cm^3/min	···	300
AsH_3 flow	cm^3/min	60	···
Growth rate	Å/min	100	200

TABLE II. Structural details of GaInP/GaAs superlattice grown by LP-MOCVD.

Sample No. II-31		Growth time (s)	Thickness (Å)
GaAs buffer layer		600	1000
10×	GaAs wells	120	$d_1 = 200$
	GaInP barriers	40	$d_2 = 135$
GaInP cap layer		210	700

TABLE III. X-ray data of GaInP/GaAs superlatices grown by LP-MOCVD.

Order n of the component of the satellite $K\alpha_1$	-3	-2	-1	0	$+1$	$+2$	$+3$
2θ (degrees)	66.97	66.66	66.35	66.02	65.73	65.43	65.12

GaAs. The ten periods of GaInP/GaAs are clearly visible with each GaInP layer measuring 140 Å and each GaAs layer 205 Å in thickness. The layers are extremely regular, no local layer thickness variations were seen in the area examined. The GaAs buffer layer can be distinguished from the GaAs substrate by a dark contamination line, most clearly visible in Fig. 2(b), whose presence has not affected the quality of the buffer layer. One defect in the superlattice was found and is shown in Fig. 2(b). It originates at the boundary between the buffer layer and the first GaInP layer.

The SIMS profile of the sample is shown in Fig. 3. The signals relative to the majority species Ga, In, As, and P have been plotted. The ten periods of the superlattice are clearly evidenced by following the oscillations of the different signals. On each side appear the $Ga_{0.49}In_{0.51}P$ top layer and GaAs substrate.

Figure 4 shows the electrochemical (polaron) profiles of the bulk GaAs and $Ga_{0.49}In_{0.51}P$ layers. Both are n doped with residual doping levels of 10^{15} cm^{-3}. This explains why a concentration of carriers of $n - = 2.9\times 10^{11}$ cm^{-2} is measured at $T = 4$ K by the classical Hall method, in the nonintentionally doped superlattice structure.

Carriers arising from the donor impurities are confined in the GaAs quantum wells, where they form a two-dimensional electron gas. This fact is evidenced by the performance of the mobility curve versus temperature (Fig. 5). The mobility reaches a constant value of 50 000 cm^2/V/s at temperatures lower than 50 K. This is clearly characteristic of transport properties of a two-dimensional electron gas. Because of the spatial separation between carriers and donor, the ionized impurity scattering becomes much less efficient than in three-dimensional systems, so that mobility does not decrease at low temperatures under this effect. We have measured a $T = 4$ K mobility of $\mu(4\text{ K}) = 80\,000$ cm^2/V/s in a $Ga_{0.49}In_{0.51}P$/GaAs single heterojunction, which is the highest value reported today, to our knowledge, in the literature.

An Auger spectrum has been taken from a GaAs/$Ga_{0.49}In_{0.51}P$ multiquantum well structure, with GaAs wells of, respectively, 15, 50, and 100 Å thickness and GaInP barriers of 1000 Å (Fig. 6). Resolution good enough to identify wells of thickness down to 15 Å was obtained by scanning the surface of a chemical bevel and correcting the arsenic signal.[8]

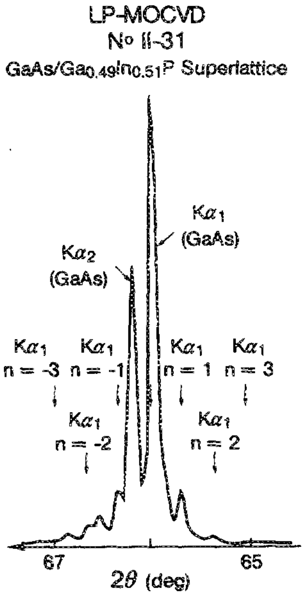

FIG. 1. Simple x-ray diffraction pattern of a typical GaAs/$Ga_{0.49}In_{0.51}P$ superlattice.

