TR-O-0090 34

The Growth of High Quality InGaAs Quantum Wells on GaAs(111)A Substrates

Michael Fahy

1996. 1.17

ATR光電波通信研究所

The Growth of High Quality InGaAs quantum wells on GaAs(111)A substrates

Michael Fahy

ATR

Optical and Radio Communications Research Laboratories
2-2 Hikaridai, Seika-cho, Soraku-gun, Kyoto 619-02, Japan

Contents

Acknowledgments

I would like to thank ATR Optical and Radio Communication Laboratories for the opportunity of spending 12 weeks working within the device group. In particular I would like to thank President Hideyuki Inomata for his encouragement and support throughout my stay.

This work could not have been so successful in so short a time without the dedication of my co-workers, in particular Dr. Watanabe, Dr. Fujita, Dr. Takahashi and Dr. Vaccaro. They were always extremely helpful, and we worked well together as a team. All four, but in particular Dr. Fujita, have greatly facilitated my stay at ATR

I should also like to mention some of the other members at ATR for there kindness and help with my many problems. Ohtawara-san for the computing, Takimura-san and Okumura-san for help with many things, Mimura-san, Hirai-san and Hosoda-san for useful discussions, Nozaki-san, Hanba-san and Ueno-san for always smiling despite all the troubles I gave them.

I should also like to thank the staff of ATRI, Kimura-san and Kohshima-san.

Abstract

The ability to grow high quality (InGa)As on the (111)A surface is essential for the production of a wide range of optoelectronic devices, however it has, as yet, received little attention. What work there has been shows it to be highly problematic, reflected in the very broad PL peaks observed for GaAs:InGaAs MQW structures. The origin of this broadening is unclear but is certainly relates to the difficulty in choosing appropriate conditions for the growth III-V's on the (111)A surface. Thus, the poor As sticking coefficient and the subsequent large group III migration lengths on this surface may combine to allow 'alloy clustering' during InGaAs growth, that is the formation of regions of high In composition. This may be expressed alternatively by stating that it is very easy for the (111)A surface to grow group III rich.

We have undertaken a study of the growth of InGaAs on the GaAs(111)A surface with the goal of achieving high quality MQW structures, the test being the ability to obtain narrow PL line widths. The key to this is an understanding of the growth mechanism and using it to predict the conditions to ensure high lateral and vertical uniformity of In composition within the InGaAs well.

We have demonstrated that 80Å 15% InGaAs(111)A single quantum wells with 12K PL peak widths of less than 8meV can be obtained by growth at 400°C under a V:III ratio of 5:1.

Introduction

Heterostructures based on the GaAs:InGaAs system have found widespread application in optical devices. To date these structures have been fabricated almost entirely on the GaAs(001) oriented substrates. More recently there has been great interest in GaAs:InGaAs structures grown on polar surfaces. This has arisen because of certain inherent advantages of devices fabricated on non(001) surfaces Thus Hayakawa found that a {111} oriented quantum well laser structure gave photoluminescence (PL) at room temperature with intensities more than fifty times greater than a similar structure grown on the (001). He speculated that this was due to the enhancement of the heavy hole excitonic transitions relative to the light hole in {111}[1].

However it is the application of the piezo-electric effect that offers the best possibilities for both improved and novel devices. The piezo-electric effect occurs when stresses or strains are applied to a crystal and an electric field is induced. An InGaAs QW in GaAs is an excellent example of such a system. However the piezoelectric effect is highly crystal orientation dependent. The (001) shows no effect and in the (110) it is in the plane of the quantum well. The {111} orientation shows the largest effect where fields as high as 10^6V/m can be induced[2]. The large internal electric field results in a tilting in the band structure as shown in figure 1 and both electrons and holes will experience a shift in energy levels. This is reflected in the PL spectra by a shift in the peak associated with the first confined heavy hole to electron transition towards lower energies. This redshift will increase in magnitude as the strain in the sample, and thus the electric field, is increased. It is also possible to screen out this effect by either applying an electric field to the sample[3] or by photogenerating carriers. [4] This is referred to as the quantum confined stark effect (QCSE).

A further potential application of this system uses the fact that the tilt is the band structure causes the electrons and holes to become spatially separated (figure 2) with the subsequent possibility of producing 2 dimensional electron gases at the heterostructure interface. This has been examined in the form of the piezoelectric field effect transistor, PEFET [5,6] which has the advantage of having a high electron density without modulation doping of the barriers.

The practical application along with a detailed study of the properties of these structures has been greatly limited by the inability to grow high quality structures on most of the non (001) orientations. Good surface morphology, high crystal quality and sharp heterostructure interfaces are clearly essential for device fabrication. These has been some work on the piezoelectric effect in structures on GaAs(110)[7,8], on misoriented GaAs(111)B as well as on the and (211)A [9] and (311)[10]. The growth of similar structures on GaAs(111)A has proved remarkably difficult. Whilst a number of workers have recently demonstrated high quality GaAs growth on GaAs(111)A there have been no similar reports for InGaAs growth. Simple 15%In, 80Å wide InGaAs quantum wells in GaAs(111)A are characterised by very weak, broad red shifted PL peaks[ref]. This has been attributed to relaxation of strain in the QW below critical thickness, poor surface morphology, In segregation and twinning. The use of (111)A substrates mis-oriented by 5° towards the [001] can dramatically improve both crystal quality and PL spectra.[11] but the difficulties have still deterred most workers. The piezoelectric effect is at a maximum in both the (111)A and (111)B directions, yet growth on the (111)A orientation offers some distinct advantages. Si, the commonly used n-type dopant in GaAs, may be used as both the p and n type dopant in the (111)A by appropriate manipulation of the growth conditions. This removes the need to use Be which has the disadvantages of being highly mobile during (and subsequent to) the growth, is difficult to obtain in high purity and is very toxic. In addition it is impossible to grow the preferred normal interface geometry on the (111)B because the field is in the wrong direction for comparatively strained InGaAs quantum wells. This has greatly limited progress in GaAs-based piezo FETs.

