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CHEMICAL BEAM EPITAXY OF III-V SEMICONDUCTOR HETEROSTRUCTURES

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Chemical beam epitaxy (CBE) combines many important advantages of molecular beam epitaxy (MBE) and organometallic chemical vapor deposition (OMCVD). This paper briefly reviews some of the recent progress in the preparation of Ga0.47In0.53As/InP and GaInAsP/InP heterostructures including quantum wells and superlattices, and their device applications.

Introduction - In all kinds of chemical vapor deposition (CVD), because the pressure inside the reactor is typically greater than \(~10^{-2}\) torr and up to atmospheric, the flow of the gaseous reactants is viscous. If however, the pressure is sufficiently reduced (down to \(<10^{-3}\) torr) so that the mean-free paths between molecular collisions become longer than the source in-flet and substrate distance, the gas transport becomes molecular beam. Such thin-film deposition process is called chemical beam deposition or chemical beam epitaxy (CBE) [1] if the thin film is an epitaxial layer. It combines many important advantages of molecular beam epitaxy (MBE) [2] and organo-metallic chemical vapor deposition (OM-CVD) [3].

The system design, growth kinetics, growth conditions have been described previously [1,4,5] and so are their advantages over MBE and OM-CVD [6]. Thus, we shall describe here a summary of the results obtained from the characterization of CBE-grown GaInAsP epilayers, Ga0.47In0.53As/InP quantum wells, superlattices, and heterostructure devices.

Ga0.47In0.53As by CBE - Very high quality GaInAs have been grown by CBE. Full widths at half-maximum intensity of the (004) Bragg reflection peak as small as 24 arc seconds were obtained from GaInAs epilayers 4-6 \(\mu\)m thick. Such linewidth is the narrowest reported thus far for GaInAs epilayer grown by vapor phase technique reported in literature. Such extreme composition uniformity was also supported by results from Auger depth profiles and 2 K photoluminescence (PL) measurements. Very intense efficient luminescence peaks due to excitonic transitions with linewidths (FWHM) as narrow as 1.2 meV were obtained. This again represents the narrowest linewidth ever reported for GaAs grown. 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 was nearly absent. This indicates that the GaInAs is of very high purity. Hall measurements of 2-5 \(\mu\)m thick epilayers grown directly on InP substrates have mobilities of 10,000-12,000 and 40,000-67,000 cm²/V.s at 300 and 77K with \(n\) = \(5 \times 10^{14}-5 \times 10^{15}\) cm⁻³.

