Growth optimization of molecular beam epitaxy grown InAlAs on InP

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The effects of different molecular beam epitaxy (MBE) growth conditions on material qualities of $In_{0.52}Al_{0.48}As$ on InP were investigated. Investigated parameters were growth temperature and As overpressure. A range of these two parameters within which InAlAs grows under the As-rich condition was first determined by reflection high-energy electron diffraction. Five different InAlAs samples were grown within this range and characterized by double crystal x-ray diffraction, Hall measurement, and photoluminescence. Based on the results of these characterizations, the optimal MBE growth condition for InAlAs was determined.

I. INTRODUCTION

The $In_{0.52}Al_{0.48}As$ ternary lattice matched to InP is of great importance for many electrical and optical devices that utilize semiconductor heterostructures. The material quality of InAlAs, however, still leaves much to be desired. It suffers from the high reactivity of Al with oxygen-containing residual species,[1] and alloy clustering[2,3] presumably due to the large difference in In–As and Al–As bond energies. Consequently, one must take great care to establish a growth condition that minimizes these degrading effects.

In growing InAlAs with a molecular beam epitaxy (MBE) machine that has ultra clean vacuum and high source purity, one has two controllable growth parameters that significantly affect the resulting material quality: substrate temperature and As overpressure. The task is, then, obtaining the optimal combination of these two that gives the best material quality. For this goal, InAlAs samples were grown by MBE with different combinations of growth temperature and As overpressure, and characterized by double crystal x-ray diffraction (DCXRD) measurements for the evaluation of crystalline quality, Hall measurements for electrical quality, and photoluminescence (PL) for optical quality.

II. MBE GROWTH

The MBE machine used in this work is a Riber 2300 equipped with an EPI valved As cracker. With a valved As cracker, As overpressure can be controlled with ease and accuracy, which was essential for our investigation. With the cracking zone kept at 550 °C, only As_4 was used for the present study. For the determination of the upper limit of growth temperature for InAlAs, the transition temperature of InAlAs at which the As-rich surface turns into Group-III-rich was studied first. During growth of InAlAs under given As overpressure, the growth temperature was raised up slowly (20 °C/min) and the pyrometer temperature was recorded when the [110] azimuth reflection high-energy electron diffraction (RHEED) pattern changed from As-rich $2\times$ to group-III-rich $4\times$ streaks. This change is usually abrupt and the transition temperature can be obtained repeatably within a few degrees of accuracy. This process was repeated under a number of different As overpressure values ranging from 5.5×10^{-6} to 1.9×10^{-5} Torr beam equivalent pressure (BEP) as measured by the flux ion gauge. Figure 1 shows the results. The target growth rate was 0.65 μm/h as was for all other InAlAs samples grown for the present study. The pyrometer calibration was done according to the characteristic RHEED pattern change at the congruent sublimation temperature of GaAs, 640 °C, and it was confirmed for each growth by the observation of the characteristic RHEED pattern change from the Fe-doped InP substrate at a chosen As overpressure value before desired InAlAs growth: The transition is observed at 505 °C under As overpressure of 8×10^{-6} BEP Torr. Since As-rich growth surface is usually required for successful InAlAs growth, the region upper bounded by the trace of transition temperature in Fig. 1 is where our interest lies. Within this region, five points were selected as shown in the figure that correspond to five combinations of two different values of As overpressure at 8×10^{-6} and 1.5×10^{-5} Torr BEP, and three different temperatures at 475, 525, and 555 °C. Five 0.65 μm thick InAlAs samples were grown under these conditions on the same day using pieces from the same (001) InP:Fe wafer. The InAlAs layers were intentionally doped with the identical amounts of Si at about 5×10^{16} cm^{-3}, the activation of which depends on growth conditions employed.[4] All the samples were capped with about 100 Å thick undoped $In_{0.53}Ga_{0.47}As$ so that any InAlAs surface oxidation is prevented and the contact resistance for Hall measurement is reduced. In anticipation of enhanced In-desorption at higher growth temperature that may affect our investigation, we grew sample L2, H2, and H3 with 4 degree higher (737 °C) In effusion cell temperature than sample L1 and H1 (733 °C) while keeping the same Al cell temperature of 1042 °C. The surfaces of all resulting samples were mirrorlike with few defects observable under Nomarski microscopy.