In this work we hope to gain an insight into the growth mechanisms of InGaAs on the GaAs(111)A substrate with a view to growing high quality InGaAs quantum wells. We have examined the PL of a series of (111)A samples with the quantum well grown under a range of V:III ratios and substrate temperatures. We have made comparisons with structures grown simultaneously on (001), (111)A, (111)A 1°and 5° off towards [001], (211)A and (311)A. This study is an essential prerequisite to the further development of device structures on the (111)A orientation..

Experimental

All samples were grown using a commercial Varian Gen II solid source MBE machine. Previous work has demonstrated the necessity for careful control of the conditions for growing on non (001) oriented substrates[12]. Great care was thus taken to standardise substrate preparation and growth parameters. The Ga and In fluxes were calibrated using reflection high energy electron diffraction (RHEED) intensity oscillations. The As flux at fluxes below 2Ml/s was measured using As induced intensity oscillations as follows, (figure 3). A flat GaAs(001) substrate, typified by a clear (2x4) RHEED pattern, is obtained by growth of a buffer layer followed by annealing for 30 minutes at 580°C. The substrate temperature is then lowered to 550°C and then Ga is deposited with the As shutter closed. During this time the RHEED specular spot intensity becomes weak as Ga droplets are formed. Often during the initial stages of Ga deposition long oscillations are observed as some of the Ga reacts with background As. It is thus better to deposit the Ga quickly, at 1 or 2 ML/s. After deposition of about 10ML of Ga the Ga shutter is closed and the As shutter opened simultaneously. The Ga droplets on the surface act as an excess Ga source for the GaAs growth which is then limited by only by the As supply. Thus the oscillations observed as the specular intensity recovers represent the supply rate of As. This measurement is only possible at relatively low As fluxes, less than about 2ML/s. Above this the background As reacts with the Ga as it is being deposited and the recovery process is extremely fast. The combination of the two prevents the observation of any As induced oscillations. The measured As flux can then be correlated with the beam monitoring ion gauge measurements for extension to higher As fluxes. The substrate temperature was measured using an optical pyrometer referenced to the GaAs(001) (2x4) - c(4x4) reconstruction (520°C under an As flux of 2Ml/s). A schematic detailing the reconstruction change is given in figure 3.

The native oxide on semi-insulating GaAs substrates with the following orientations, (001), (111)A, (111)A 1°and 5° off towards [001], (211)A and (311)A was removed with H_2SO_4 followed by rinsing for 5 minutes in de-ionised water. The substrates were then etched with NH_4OH:H_2O_2:H_2O (2:1:95) for 80s, rinsed in de-ionised water and then blown dry with N_2. The samples were then mounted into a specially designed 6 sample molybdenum substrate holder without the use of In and immediately loaded into the MBE machine. After outgassing at 300°C for 1 hour the substrate was transferred to the growth chamber where the oxide was removed by heating at 650°C for 5 minutes under As_4 flux of $3.2x10^{15}$molecules s^{-1} cm^{-2} The substrate was then cooled to 580°C and a 2000Å GaAs buffer layer grown prior to the growth of the quantum well structure. The buffer was grown at 1ml/s with a V:III ratio of 10:1. These conditions have been established to give high quality GaAs on all the orientations studied.

The structure of the quantum well used throughout this study is given in figure 5. The In composition was fixed at 15% and the well thickness to 80Å in all samples, values chosen to produce a well on the (001) orientation that is far below the critical thickness. This should ensure the quantum well layer is biaxially compressed to match the GaAs substrate. In fact, theoretical studies using a model proposed by Matthews and Blacksee suggest that the critical thickness for layers grown on the {111} orientation should be some 30% larger [13]. We chose to grow the well with substrate temperatures of 400, 440, 480 and 520°C under V:III ratios of either 2:1, 5:1 and 10:1, giving a total of 12 growth conditions. To give time to stabilise the conditions prior to growth of the quantum well and to remove the need for an interrupt the temperature was lowered during deposition of 500Å of GaAs. At this point the As_4 flux was changed if necessary and the conditions allowed to stabilise during deposition of a further 500Å of GaAs. The As_4 flux could be changed rapidly by switching between 2 As cells. Subsequent to the quantum well growth 100Å of GaAs was deposited before the growth temperature was increased back to 580°C to grow the top GaAs layer. This was to minimise segregation of the In from the quantum well.

Photoluminescence measurements were typically performed at 12k using an Ar^+ laser, a monochrometer and an InGaAs photomultiplier as the detector. The laser intensity was set at 15mW unless otherwise stated. Transmission electron micrographs were obtained using a 200KeV JEOL 2000FX, with samples being thinned using conventional methods.

Results and Discussion:

a) Surface Morphology

In all samples a 2000Å buffer layer was grown at a substrate temperature of 580°C and a V:III ratio of 10:1. These conditions are well known to produce GaAs with good surface morphology on all of the substrate orientations studied[14]. The surface morphology observed in our samples can thus be attributed almost entirely to the InGaAs layer and its effect on the subsequent GaAs.

The layers grown on GaAs(001) and (211)A were flat under all growth conditions. The (311)A was also flat under most growth conditions, the exception being the layer grown at 400°C under a V:III ratio of 10:1. This sample showed small rings of pyramids surrounding flat regions. This pattern of rings is similar to that observed in a dislocation etch of the substrate. It may be therefore that in this case the morphology is not representative of the growth process, but related to a problem with the etching of that particular sample.

Normaski interference micrographs of the (111)A oriented samples grown at 400°C and 520°C are given in figure 6. There is a clear pattern, with high V:III ratios and low temperatures giving better surface morphology with the growth at 520°C with a V:III ratio of 2:1 is being highly faceted. This trend is typical of that observed in GaAs on GaAs(111)A growth[15], but with the optimum growth conditions being shifted to lower temperatures or higher V:III ratios by the inclusion of In.