GaInAsP Quaternaries by CBE - GaInAsP epilayers closely lattice-matched, \(\Delta a/a < 5 \times 10^{-4}\), have been reproducibly grown over the whole range of composition \((y=2.2x, 1 > y > 0)\) by Chemical beam epitaxy. Figure 1 shows the double-crystal x-ray diffraction spectra for three \(\sim 1.5\) \(\mu\)m bandgap GaInAsP epilayers (\(\sim 1.0 \mu\)m thick) having different amounts of \(\Delta a/a\). Very intense efficient luminescence peaks due to excitonic transitions with linewidths (FWHM) as narrow as 3 meV were obtained. Such a linewidth corresponded closely to the intrinsic linewidth due to alloy scattering in GaInAsP alloys. Further, the photoluminescence spectra revealed that the donor-to-acceptor pair recombination was nearly absent. Hall measurements on GaInAsP epilayers lattice-matched to InP at 300K at 77K yielded electron mobility values that agreed closely with theoretical values calculated by Takeda [7] using the one-LO-phonon model and the Phillips’ electronegativity difference as the alloy scattering potential having residual doping levels between \(1 \times 10^{15}\) cm⁻³ and \(1 \times 10^{16}\) cm⁻³. The 77K electron mobilities ranged from \(2.2 \times 10^{4}\) cm²/V.s to \(6.7 \times 10^{4}\) cm²/V.s depending on the quaternary composition.
Single Quantum Wells - Ga$_{0.47}$In$_{0.53}$As QW's have been prepared by many growth techniques including MOCVD [8-11] chloride transport vapor phase epitaxy (VPE), [12] MBE using solid arsenic and phosphorous sources [13,14] and arsine and phosphine sources [15,16]. Recently, it was shown that GaInAs QW's prepared by CBE are of extremely high quality. The optical emission from these QW's is intense and of narrow linewidth [4]. Figure 2 shows a transmission electron microscopy (TEM) photograph of the cross-sectional view of a stack of single Ga$_{0.47}$In$_{0.53}$As QW's separated by InP down to a thickness of ~6Å. Emission as short as 1.09 μm at 2K (1.14 μm at 300K) was obtained. Very sharp intense luminescence peaks due to excitonic peaks due to excitonic transitions were obtained from all quantum wells. The PL linewidths at 2K were the narrowest that have ever been reported for Ga$_{0.47}$In$_{0.53}$As quantum wells grown by any technique. [8,9,11,12,16] Fig. 3 represents a compilation of PL linewidths (FWHM) as a function of well thickness for the best published Ga$_{0.47}$In$_{0.53}$As/InP quantum wells grown by OM-CVD and MBE together with present results grown by CBE. The dashed curve was calculated broadening due to band-filling from impurities. A sheet carrier density of 2 x 10$^{12}$ cm$^{-2}$ was used. The dotted curve was calculated broadening due to 'effective' interface roughness, $L_{eff}$ of $a_0/2$ assuming finite-height barriers. These linewidths indicate the 'effective' interface roughness to be 0.12 lattice constant, which can be interpreted as that the quantum well was largely consisting of a big domain of the same thickness $L_{eff}$ perforated with small domains of $(L_{eff} + a_0/2)$, where $a_0$ (~5.86Å) is the lattice constant. No broadening due to band filling from impurities was found. Alloy broadening in Ga$_{0.47}$In$_{0.53}$As was limited to the intrinsic value of 1.3 meV [4,5]. Also, for the first time in Ga$_{0.47}$In$_{0.53}$As quantum wells, the measured PL energy upshifts were in excellent agreement with theoretical values.

The extremely small Stark shift between the PL peak and the absorption spectra from a superlattice sample grown under similar conditions as shown in Fig. 4 also confirms that the quantum well is uniform.

For GaAs/Al$_x$Ga$_{1-x}$As single and multiquantum well heterostructures, studies [6] using low temperature photoluminescence and excitation spectroscopy techniques also show that on the average the samples are similar in quality to similar structures grown by MBE and in certain characteristics superior to the MBE ones. For example, unusually sharp excitation peaks have been obtained up to quantum transition levels as high as $E_{3h}$. Further, in some important respects, especially the absence of band-filling due to impurities they are also superior to those grown by OM-CVD [17]. Compared to AlGaAs/GaAs QW's almost no photoluminescence excitation spectroscopy (PLE) has been reported on GaInAs quantum wells although such data could give valuable information on important parameters such as band offsets and relevant electron and hole masses [18]. Taking advantage of the narrow and extremely intense emission of excitons confined to InGaAs quantum wells grown by the CBE technique, PLE [19] spectra were excited by a 100W halogen lamp in conjunction with a 0.3m McPherson grating monochromator at a blaze wavelength of 1.6 μm. The photoluminescence (PL) light was detected at 90 degrees by a 0.6m Jobin-Yvon grating single monochromator with 1.5 μm blaze wavelength. Figure 5 shows the PLE spectra from a seven-layer quantum well structure grown on an InP substrate wafer. All the transition levels can be clearly assigned for the first time demonstrating indeed the excellent quality of the CBE-grown GaInAs/InP QW's.

