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Metalorganic molecular beam epitaxy of 1.3 μm quaternary layers and heterostructure lasers

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Metalorganic molecular beam epitaxy of InGaAsP quaternary layers with the composition corresponding to the band gap at 1.3 μm has been investigated for growth temperatures ranging from 485 °C to 530 °C. From the x-ray diffraction and room temperature photoluminescence measurements Ga incorporation was found to be extremely growth temperature dependent. Photoluminescence linewidths increased rapidly for a negative lattice mismatch exceeding the critical value, whereas for positive mismatch no such broadening was observed. For lattice matched layers linewidths were broader for the higher growth temperatures. Threshold current densities ranging from 0.7 to 2.0 kA/cm^2 were measured for conventional and multi-quantum-well broad area lasers with the active layers based on the 1.3 μm quaternary.

The importance of InP based compounds for electronic, photonic, and optoelectronic devices has been well documented. Epitaxy of these compounds has been achieved by a variety of growth techniques. The gas-source molecular beam epitaxy, (GSMBE) growth methods, hydride source MBE (HSMBE), and metalorganic MBE (MOMBE), have proven to be very successful for the growth of optical and electrical devices.[1–4] Ternary ($In_{1-x}Ga_xAs$) and quaternary ($In_{1-x}Ga_xAs_yP_{1-y}$) materials with mobilities and photoluminescence efficiency comparable to the best material grown by other epitaxy methods have been reported.[5–7]

The quaternary composition having a band-gap energy of 0.95 eV (1.3 μm) is of particular importance for use in optical devices because it coincides with the minimum dispersion wavelength of silica fibers. A recent study of the growth of this quaternary composition by HSMBE has shown an instability in As incorporation as a function of temperature,[8] while a study of its growth by MOMBE indicated an unusually strong dependence of composition on the substrate temperature.[9] In the latter study, the first lasers using 1.3 μm quaternary material grown by any GSMBE method were reported.

In this letter we present data on the growth of 1.3 μm bulk layers and quantum wells on InP by MOMBE. The material quality is demonstrated by the low threshold lasers emitting at 1.3 μm. All of the structures were grown in a VG-V80H MBE system modified for MOMBE growth by the addition of a 2200 l/s turbomolecular pump, a low pressure cracker for the group V elements, and a heated inlet tube at the growth chamber's center port for the metalorganics. The source materials were 100% AsH_3 and PH_3 for the group V elements and triethylgallium (TEG), and trimethylindium (TMI), for the group III elements. For the lasers the dopant elements (Be and Sn) were introduced from conventional effusion sources. No carrier gas was used for any of the sources, and flux control for the major components was achieved in the gas handling system by pressure regulation of the source materials vaporizing under their own vapor pressure. The sample manipulator of the MBE machine was modified to permit temperature measurement with a retractable thermocouple in direct contact with the substrate block. In order to maintain precise temperature control the samples were not rotated during growth.

The growth of single quaternary layers was done on semi-insulating wafers and the laser structures were grown on *n*-type wafers. In all cases growth was on a (100) surface. The substrates were first cleaned with distilled chloroform, acetone, and methanol and given a final etch in 3:1:1 $H_2SO_4H_2O_2$:H_2O before loading into the system. Samples were soldered to Mo sample blocks with In. The native oxide was desorbed at 510 °C with sufficient P_2 flux to prevent decomposition of the InP surface. The growth rates for InP, InGaAs, and quaternary were 1.6 , 1.6, and 1.0 μm/h, respectively.