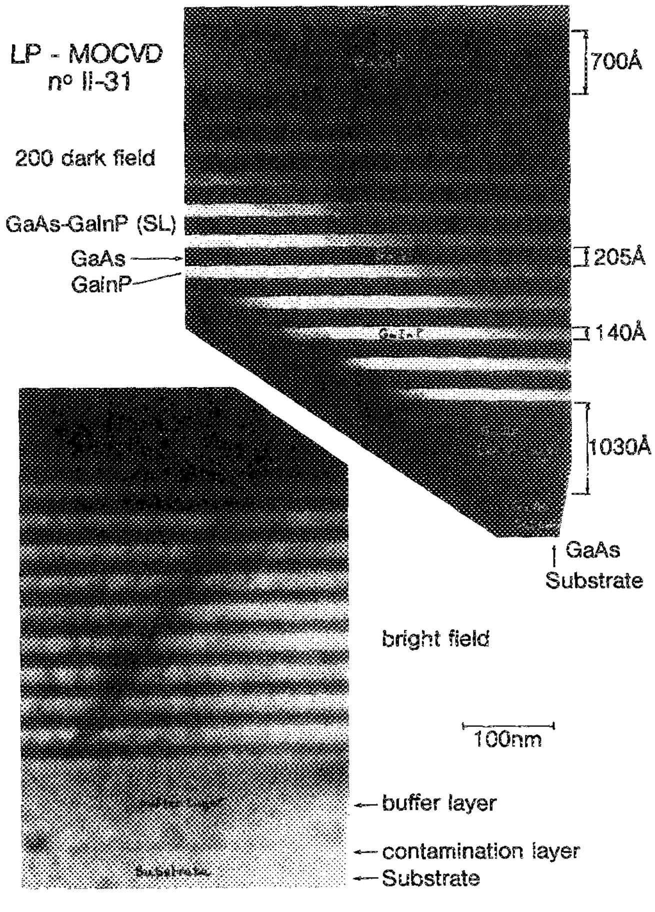

FIG. 2. Transmission electron micrograph of a typical GaAs/$Ga_{0.49}In_{0.51}P$ superlattice.

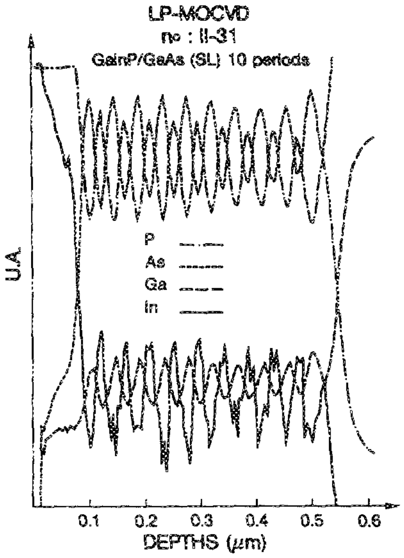

FIG. 3. SIMS profile relative to the majority species In, Ga, As, and P of a typical GaAs/$Ga_{0.49}In_{0.51}P$ superlattice.

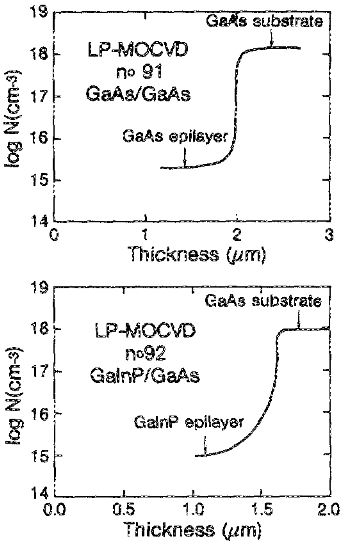

FIG. 4. Polaron profile of bulk GaAs and GaAs/$Ga_{0.49}In_{0.51}P$.

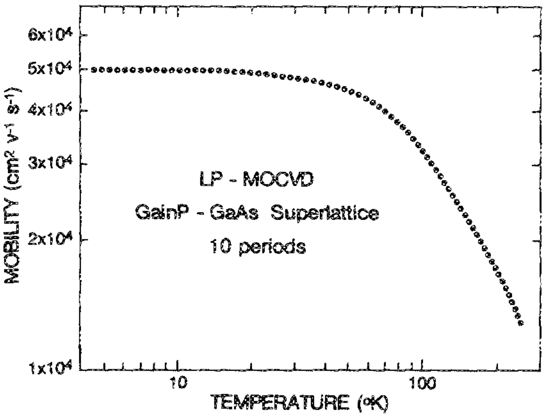

FIG. 5. Mobility curve, vs temperature, of a typical GaAs/$Ga_{0.49}In_{0.51}P$ superlattice.