Superlattices - Ga$_{0.47}$In$_{0.53}$As/InP superlattices were also grown by CBE and characterized by low temperature photoluminescence, room-temperature absorption and photocurrent spectroscopies [20]. Figure 6 shows a cross-sectional TEM of a portion of a 100-period GaInAs (110Å)/InP (130Å) superlattice. The general picture of interface abruptness and smoothness are clearly conveyed. Room-temperature absorption spectroscopy was performed on several samples of different well thicknesses. Figure 7 shows two typical spectra. Not only are the various principal quantum transitions clearly identified, the forbidden $E_{13h}$ transition can also be identified for the first time from absorption spectra.

Photocurrent (PC) measurements were also performed at temperatures as high as 102°C. Spectra from a typical superlattice sample is given in Figure 8. Again, all quantum transitions even $E_{13h}$ and as high as $E_{3h}$ (for the first time in PC) were clearly resolved. In addition to these measurements, low-temperature PL of these superlattices also gave FWHM similar to those of single QW's.

RHEED Intensity Oscillations During CBE - Reflection high-energy diffraction (RHEED) intensity oscillations during the growth of GaAs using triethylgallium in CBE was studied [21]. The oscillation period corresponds exactly to the time required for the growth of one monolayer. RHEED oscillation studies also suggest the absence of flux transients due to switching of gas flows, abrupt and complete initiation and termination of growth with submonolayer resolution, and that CBE is capable of thickness control with submonolayer precision when coupled with the use of in situ RHEED intensity.
monitoring technique as displayed in Fig. 9. These results further support the above results obtained from quantum well and superlattice characterizations. The temperature and flux dependence of growth rates are also studied using RHEED oscillations. Results indicate that CBE growth is predominantly via a two-dimensional layer-by-layer mechanism.

**GaInAs/InP p-i-n Photodiodes** - Mesa-type double-heterostructure InP/GaInAs/InP p-i-n photodiodes have been fabricated from wafers grown by CBE [22]. These devices have exhibited very low dark current, good quantum efficiency of 70% (without anti-reflection coatings) and transit-time-limited pulse response. The lowest dark currents, less than 1 nA at -10 V bias, have been achieved with the double hetero-junction devices in spite of the fact that the p-n junction is coincident with a heterojunction interface. This attests to the excellent quality of hetero-junction interfaces grown by CBE. Such results are among the best p-i-n photodiodes grown by other techniques.

**InP/InGaAsP/InGaAs Avalanche Photodiodes** - High performance InP/InGaAsP/InGaAs avalanche photodiodes (APDs) were grown by CBE. These APDs exhibit low dark current (< 50 nA at 90% of breakdown), good external quantum efficiency (> 90% at λ=1.3 μm), and high avalanche gain (M_0 ~ 40). In the low-gain regime (M_0 ~ 4) the bandwidth is 5.5 to 8.5 GHz. At higher gains a gain-bandwidth-limited response is observed; the gain-bandwidth product is as high as 70 GHz.

**GaAs/AlGaAs and GaInAsP/InP Double-Heterostructure Lasers** - Double heterostructure lasers of GaAs/AlGaAs and GaInAsP/InP, lattice matched to InP and emitting at 155 μm have been grown by CBE [23-25]. Broad-area lasers fabricated from these wafers had pulsed room-temperature threshold current densities J_th and differential quantum efficiencies that are similar to the best results obtained from wafers grown by liquid phase epitaxy and metalorganic chemical vapor deposition. For GaAs/AlGaAs lasers, very low averaged current threshold densities of ~500A/cm² were obtained for wafers with active layer thicknesses of ~500-1000 Å and confinement layers of Al0.5Ga0.5As. Such current threshold densities were similar to those obtained from the best wafers grown by other techniques as shown in Fig. 10. For GaInAsP/InP emitting at 1.5 μm, the lowest J_th obtained was 1 kA/cm² with an active layer thickness of 0.14 μm. Figure 11 shows a comparison of CBE lasers and those grown by MO-CVD and LPE. Differential quantum efficiencies were ~15-18% per facet. Lasing was obtained with these broad-area lasers up to 106°C with relatively weak degradation of quantum efficiency. Excellent device uniformity and wafer-to-wafer reproducibility were obtained with CBE. CBE grown GaInAsP/InP double-heterostructures have also been used in conjunction with liquid phase epitaxial regrowth to fabricate high-performance buried heterostructure lasers operating at a wavelength of 1.5 μm. These lasers show room-temperature threshold currents as low as 12 mA, as shown in Fig. 12, external quantum efficiencies as high as 0.2 mW/mA per facet, and in general linear output power up to ~10 mW/facet. The 3dB bandwidth at optimal biasing is about 8 GHz and is believed to be limited by the heat-sink stud. The intensity noise is low, < -150 dBm/Hz at 1 GHz for bias currents from 50 mA to above 150 mA. Multi-quantum well lasers also demonstrated some improvement in the threshold-temperature dependence.