The ternary and quaternary layers in the samples grown for x-ray and photoluminescence (PL) measurements were 250 nm thick and bounded by InP buffer and cap layers. In Fig. 1 the lattice mismatch $\Delta d_{400}/d_{400}$ is plotted as a function of the growth temperature for the 1.3 μm quaternary and ternary compositions. The x-ray measurements of the in-plane lattice parameter showed little or no mismatch, consistent with the absence of significant relaxation. The quaternary data were obtained for two sets of samples that were grown with different Ga fluxes. The trend was not changed with the Ga flux. The effect of growth temperature on the efficiency at which Ga is incorporated into GaAs and InGaAs when using TEG and TMI in MOMBE has been studied previously.[10,11] A peak in efficiency with which Ga was incorporated into the solid (with the constant source flux) at about 500 °C was attributed to increasing decomposition efficiency of TEG below 500 °C, and to the increasing importance of the evaporation of diethylgallium, an intermediate decomposition product, above 500 °C. Our data for ternary growth in this temperature range, also shown in Fig. 1, are consistent with those studies. The data in Fig. 1 for the 1.3 μm quaternary are significantly different than for the ternary in

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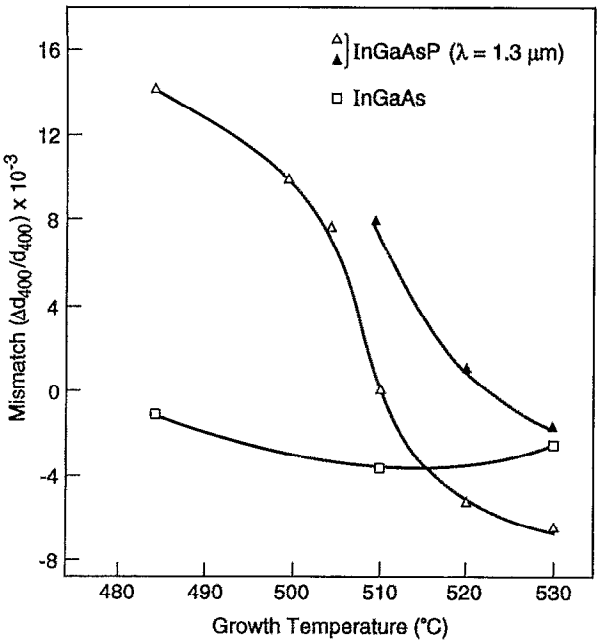

FIG. 1. Lattice mismatch vs growth temperature for InGaAs and InGaAsP ($\lambda = 1.3$ μm). For InGaAsP two different Ga fluxes are plotted, the data represented by the close triangles have a TEG flux 18% lower than that of the open triangles.

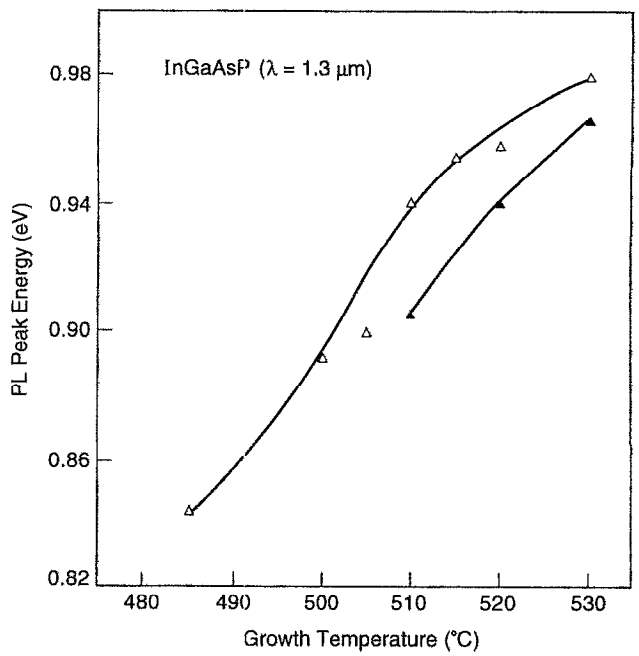

FIG. 2. Photoluminescence peak energy of InGaAsP vs growth temperature. The open and closed triangles correspond to the same data set shown in Fig. 1.

that the lattice mismatch is much more sensitive to growth temperature and does not exhibit a mismatch minimum in the temperature range 485–530 °C. These results are similar to those reported by Benchimol *et al.*[9] who showed that the minimum for the quaternary is close to our highest temperature. At the steepest part of the curve the rate of change in mismatch is $\Delta d_{400}/d_{400} = 0.15\%/°C$.