Earlier work on the (111)B[16] suggests that misorientating the [111] surface can dramatically improve surface morphology. Yet, in this work, tilting the (111)A by 1° towards the (001) made little improvement to the morphology. worse. However, increasing the mis-orientation to 5° produced a dramatic improvement in morphology, with flat surfaces being obtained under all the growth conditions studied. A 5° mis-orientation induces a significant change in the character of the surface yet a small mis-orientation of the surface, in order to promote growth from the step edge, does not seem to be enough to greatly improve the quality of the growth. In view of the excellent morphology of the structures grown on 5° misoriented (111)A substrates the question arises as to why it is important to continue the work on the singular surface. The small mis-orientation will cause only a small decrease in the piezoelectric coefficient. However, mis-orientation has a profound effect on the incorporation behavior of Si. In contrast to the singular surface where Si can be easily used as a p or n type dopant, it is difficult to obtain p type GaAs with Si on (111)A substrates mis-oriented by 5°. Hence the study of just the mis-oriented surface will remove on of the main justifications for studying the A surface. However, in the context of this work the 5° off sample does provide a useful reference sample for the PL measurements.

2) Photoluminescence

In order to check the growth uniformity over the full area of the substrate holder, a 15% 80Å single InGaAs quantum well on GaAs(001) was grown under optimum growth conditions (520°C at V:III = 5:1). A GaAs(001) sample was mounted in each of the six positions in the substrate holder. The 12K PL spectra was measured as a function of position on the each of the samples. In all cases a bright, narrow peak was observed. The peak position is plotted as a function of distance from the centre of the substrate holder in Figure 7. Despite the use of rotation during the growth there is a clear radical distribution of the flux about the centre of the substrate holder. Assuming a well of 80Å the In content in the well was calculated and this is also shown in figure 7. In all subsequent PL measurements a position on each sample that was 20mm away from the centre of the Mo block was used. This corresponded to a well containing 15% In. By taking these precautions we can expect a reproducibility when comparing samples within a growth run to be better than a few meV. This allows us to be confident that our observations are real and not simply an artifact of the MBE growth process.

Figure 8 shows the 12K PL spectra for the 15%, 80Å single InGaAs quantum wells grown on each of the substrate orientations at growth temperatures of 400, 440, 480 and 520°C under a V:III ratio of 2:1. Figures 9 and 10 give similar data for samples grown at V:III ratios of 5:1 and 10: respectively. The numbers on intensity axis, whilst not absolute, give a good indication of the relative intensities involved from sample to sample and growth run to growth run. The peak position, full width at half maximum and peak intensity are summarised in figures 11-13. Some general comments can be made. As has been reported by many others[17] luminescence intensity is greatly improved by increasing the growth temperature. This has been attributed to the poor crystalline quality obtained at low growth temperatures and hence the introduction of large numbers of non radiative recombination centres in the material. In this particular sample set we need to consider two effects, the quality of the quantum well itself and secondly the quality of the GaAs cladding layer either side of the quantum well, which is grown under far from optimum conditions.

(i) GaAs (001)

The 12K PL peak position from the SQWs grown on GaAs(001) is relatively independent of growth temperature at V:III ratios of 5:1 and 10:1. However, at the V:III ratio of 2:1 there is a small blue shift in the peak position as the growth temperature is increased. This can be accounted for by desorbtion of some 3-4% of the supplied In at 520°C and somewhat less at 480°C. It has been previously noted that In desorbtion is reduced by increased V:III ratio during the growth[18] and hence we observe only very small loss of In in the layers grown at V:III ratios of 5:1 and 10:1

The peak luminescence intensity is high for all the samples grown at 520°C, decreasing slightly for the samples grown at higher V:III ratios. The peak intensity falls dramatically as the growth temperature is lowered to 480°C and below, probably due to the poor crystalline quality of the GaAs in the layers either side of the quantum well. These cladding layers are grown under conditions far from optimum for high quality GaAs(001) which is typically 580°C under a V:III of 2:1. It has been demonstrated by previous workers that luminescence from GaAs grown at low temperatures and high V:III ratios is very weak[19], mainly due to defects related to excess As incorporated during the growth. In contrast InGaAs is expected to be much less sensitive to reductions in the growth temperature.

The PL peak width, of between 3 and 4meV, are typical for this kind of structure. This indicates that quantum wells are of good quality and that the MBE machine is capable of generating high quality material.

(ii) GaAs(311)A

The SQWs grown on GaAs(311)A have PL spectra broadly similar to those grown observed in GaAs(001). The wells grown at 520°C have peak intensities similar to those obtained on the (001), but with a slightly larger full width at half maximum, FWHM. As the growth temperature is lowered to 480°C and below the PL peak intensity is dramatically reduced. However, this fall is not as severe as that seen in the SQWs grown on the (001) samples with the wells grown at 400°C being significantly brighter. The FWHM is typically 4-5meV for the wells grown at 520 and 480°C increasing to 10-12meV in the layers grown at 440°C and decreasing again as the growth temperature is lowered to 400°C. This trend is observed at all V:III ratios. with the increase in FWHM at 440°C being accentuated as the V:III ratio is increased. The origin of this increase is unclear. However, in general broadening can be ascribed to inhomogenities in the QW such as thickness and composition variations or interface roughness. We could speculate that at low growth temperatures the wells are uniform, but have rough interfaces. The surface mobility of the group III atoms is lowered when the V:III ratio is increased and this is likely to exacerbate the interface roughness. However, at very low temperatures the growth becomes a well defined layer by layer process and hence the interfaces start to become smooth again.

Under all growth conditions the PL peak position of the (311)A samples are close to that from the (001). Theoretical studies predict that that for a 15%In, 80Å QW the piezoelectric field should be 60KV cm^{-1}, equivalent to a red-shift in the PL peak of approximately 4meV with respect to the (001). However, earlier work by Vaccaro et al[20] on more highly strained systems showed red shifts of 3meV, some 30% lower than predicted. The difference between the theory and experiential observation was attributed to a space charge of $7x10^{-5}C\ m^{-2}$ at the heterostructure interface. This produces an electric field which acts in the opposite direction to the piezoelectric induced field, thus reducing the tilt in the band structure. A similar space charge in our samples would in significantly lower any piezoelectric induced fields, and thus reduce any red shift of the PL peak below the limits of experimental error. Strain relaxation, which would also reduce the observed red shift should be negligible for this In composition and well thickness. In addition the lowering of the exciton binding energy due to the electric field should be much less than 1meV[21].