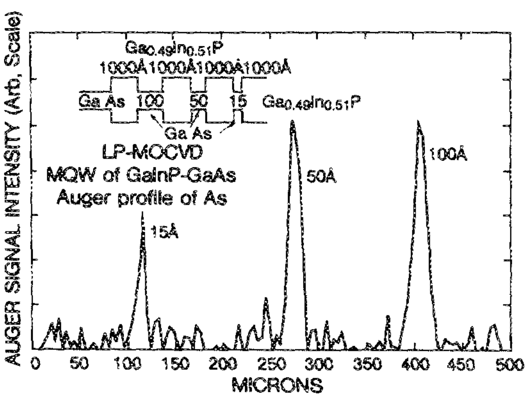

FIG. 6. Auger spectrum of As species of a typical GaAs/$Ga_{0.49}In_{0.51}P$ multiquantum well.

B. Growth of GaAs on Si substrates, using GaAs/$Ga_{0.49}In_{0.51}P$ superlattices as buffer layer

GaAs/$Ga_{0.49}In_{0.51}P$ superlattices have been used as buffer layer for growing GaAs on a silicon substrate. This one was initially heated up to 1000 °C, after introduction into the reactor, in order to remove the oxide present on its surface. It was then cooled to 550 °C and growth was initiated at the conditions of Table I by simply introducing gallium and arsenic.

The structure of the sample is shown in Fig. 7. Two thin layers (500 Å) have been grown before the thick top layer of 0.6 μm. They were separated by two GaAs/$Ga_{0.49}In_{0.51}P$ superlattices, that were introduced to prevent the propagation of misfit dislocations due to the lattice mismatch between GaAs and Si. An intense $T = 77$ K photoluminescence signal was obtained, which demonstrates the good optical properties of the GaAs epilayer. A full width at half-maximum of 20 meV was determined.

A simple x-ray diffraction pattern of the structure is shown in Fig. 8. The epilayer has the same (111) orientation as that of the substrate. No trace of disorientation has been found. The good crystallographic quality of the GaAs is evidenced by the clear separation between $K\alpha_1$- and $K\alpha_2$-related signals [we used GaAs substrate (111) orientation, because at the time we did not have (100) orientation substrate].

We found that the optical, electrical, and structural

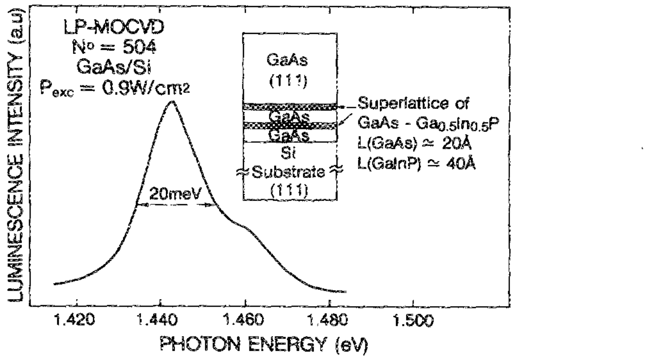

FIG. 7. Photoluminescence spectrum at $T = 77$ K of bulk GaAs grown on a silicon substrate, using GaAs/$Ga_{0.49}In_{0.51}P$ superlattice as buffer layers.

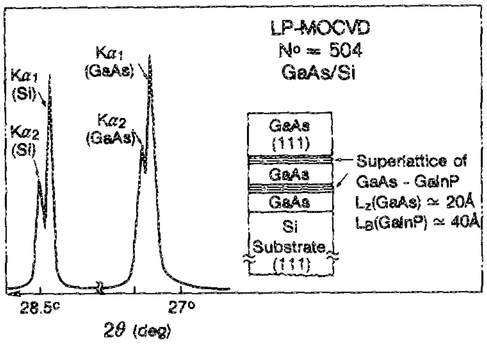

FIG. 8. Simple x-ray diffraction profile of bulk GaAs grown on a silicon substrate, using GaAs/$Ga_{0.49}In_{0.51}P$ superlattice as buffer layers.

properties of the GaAs epilayer grown directly on the Si susbtrate are poorer than those of the GaAs epilayer grown on Si, using GaAs/GaInP superlattices as buffer layers between the Si substrate and the GaAs epilayer.

II. CONCLUSION

We have reported the growth of excellent quality GaAs-$Ga_{0.49}In_{0.51}P$ superlattices by LP-MOCVD. Their structural and transport properties have been investigated by various means such as x-ray simple diffraction, SIMS, and Hall measurements. They all confirmed that LP-MOCVD is well adapted to grow multiquantum wells in this new system. GaAs-$Ga_{0.49}In_{0.51}P$ superlattices have been used, in addition, as buffer layers to grow GaAs on silicon substrates.

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