To determine which element of the quaternary was changing, room temperature PL measurements were done to determine the approximate band gap. These data are plotted in Fig. 2. Taken together with the x-ray data, and the known relationship between the quaternary composition, the band gap, and lattice parameter,[12] the PL results show that the change in composition is due to a change in the efficiency with which Ga is incorporated. We have estimated the flow conditions under which the layers of Figs. 1 and 2 were grown, and find that the efficiency of Ga incorporation is 20% less for the quaternary than the ternary at the lower temperatures and that this efficiency then increases more rapidly with the temperature than for the ternary. These results suggest that the major effect of the addition of P to the solid solution is to change the efficiency, and temperature dependence of the efficiency, with which the decomposition of the TEG is catalyzed by the growing surface. At the higher growth temperatures, >520 °C, we observe that the rate of increase of Ga incorporation is decreasing. This is most likely due to the competing process of desorption of partially decomposed TEG species as is observed in the growth of ternary. The overall effect is to decrease the efficiency of Ga incorporation in InGaAsP as compared to InGaAs at the lower growth temperatures, and to shift the minimum in $\Delta d_{400}/d_{400}$ to higher temperature. Benchimol *et al.*[9] observed the minimum at the 525 °C while in this work we approach it at 530 °C for the runs with lower TEG flux.

The PL linewidth is plotted in Fig. 3 as a function of lattice mismatch for the three growth temperatures, 510 °C, 520 °C, and 530 °C. For negative mismatch (tensile strain) a significant increase in the PL linewidth and decrease in peak intensity was observed. The onset of these effects coincided well with the expected critical value of mismatch.[13,14] However, for positive mismatch (compressive strain), no change in the PL linewidth or intensity was observed for layers with values of mismatch well above the

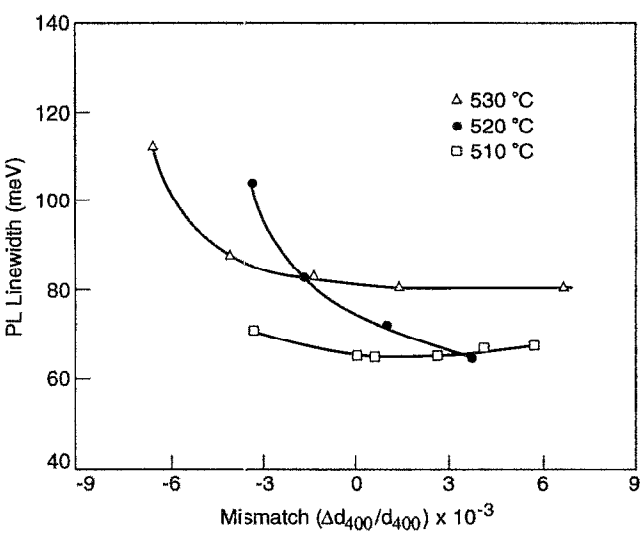

FIG. 3. Photoluminescence linewidth of InGaAsP vs lattice mismatch for growth temperatures of 510 °C, 520 °C, and 530 °C.

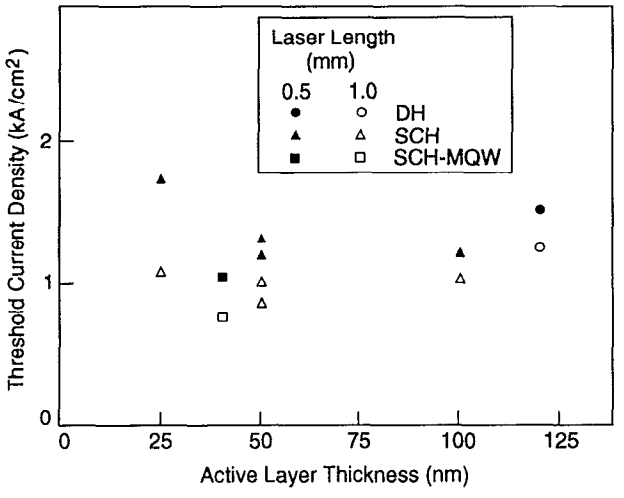

FIG. 4. Threshold current densities vs active layer thickness for DH, SCH, and SCH-MQW lasers.