It is clear that the (311)A oriented substrates may provides a good alternative substrate to the (001) with the PL peak intensity and FWHM are much less sensitive to the exact growth conditions. The reason for this is likely to be found in the growth mechanism. Many workers have speculated that the weak PL in (001) based QWs grown at low temperatures is the inclusion of excess As. The nature of the (311)A surface, with its large number of single dangling bonds will make it more difficult for excess As to be incorporated. This is reflected in the ability of the (311)A to incorporate Si on both As and Ga sites in contrast to the (001) where the As terminated surface only allows incorporation on Ga sites. This is also consistent with the low incorporation coefficient of As observed on other (n11)A surfaces[22].

(iii) (211)A.

Much of the preceding discussion about the SQWs produced on the (311)A is also applicable to the (211)A. The peak intensities are broadly similar, although those from the (211)A are slightly weaker at the lowest growth temperatures. There is a steady increase in the FWHM as the growth temperature is lowered, with the layers grown at 400°C being about 15meV broad. The improvement in the FWHM at 400°C seen on the (311)A samples was not observed. This may be attributed to the much lower step density on the (211)A which may make it more difficult to get flat interfaces at low temperatures.

The PL peak positions of the wells grown with V:III ratios of 5 and 10 show red shifts of 7-8meV with respect to the (001). We can attribute this to the piezoelectric effect. If we assume that there is a similar space charge at the heterostructure interface as in the (311)A sample we can then estimate a piezoelectric field of about 120KV cm^{-1}. This is close to the theoretically predicted value. The wells grown at the lowest V:III ratios have a similar PL peak position to both the (311)A and (001). There are two possible explanations for this, both of which rely on the low V:III ratio distorting the growth of the well. If the As flux is to low to grow good smooth InGaAs there will be some In segregation. This may produce in turn give rise extra defects at the top of the well and hence a larger space charge at the heterostructure interface than in the samples grown at higher V:III ratios. However, it seems unlikely that such the charge at the interfaces could be changed in this way. A more plausible explanation is that the segregation of the In under these growth conditions is large enough to smear out the strain induced electric field over a greater distance. This lowers the tilt in the band structure and hence reduces the red shift of the PL peak position. This explanation is supported by the examination of the (211)A SQWs grown at 400°C where we would expect In segregation to be negligible. The PL peak position is then in approximately the same place as observed in the SQWs grown at higher V:III ratios. It should be emphasised at this point that it there is some uncertainty within the data. This can be attributed to the difficulties of exactly reproducing growth conditions and in particular in controlling the growth temperature at the lower temperatures and the As flux at low V:III ratios.

(iv) Mis-oriented (111)A

The (111)A samples misoriented by 5° to the (001) show PL peak intensities that are much lower than the equivalent (100) for samples grown at 520°C, but slightly better for those grown at lower temperatures. The SQWs on the (111)A misoriented by 1° to the (001) gave weak luminescence under all growth conditions. The FWHM of the peaks from the 5° off samples grown with a V:III ratio of 2:1 are between 15 and 20meV, decreasing as the growth temperature is lowered. The peaks from the 1° off sample are much broader, 40-50meV. Increasing the V:III ratio improves the FWHM for both sets of samples at all growth temperatures. The FWHM from SQWs grown on the 1° off surface decreases dramatically as the growth temperature is lowered but the intensity is however, very low.

The PL peak position for the 5° off sample grown at V:III of 2:1 is at 1.387eV and falls to 1.36 for SQWs grown at lower temperatures. The value of 1.36 is consistently obtained from the SQWs grown at higher V:III ratios under all growth temperatures and may thus be considered to be the real peak position if there are no distortions induced by the growth conditions. This value of 1.36 is also observed from the 1° off samples grown at low temperatures and high V:III ratios. The mis-orientation of the samples has little effect on the magnitude of the piezoelectric field and hence we can ascribe the red shift of 35meV with respect to the peak position in the (001) to the piezoelectric effect. This data fits well with the red shifts observed by Vaccaro et al [23] for similar structures grown on (111)A misoriented by 5° to the (001) which were fitted to a piezoelectric coefficient of 150KVcm^{-1}. This value is again some 30% lower than that expected from theory (230KVcm^{-1}) however, as with the (211)A and (311)A structures we can ascribe this to a charge layer at the heterostructure interface. The small redshift obtained from the sample grown under low V:III ratios can be explained in a similar way to the same observations on the(211)A. That is that the limited amounts of As at the higher growth temperatures allows In segregation and the subsequent smearing of the piezoelectric field over a much wider well.

(iv) Singular (111)A

SQWs grown on singular GaAs(111)A give weak luminescence for all growth conditions. Reducing the growth temperature further reduces the PL peak intensity. The SQWs grown under a V:III ratio of 2:1 are very broad, with FWHMs up to 100meV. Increasing the V:III ratio narrows the FWHM for all the (111)A samples at all growth temperature. The FWHM value of 6meV obtained for the SQW grown at 400°C under a V:III ratio of 5:1 is by far the lowest ever reported for this system. The intensity however is very low.

It is only for growth under low temperatures and high V:III ratios that a PL peak position of 1.36eV, consistent with the 5° misoriented sample, is obtained. The position of the peak agrees well with previous work and suggests that under these growth conditions a true 15% 80Å InGaAs quantum well has been obtained. As mentioned for the 5° off sample this result is consistent with the work of Vaccaro et al [24] and a piezoelectric coefficient of 150KVcm^{-1}. At higher growth temperatures and/or lower V:III ratio the peaks are further red shifted, to around 1.32eV, as observed by previous workers.

At this point is useful to speculate on the origin of this extra red shift. At high growth temperatures and low V:III ratios the In will be highly mobile on the growing surface, and may easily form small In rich clusters in a manner analogous to the formation of the InAs dot structures observed by Ploog at al.[25]. The possibility of alloy clustering has also been raised by Singh et al.[26] The high In composition in the clusters will strongly redshift the PL peak. A local increase in the In concentration of the InGaAs from 15% to 25% would be more than enough to account for the biggest observed shift (100meV). Further, as there will be a distribution of cluster sizes and In compositions there will be a wide range of PL transitions and hence very broad PL peaks.. In all the SQWs the extra red shift is reduced as the growth temperature is lowered. This fits well with our model, with the lower substrate temperature lowering the In migration lengths and hence reducing the amount of In entering the clusters.