III. MATERIAL CHARACTERIZATION

Three different DCXRD measurements were done on three different spots on each sample, and the average values of substrate and InAlAs peak separations and InAlAs peak full-width-at-half-maximum (FWHM) were determined. The details of DCXRD measurement setup can be found elsewhere.[5] Figure 2 shows the amounts of InAlAs lattice mismatches determined from the x-ray peak separations, where the magnitudes of mismatches are no more than

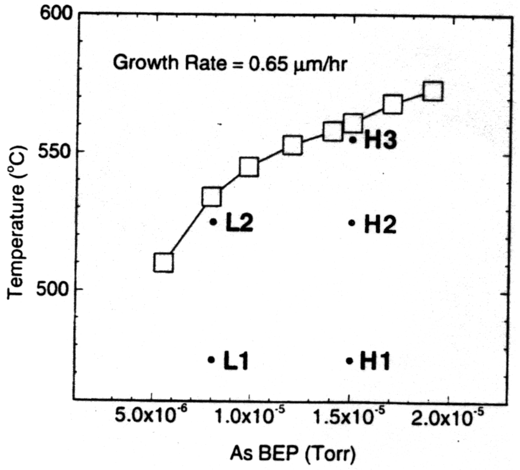

FIG. 1. Dependence of the As-rich to group-III-rich transition temperature on As overpressure. Also shown are five different growth conditions investigated with their IDs that are used in this article.

1.03×10^{-3} (for H3) for all five samples. Also shown in the figure are the values of In cell temperature that would be required for perfectly lattice-matched InAlAs on InP with Al cell temperature at 1042 °C. These values were estimated from the shown mismatch values and the measured In flux activation energy. It can be seen from the figure that As overpressure has little effect on lattice matching for the range investigated here, but higher growth temperature causes enhanced In desorption and requires higher In cell temperature. This has a significant consequence in that one has to control growth temperature as well as effusion cell temperature in order to grow satisfactorily lattice-matched InAlAs on InP.

Figure 3 shows the results of material characterizations performed on different samples: (a) x-ray FWHM, (b) 77 K Hall mobility and electron concentration, and (c) 10 K PL FWHM and integrated intensity. Hall measurements were done on about 0.5×0.5 cm van der Pauw samples with In dot contacts. PL measurements were done for three different spots from each sample, and the average values are show From these, the following observations can be made. Firs InAlAs qualities are better if grown under high As overpressure than low As, as can seen from the better qualities of

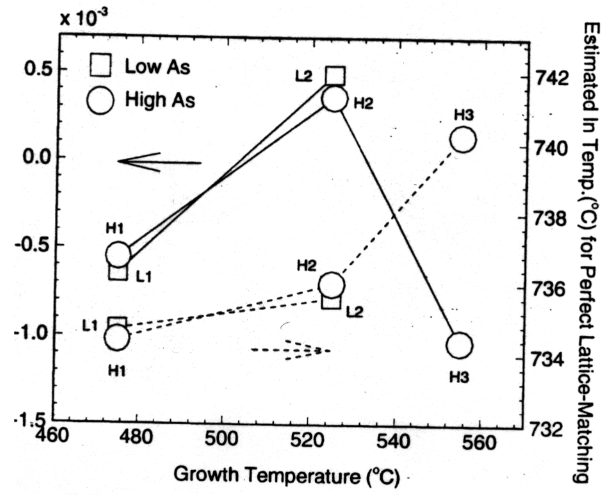

FIG. 2. Lattice mismatches of five samples measured by DCXRD. Also shown are indium cell temperature that would be required for perfectly lattice-matched InAlAs on InP for different growth conditions.