**Optical Logic Etalon** - All-optical logic etalons operating in the 1.55-μm wavelength region using InGaAs/InP multiple-quantum-well (MQW) structures were also constructed and demonstrated for the first time [26]. These etalons have low energy requirements with several ns recovery times, exhibit high on/off contrast (> 20:1 if desired) with large on-state transmission (>40%), and have signal gain, thus make them possible to cascade. For example, we have performed gating using 6-pJ input energy with 5:1 contrast and gain about 2 at 100 MHz operating frequency. The nonlinear coefficients for the InGaAs/InP MQW deduced from experimental results are found to be on the same order as those for GaAs quantum wells.

**High-Mobility Two-Dimensional Electron Gas at Ga0.47In0.53As/InP Hetero-Interfaces** - Shubnikov-de Haas, quantum Hall effect, and cyclotron resonance measurements revealed the existence of a high mobility, two-dimensional electron gas at the Ga0.47In0.53As/InP heterointerface grown by CBE [27]. Enhanced electron mobilities were as high as ~130 x 10⁶ cm²/V.s at 4.2 K. Shubnikov-De Haas oscillations were observable up to a Landau level filling factor of around 50, corresponding to a Landau level index of 25 indicating that the sample is of high quality.

**Summary** - CBE has been shown to be a very successful epitaxial growth technique for preparing III-V compound semiconductor heterostructures, quantum wells and superlattices. Opto-electronic devices prepared by this technique are of high performance.
REFERENCES

Fig. 1 The double-crystal x-ray diffraction spectra for three ~1.5μm bandgap GaInAsP epilayers (~1.0μm thick) having different amounts of lattice mismatch.

Fig. 2 TEM photograph of a stack of GaInAs quantum wells down to a thin as 6Å.

Fig. 3 PL linewidth versus QW thickness.

Fig. 4 Shows the small Stark shift between PL peak and the absorption peak from a superlattice sample.
Fig. 5 Photoluminescence excitation (PLE) spectra of the multi-layer sample at 2K. Light detection is at the PL energy positions. An area of ~1.5 x 1.5 mm$^2$ is excited. Weak peaks are shown hatched for clarity.

Fig. 6 A cross-sectional TEM of a portion of a 100-period GaInAs (100Å)/InP (130Å) superlattice.

Fig. 7 Two typical room-temperature absorption spectra of CBE-grown superlattices.

Fig. 8 Photocurrent spectra from a typical superlattice.
Fig. 9 (a), (b), (c) several temperatures above 300K are the RHEED oscillations providing direct proof that CBE is capable of initiating and terminating growth with submonolayer (<0.05 monolayer) resolution by switching in and out of TEGa flow.

Fig. 10 Threshold current density versus active layer thickness for GaAs/AlGaAs lasers.

Fig. 11 Threshold current density versus active layer thickness for GaInAsP/InP lasers at 1.5 µm wavelength.

Fig. 12 Light versus dc current for a 1.5 µm DCPBH laser.