The regions surrounding the cluster will also be comprised of InGaAs, but with a reduced In content. The PL peak from these areas are not observed in the PL spectra as the exciton will tend to be trapped in the deepest parts of the well - i.e. in the regions associated with the In clusters. Increasing the temperature of the PL measurement should allow the excitons to move away from the deepest areas of the well and sample shallower regions. This is typically observed by the appearance of new peaks in the PL spectra, or more often by changes in relative peak intensities. Examination of the strongly red shifted peak in the sample grown at 520°C under a V:III of 2:1 showed only a decrease in the peak intensity as the PL measurement temperature was increased to 70K (figure 14). The laser intensity was increased from the previous 15mW to 150mW for these measurements to give the maximum possible signal. No new peaks appeared. This is not unreasonable given that the observed peak is almost 100meV shifted from the expected well position of approximately 1.36eV. To supply enough energy to remove the exciton from the cluster would thus need a PL measurement temperature of more than 1000K. The results do show, however, that there is a clearly defined 'defect' from which the luminescence is derived. A similar study was made on the sample grown at 400°C under a V:III of 2:1 (figure 15). The sample showed two distinct peaks, at 1.36 and 1.33eV, with a strong shoulder on the low energy side of the latter peak. As the measurement temperature is increased the intensity of the low energy peaks falls with respect to the peak at 1.36eV until at 90K both peaks have approximately equal intensity. Unfortunately the weakness of the signal at this point did not permit higher temperatures to be studied. In this case the PL peak is only red shifted 30meV increasing the measurement temperature to 90K will allow some of the excitons to escape from the cluster and sample the surrounding well. This supports our proposition that the InGaAs forms a SQW with strong variations in In content within it and that at low PL measurement temperatures we can only observe the deep well.

The piezoelectric effect in a quantum well may be screened by carriers inside the well. These carriers may be generated by the optical excitation of electron hole pairs by the PL laser. This would be manifested by a reduction in the piezoelectric induced red shift of the PL peak as the excitation intensity is increased. To obtain more information about the (111)A quantum wells the PL spectra for each sample was studied as a function of the PL laser intensity. These results are given as function of growth temperature in figures 16, 17 and 18 for V:III ratios of 2:1, 5:1 and 10:1 respectively. Screening of the piezoelectric field can only be clearly observed in the (111)A sample grown at 520°C under high V:III ratios. There is a clear blue shift in the peak as the laser intensity is increased. This is clear evidence that the observed luminescence is not from a growth related defect such as excess As, but from a strained quantum well. However, the very large initial red shift of the PL peak along with its 50meV FWHM suggest the well is not uniform but contains regions with high In content as discussed above. Small blue shifts can also be seen in the SQWs grown at 480°C, 5:1 and 10:1 and 440°C, 10:1.

The samples which have the narrowest peaks at the expected value of 1.36eV show no shift as the laser intensity is increased. This was contrary to initial expectations. However, the luminescence intensity from these samples is very low, suggesting that the carrier recombination is very fast. It is thus impossible to build up a significant concentration of carriers to screen the piezoelectric field. The very fast recombination times have been demonstrated in preliminary time resolved photoluminescence measurements.

(v) Transmission Electron Microscopy

The PL study of this system suggests that at all but the lowest growth temperatures and highest V:III ratios In has a propensity to accumulate. Transmission electron microscopy was performed to further examine this. TEM is not very sensitive to In composition changes, so we studied only the two extreme cases. That is the sample with the widest, most red shifted peak (T=520°C, V:III=2:1) and that with the narrowest, unshifted peak (T=400°C, V:III=5:1). In both cases TEM of a similar structures grown on the (001) shows a uniform clearly defined well (figure 19a). Figures 19b shows a TEM from the SQW grown at 400C and V:III=5:1. The top half of the picture is from an unrelated sample and should be ignored. There is a clear well defined continuous dark stripe associated with the quantum well at the expected distance below the surface. Figure 19c shows the same sample using a higher magnification.. The quantum well itself is very flat, showing that the GaAs(111)A grows well under the conditions used in the barriers. The origins of the surface roughness must therefore be the InGaAs layer. A number of twins can also be observed, reflecting the difficulty of growing high quality GaAs on this orientation. They are frequently observed in MBE grown GaAs(111)A. Figure 19d and e are from the SQW grown at 520°C with a V:III of 2:1. The well is not longer uniform instead appearing as a series of lumps with regions in between containing little or no In. This accumulation of In agrees well with our model.

(vi) PL from a three well sample

The optimum growth conditions of 400°C and V:III =5:1 were used to grow a three quantum well sample. The wells contained 15% InGaAs and were 30, 50 and 80Å thick. The wells were separated by 500Å of GaAs. The 12K PL spectra from all of the samples was very weak, probably due to the growth of the GaAs barriers. The spectra from the (001) sample was below the background noise level. However, the (311)A, which we showed earlier gives very similar peak positions to the (001), but with higher intensity, was suitable as a reference . The spectra for the three quantum well (311)A and (111)A samples are given in figure 20. In the (311)A sample the 30, 50 and 80Å peaks can be seen at 1.451, 1.42 and 1.393eV respectively. The corresponding peaks in the (111)A are at 1.437, 1.401 and 1.36eV. The peak position and red shift associated with the piezoelectric effect in the (111)A sample agrees well for the 80Å thick QW measurements discussed above. The red shift from the narrowest quantum well is somewhat larger than expected. This may be because the peak is extremely weak and thus very difficult to accurately position. In addition we would expect the 30Å well to be the brightest as it nearest to the surface, as is the case with the (311)A. The reason for the general increase in peak intensity in the (111)A samples is unclear and needs further work.

