Chemical beam epitaxial growth of extremely high quality InGaAs on InP

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Full widths at half-maximum intensity of the (004) Bragg reflecton peak as small as 24 arcs are obtained from InGaAs epilayers 4–6 μm thick. Such linewidth is the narrowest reported thus far for an InGaAs epilayer grown by any vapor phase technique reported in literature. Such extreme composition uniformity is also supported by results from Auger depth profiles and 2 K photoluminescence measurements. Very intense efficient luminescence peaks due to excitonic transitions with linewidths (FWHM) as narrow as 1.2 meV are obtained. This again represents the narrowest linewidth ever reported for InGaAs grown by any technique. In fact, such a linewidth represents the narrowest linewidth ever measured for any alloy semiconductor. Further, the photoluminescence spectra reveal the donor-to-acceptor pair recombination is nearly absent. This indicates that the InGaAs is of very high purity. Hall measurements of 2–5-μm-thick epilayers grown directly on InP substrates have mobilities of 10 000–12 000 and 40 000–57 000 $cm^2/V\,s$ at 300 and 77 K with $n = 5\times10^{14}$–$5\times10^{15}\,cm^{-3}$. These values are among the highest of all the results for InGaAs grown by other techniques.

Even though chemical beam epitaxy (CBE)[1] combines many advantages of organometallic chemical vapor deposition (OMCVD)[2] and molecular beam epitaxy (MBE),[3] its utilization as a future epitaxial growth technique depends on the quality of the semiconductor epilayers it produces. InGaAs lattice matched to InP has emerged as a very important semiconductor material. High electron mobility and peak velocity are attractive for ultrahigh speed devices. The band gap of 0.75 eV (1.65 μm) is ideal for photodetectors in optical communication systems in the optimum wavelength range of 1.3–1.6 μm. Thus, it is our intention to demonstrate here that very high quality InGaAs can be grown by CBE.

Previously, the growth of InGaAs by CBE[4] has been investigated by using thermally decomposed trimethylarsine (TMAs), which proved to be rather poor in purity. Thus, in the present experiment arsine (AsH_3, 100%, Phoenix) is employed. A low-pressure arsine and phosphine cracker[5,6] with a reduced input pressure of ~200 Torr was maintained on the high-pressure side of an electronic mass flow controller. The cracking temperature was ~920 °C. Complete decomposition of arsine and phosphine into arsenic, phosphorus, and hydrogen was routinely achieved as observed by the absence of arsine and phosphine peaks inside the growth chamber with an *in situ* residual gas analyzer. Triethylgallium (TEGa) maintained at 30 °C and trimethylindium (TMIn) at 37 °C (both from Alpha) were used. Hydrogen was used as a carrier gas for both TEGa and TMIn. The TEGa and TMIn flows were combined to form a single emerging beam impinging line of sight onto the heated substrate surface. This single-beam nature automatically guarantees lateral spatial composition uniformity.[4] In CBE, thermal pyrolysis occurs entirely on the substrate surface. The composition x was obtained by controlling the relative flow rate of the TEGa and TMIn with electronic mass flow controllers. The growth temperature was ~550–600 °C. The growth was typically 3.65 μm/h. Thermally decomposed PH_3 was used to stabilize the InP substrate during the initial heat up to desorb the surface oxides.

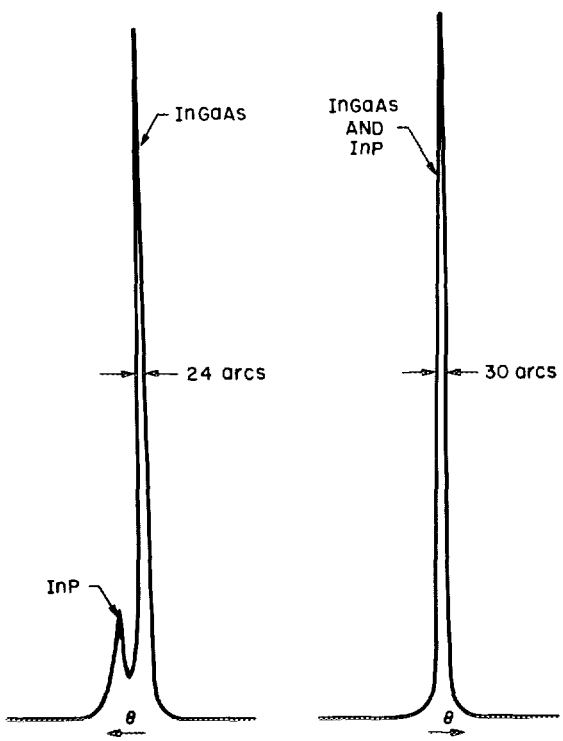

FIG. 1. (a) and (b) show the (004) Bragg reflections of double-crystal x-ray diffraction of two InGaAs epilayers (~6 μm) grown by CBE on InP.