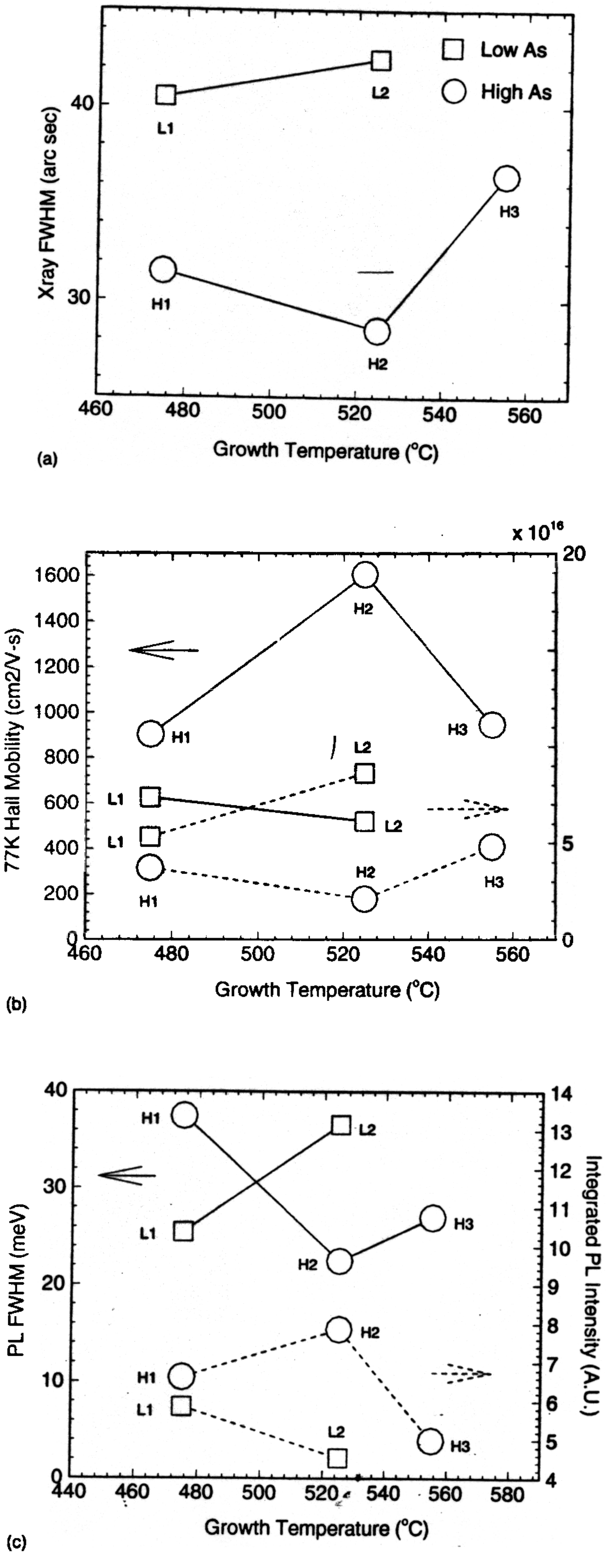

FIG. 3. Results of various material characterizations for InAlAs grown under different conditions: (a) x-ray FWHM, (b) 77 K Hall mobility and electron concentration, and (c) 10 K PL FWHM and integrated intensity.

served for H1 than L1, and H2 than L2. This is believed due to reduced As vacancies and/or reduced alloy clustering at high As overpressure. High As overpressure is expected to reduce alloy clustering since, with the resulting lower surface adatom mobilities, it can reduce the thermodynamically favored phase separation between InAs and AlAs. The only exception to this observation is PL FWHM where H1 has larger FWHM than L1, the cause of which is not presently known. Second, InAlAs qualities are better if grown at high temperature given sufficient As overpressure, as can be seen by comparing qualities of H1 and H2. This is believed due to reduced impurity incorporation at high growth temperature. However, if growth temperature is too high causing a significant amount of As desorption, then the advantage of high growth temperature is offset by the degrading effects of As vacancies and/or enhanced alloy clustering. This can be seen from the poor qualities of H3 and L2. These two observations qualitatively agree with the results of Welch *et al.* who investigated the optical quality of InAlAs grown under different conditions.[6]

It should be noted that the above x-ray FWHM data are considerably better than other reports: For example, that of Tournié *et al.* who obtained x-ray FWHM values comparable to the present work only if InAlAs layers were grown at very high temperature of 600 °C, or on top of a thick InGaAs or a InGaAs/InAlAs superlattice buffer.[7] It is also notable that the electron concentration depends greatly on the growth condition employed. Although the details of this dependence is presently not known, the possible causes are the influence of growth condition on Si activation and the incorporation of donorlike impurities.[4]

As for Hall mobilities and PL FWHM, the best values obtained in this study—Hall mobilities of 1608 and 1016 cm^2/V s at 77 K and room temperature, respectively, and PL FWHM of 17 meV at 10 K obtained with narrower monochrometer slit width than used for data shown in Fig. 3(c)—are respectable, but further improvements are desirable. Consequently, more studies are needed to further reduce alloy clustering and defect incorporation in the growth of InAlAs by MBE.

IV. CONCLUSION

The optimal InAlAs growth conditions has been investigated by growing InAlAs samples under different combinations of growth temperature and As overpressure, and characterized by DCXRD, Hall, and PL measurements. Within the investigated range, growth temperature of 525 °C and As overpressure of 1.5×10^{-5} Torr BEP gave the best InAlAs quality. This condition is believed to provide a sufficient amount of As to the growth surface, and reduces impurity incorporation. In addition, this growth temperature does not severely suffer from In desorption, which makes the task of lattice matching more reliable.

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