Proposal for Future Work

This work has clearly demonstrated that InGaAs quantum wells with PL having narrow FWHM are only achieved under very severe conditions of high V:III ratio and low growth temperature. However these conditions are far from suitable for the growth of the GaAs layers either side of the InGaAs well and this is what leads to the very low intensity of the luminescence peaks. A full study is therefore needed to examine how to improve the quality of the GaAs growth without compromising the quality the InGaAs. There are a number of possibilities;

(i) The use of growth interrupts at either, or both, heterointerfaces. This has the drawback of higher impurity incorporation and, at the inverted interface, increased opportunity for the In to move around.

(ii) More subtle grading of the growth conditions between the GaAs and InGaAs to allow the growth conditions to be changed in a shorter time, but without an interrupt. However, this becomes very complicated when used to grow MQW structures.

(iii) Increasing the InGaAs growth rate. This will reduce the mobility of the In and hence may allow the use of higher growth temperatures.

(iv) The use of As2 as the As species. It has been reported that As2 is very effective at reducing In migration.

(v) The use of Al in both the well and barrier may help to reduce the In migration length.

Once the optimum growing conditions have been determined then we will at last have the ability to grow structures to begin to explore the multitude of novel device that can be produced on this orientation.

Conclusion

We have grown 80A, 15% InGaAs quantum wells on GaAs(111)A substrates with a FWHM of less than 7meV. This is vastly superior to the best previously reported. We have shown that to obtain such narrow peaks it is necessary to grow the well at low temperatures and high V:III ratios. The luminescence intensity is weak under these conditions, probably due to defects in the GaAs in the layers adjacent the quantum well, which were grown under highly unsuitable conditions. It should be possible to change the growth conditions to optimise the quality of the cladding layers without deteriorating the quality of the well.

The origin of the broadening and large red shifts in InGaAs(111)A QWs observed by previous workers and in the samples in this work grown at higher temperatures and low V:III ratios has been attributed to accumulation of In. This is a particular problem on the (111)A surface because of the long In migration length.

References

[1] T. Hayakawa, M. Kondo, T. Suyama, K. Takahashi, S. Yamamoto and T. Hijikata, Jpn. J. Appl. Phys. 26, (1987) L302

[2] D. L. Smith and C. Mailhiot, J. Appl. Phys. 63(8), 1988, 2717

3 J.L. Sanchez Rojas, A. Sacedon, F. Gonzalez, E. Calleja and E. Munoz, Appl. Phys. Lett. 65(16) (1994) 2042

4 P.J. Rodriguez and G.J. Rees, IEEE Photonics Tech. Lett. 7(1) (1995) 71.

[5] S.S. Lu and C.L. Huang, Elect. Lett. 30(10) (1994) 823

[6] E.S. Snow, B.V. Shanabrook and D. Gammon, Appl. Phys. Lett, 56(8) (1990) 758.

7 D. Sun, IEEE Journal of Quantum Elect., 30(3) (1994) 466.

[8] M. Iig, K.H. Ploog and A. Trampert, Phys. Rev. B 50 (1994) 17111.

[9] I. Sela, D.E. Watkins, B.K. Laurich, D.L. Smith, S. Subbanna and H. Kroemer, Appl. Phys. Lett 58(7) (1991) 684

[10] O. Brandt, K. Kanamoto, Y. Tokuda, N. Tsukada, O. Wada and J. Tanuimura, Phys Rev B, 48 (1993) 17599

[11] K. Kobayashi, T. Takabe, T. Yamamoto, M. Fujii, M. Inai and D. Lovell, J. Electon. Mater. 22 (1993) 161

[12] T. Yamamoto, M. Inai, T. Takebe and T. Watanabe, J. Vac. Sci and Tech., 11 (1993) 631. K. Sato, M.R. Fahy and B.A.Joyce, Jpn. J. Appl. Phys. 33 (1994) L905.

[13] J.W. Matthews and A.E. Blacksee, J. Cryst. Growth 111, (1991) 407.

[14] M.R. fahy, K. Sato and B.A. Joyce, Appl. Phys. Lett., 64(2) (1994) 190.

[15] K. Sato, M.R. Fahy and B.A. Joyce, Jpn. J. Appl. Phys., 33 (1994) L905

[16] K. Yang, L.J. Schowalter, B.K. Laurich, I.H. Campell and D.L. Smith, J. Vac. Sci. technol., B 11(3) (1993) 779.

[17] K. Muraki, S. Fukatsu, Y. Shiraki and R. Ito, Appl. Phys. Lett., 61(5) (1992) 557

[18] D.C. Radulescu, W.J.Schaff, L.F.Eastman, J.M.BAllingall, G.O.RAmseyer and S.D.Hersee, J. Vac. Sci Tech. B 7(1), (1989) 111.

[19] M. Kaminska, E.R. Weber, Z.Lilental-Weber, R. Leon and Z.U. rek, J. Vac. Sci. Tech. B7 (1989) 710

[20] P. Vaccaro, ATR technical report, TR -O-0085, 1995

[21] G. Bastard: Wave Mechanics Applied to Semiconductor Heterostructures (Halsted Press, New York, 1988) Chapter 8.

[22] K. Sato, M.R. Fahy and B.A. Joyce, Jpn. J. Appl. Phys., 33 (1994) L905

[23] P. Vaccaro, M. Takahashi, K. Fujita and T. Watanabe, J. Appl. Phys. 76(12) (1994) 8037

[24] P. Vaccaro, M. Takahashi, K. Fujita and T. Watanabe, J. Appl. Phys. 76(12) (1994) 8037