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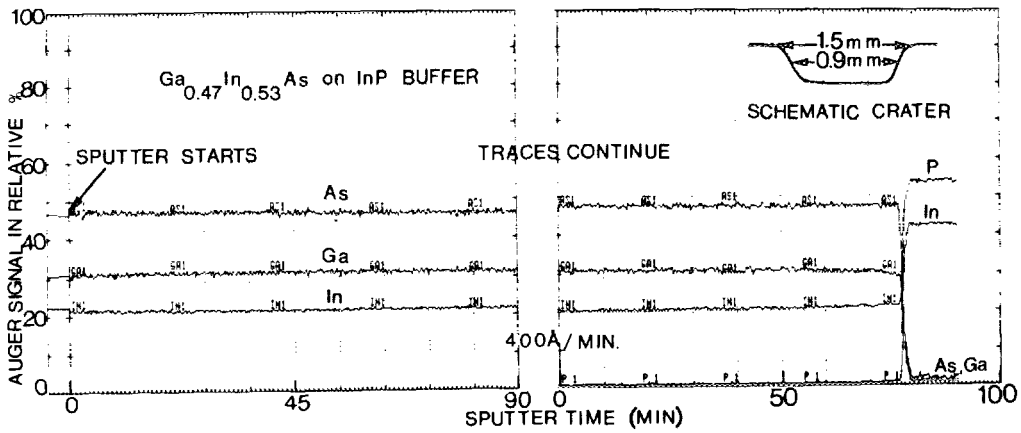

FIG. 2. Example of the raw data of an Auger compositional depth profile of ~6-μm-thick $In_{0.53}Ga_{0.47}As$ epilayer through the $In_{0.53}Ga_{0.47}As$/InP buffer layer interface obtained with a PHI 590 scanning Auger microprobe. The compositional displacement between the left and right figures is graphical. The slight compositional variations near the GaInAs/InP interface are believed to be due to roughness of cracker bottom.

Double-crystal x-ray diffraction was used to evaluate the lattice mismatch and structural perfection of the InGaAs epilayers. High-resolution x-ray diffraction scans of GaInAs/InP samples were performed on a Blake Industry double-crystal diffractometer equipped with an InP monochrometer. The entrance slit was adjusted to eliminate $K\alpha_1$ Cu radiation which achieved sizes of 0.5 mm × 200 μm for the vertical/horizontal directions. Substrates were held in the center of the diffractometer by means of a strain-free magnetic holder. Minor adjustments of the sample position were performed to minimize the rocking curve width at the (004) Bragg reflection. The (004) reflection is illustrated by two examples shown in Fig. 1. The example (6 μm thick) in Fig. 1(a) was chosen because the substrate and the epilayer peaks could be readily distinguished. Hence, their respective linewidths can be measured. The full width at half-maximum (FWHM) intensity ($W_{1/2}$) of the (004) Bragg reflection from the InGaAs is as small as 24 arcs, while that of the InP substrate underneath is ~27 arcs. To the best of our knowledge, such reflection width is the narrowest reported thus far for InGaAs epilayers grown by any vapor phase technique[7–15] that show a single clean structureless (004) Bragg reflection. The fact that both (004) and (002) InGaAs Bragg reflections are narrower than those observed for InP substrate underneath suggests compositional fluctuations are minimal (equivalent to less than one arc). The observed widths for both InP and InGaAs originate from Darwin width, bending, and dispersion contributions. The closely lattice-matched sample (6 μm) in Fig. 1(b) has a total $W_{1/2}$ of ~30 arcs.