critical value. Similar effects have been observed for the growth of InGaAs on GaAs where the sign of the mismatch is always positive.[14] Maree *et al.*[15] proposed that the dissociation of 60°-mixed dislocations may lead to a difference in the accommodation of strain for positive and negative mismatch. We have not observed this effect in the growth of ternary quantum wells by HSMBE[16] where the applied strain was close to the critical value. Morphologically we also observe an asymmetry between films with opposite strain. For positive mismatch greater than the critical value smooth layers are still observed, whereas for negative mismatch surface morphology was observed to rapidly degrade as the mismatch was increased above the critical value.

The data of Fig. 3 also show a general increase in PL linewidth as the growth temperature was increased. We speculate that this may be caused by the strong dependence of Ga incorporation on growth temperature, since at higher temperatures the T^4 dependence of the radiated energy from the growing crystal makes the control of the surface temperature more difficult.

To further evaluate the 1.3 μm quaternary material, double heterostructure (DH) and separate confinement heterostructure (SCH) bulk active layer and multi-quantum-well (MQW) lasers were grown using the 1.3 μm quaternary for the active layer. Broad area devices were fabricated with active region dimensions ranging from 0.5–2.0 mm in length and 100 μm in width. Active layer thicknesses were 120 nm for the DH lasers and 25–100 nm for the SCH lasers. The waveguide of the SCH structures used two 75-nm-thick layers of quaternary (1.1 μm composition) incorporated between the active and InP cladding layers. The quantum well lasers contained four wells, each 10 nm thick separated by 25-nm-thick 1.1 μm quaternary barriers, and 75 nm, 1.1 μm quaternary layers between the InP cladding layers and active region. In Fig. 4 we plot the threshold current densities, J_{th}, for all of these laser structures. All of the J_{th} values are the average of randomly selected lasers from a sample wafer. The lowest J_{th} value of 0.7 kA/cm^2 was obtained for a SCH-MQW structure with the cavity length of 1 mm. The J_{th} for conventional SCH structures ranged from 0.9–2.0 kA/cm^2 for the active layer thickness increasing from 25 to 100 nm. A decrease in the threshold current density is expected in the thin active layer SCH structures. For all of the 1.3 μm broad area devices J_{th} reached a minimum for a cavity length of about 1 mm. The values for J_{th} increased rapidly for longer cavities. This is unusual, especially in MQW-SCH lasers in which the internal loss is low and, as a result, lower threshold current densities are expected in longer devices. We interpret this length dependence as the evidence for an extrinsic loss mechanism. Its likely source is the compositional fluctuations associated with the strong growth temperature dependence of Ga incorporation. Nevertheless, the threshold current densities obtained here are similar to the state-of-the-art value reported for 1.55 μm lasers of similar cavity length. Buried heterostructure lasers fabricated from these wafers by MOCVD overgrowth had cw threshold currents as low as 20 mA.

In summary, we report MOMBE growth of high quality bulk and MQW lasers using the 1.3 μm quaternary material in the active layer. A strong growth temperature dependence of Ga incorporation was observed for this quaternary composition in the temperature range of 485 °C–530 °C. This results in a large lattice mismatch dependence on the growth temperature with the resultant variation in the band gap energy, PL efficiency, and the PL linewidth. These effects are not observed in the growth of the ternary layers. Threshold current densities of 0.7–2.0 kA/cm^2 were measured in lattice matched broad area lasers.

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