[25] R. Notzel, L. Daweritz and K. Ploog, J. Cryst. Growth, 127 (1993) 858

[26] J. Singh, S. Dudley, B. Davies and K. Bajaj, J. Appl. Phys., 60 (1986) 3167

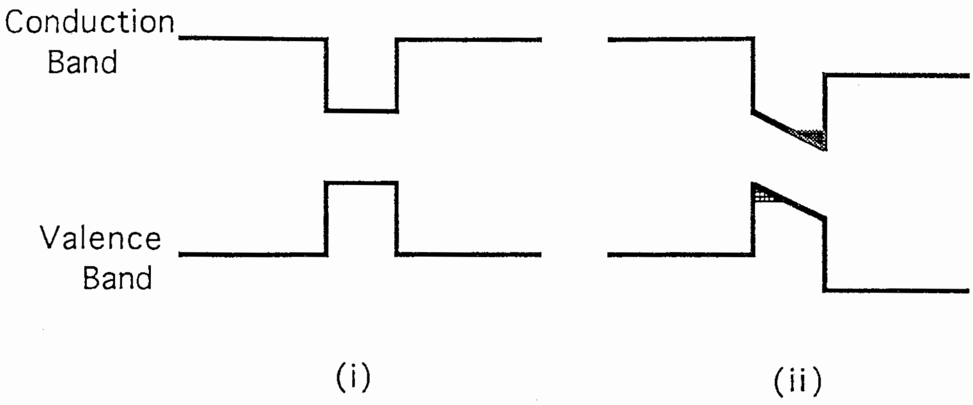


Figure 1: A simplified band structure of an InGaAs quantum well in GaAs, with (i) and without (ii) the piezo-electric effect. The energy levels of both the holes and electrons are changed and they are spacially separated.

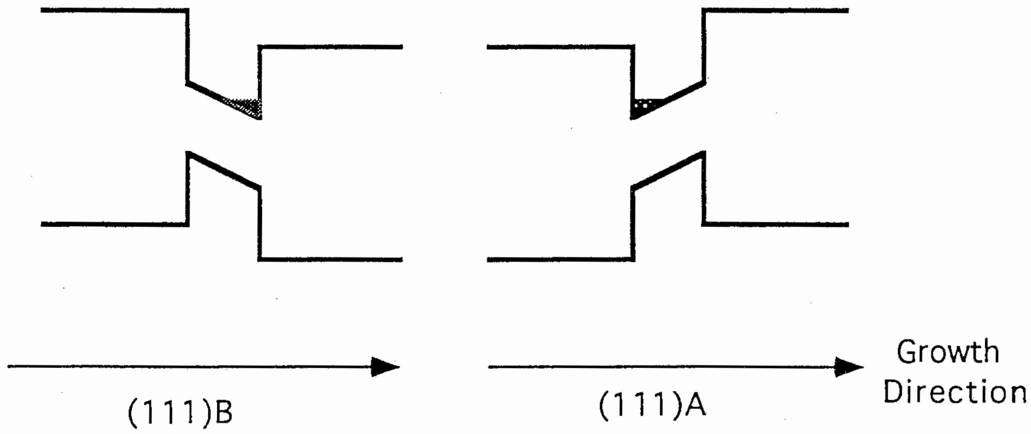


Figure 2: By growing on the A or B surface we can confine the electrons at either the bottom or top interface of the quantum well. This may have significant advantages when making 2 dimensional electron gas structures....

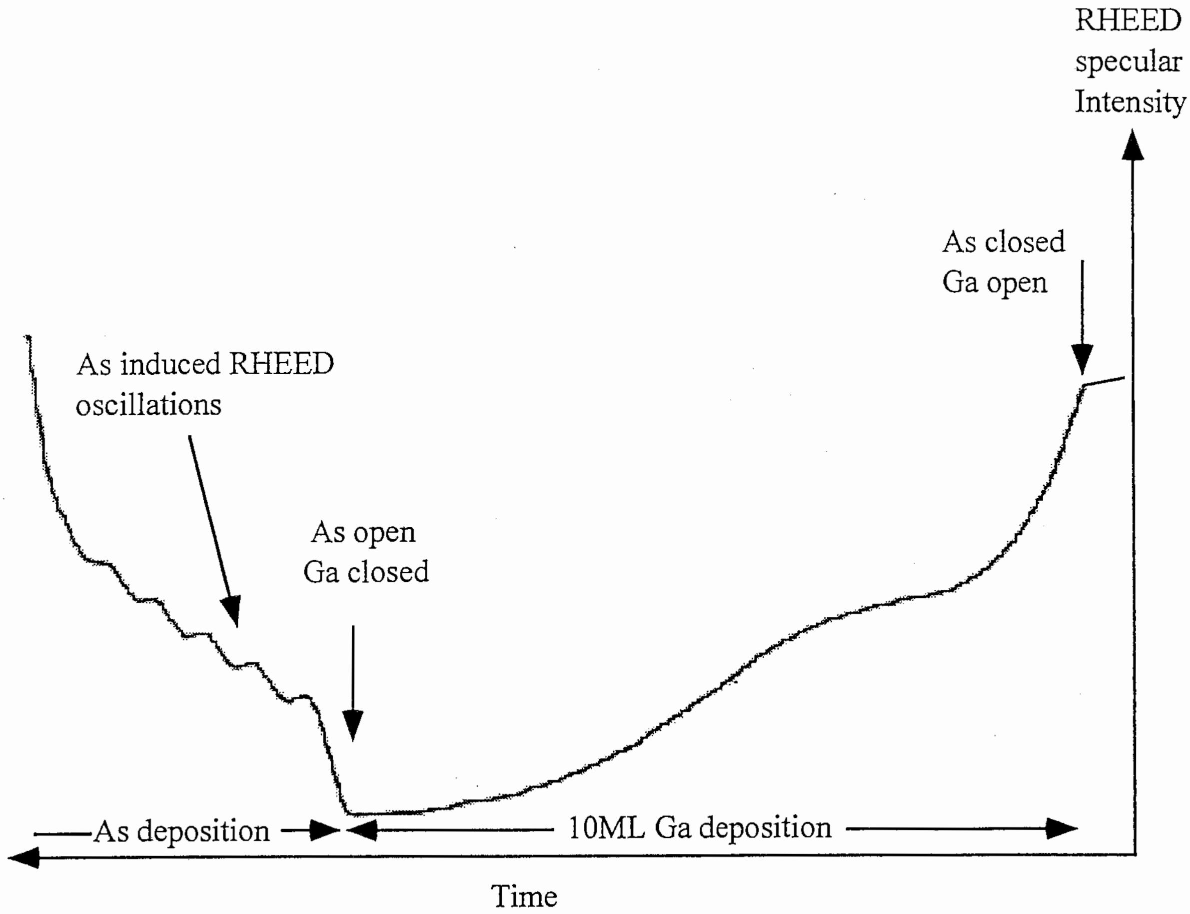
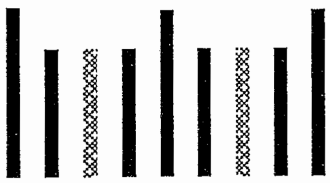