Such extreme composition uniformity is also supported by results from Auger depth profiles and low-temperature (~2 K) photoluminescence measurements. Figure 2 shows the raw data of Auger compositional depth profile of ~6-μm-thick $In_{0.53}Ga_{0.47}As$ through the $In_{0.53}Ga_{0.47}As$/InP buffer layer interface obtained with a PHI 590 scanning Au-

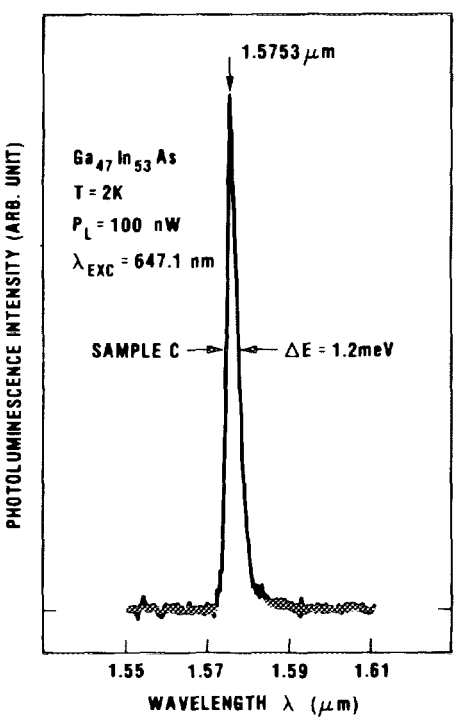

FIG. 3. 2 K photoluminescence spectrum for an epilayer with a thickness of 0.2 μm. Note the absence of the donor-to-acceptor pair recombination peaks.

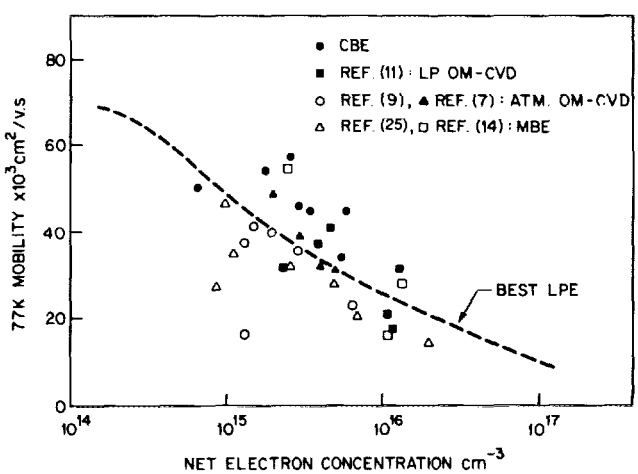

FIG. 4. 77 K Hall mobility vs net electron concentration for closely lattice-matched InGaAs epilayers without two-dimensional electron gas effect (Ref. 11).

ger microprobe. In the figure on the left, the signals before 0 min are the presputter surface composition. Sputtering started at 0 min. The composition at the surface was similar to that in the bulk with our system. The electron beam voltage and ion beam voltage used are 5 and 4 kV, respectively. The sputtering crater size at the top was 1.5×1.5 mm (see inset in Fig. 2). The slight compositional displacement between the left and right figures is graphical. The slight compositional variations near the GaInAs/InP interface are believed to be due to roughness of the crater bottom. It is evident that the composition is extremely uniform and stable throughout the entire thickness and no flux transient was detected. Such uniformity and interface quality are superior to those published in literature grown by OMCVD[16,17] or MBE.[12,18]

Very intense efficient luminescence peaks due to excitonic transitions with linewidths (FWHM) as narrow as 1.2 meV were obtained for $In_{0.53}Ga_{0.47}As$ at 2 K. An example is given in Fig. 3 for an epilayer with a thickness of 0.2 μm. A FWHM of 1.9 meV was measured even for epilayers as thick as 4.0 μm. These FWHM values again represent the narrowest linewidths ever reported for $In_{0.53}Ga_{0.47}As$ grown by any technique. In fact, to the best of our knowledge, the FWHM of 1.2 meV is the narrowest linewidth obtained for any alloy semiconductor.[19–22] Furthermore, the photoluminescence spectra show very little or no indication of donor-to-acceptor pair recombinations. This indicates that the $In_{0.53}Ga_{0.47}As$ is of very high purity. Similar clean spectra were also obtained with some CBE-grown GaAs epilayers.[23]

Hall measurements of 2–5-μm-thick $In_{0.53}Ga_{0.47}As$ epilayers grown directly on InP substrates have mobilities of 10 000–12 000 and 40 000–57 000 cm^2/V s at 300 and 77 K with background net electron concentration $(N_D - N_A) = 5\times 10^{14}$–$5\times 10^{15}$ cm^{-3}. These values are compared with those obtained by both atmospheric and low-pressure OMCVD[7,9–11,24] and MBE[13,14,18,25] results as given in Fig. 4. It is evident that the present results are among the highest of all the results. The dotted curve represents the best reported results from liquid phase epitaxy.[26,27]

In summary, the data suggest that these are the highest quality $In_{0.53}Ga_{0.47}As$ epilayers reported to date grown by any technique.

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