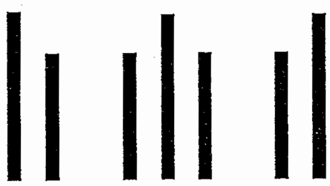
Figure 3. Changes in the RHEED specular intensity during the measurement of As induced RHEED oscillations for calibration of the As flux

GaAs(001) (2x4) - c(4x4) reconstruction change as observed in the $[1\bar{1}0]$ azimuth

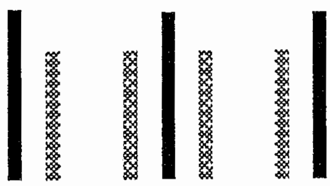
Typical (2x4) reconstruction in $[1\bar{1}0]$ azimuth
T >540



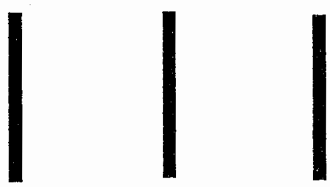
As temperature is lowered, 1/2 order start
to become weak.......



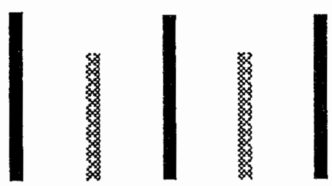
and eventually disappear.. This is about 530C



The 1/4 order then also become weaker....



and disappear at about 520C



and soon after the 1/2 order start to reappear

and by 510C a clear c(4x4) reconstruction can be seen

Figure 4:The temperatures given here assume an As flux of about 3Ml/s. Increasing the As flux will raise the temperature at which the transition takes place. The temperatures quoted are not absolute but represent a simple method of consistantly reproducing growth temperature calibrations.

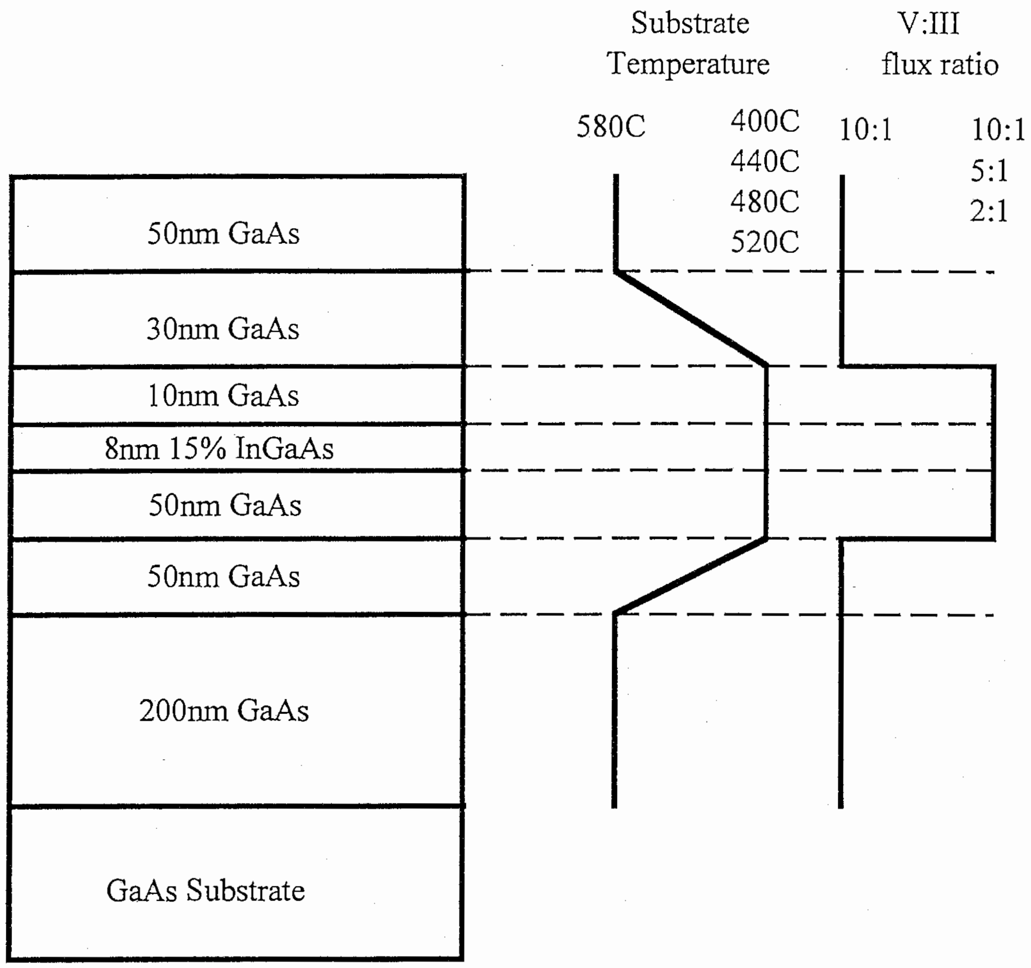
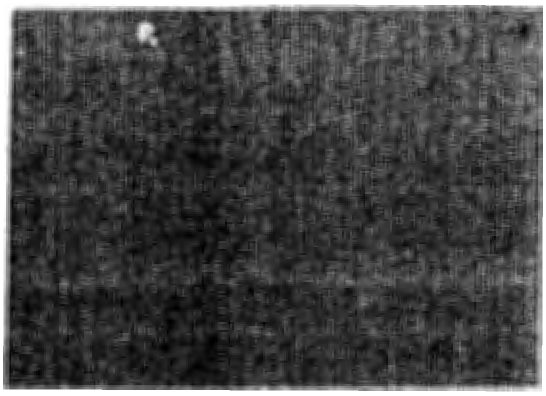
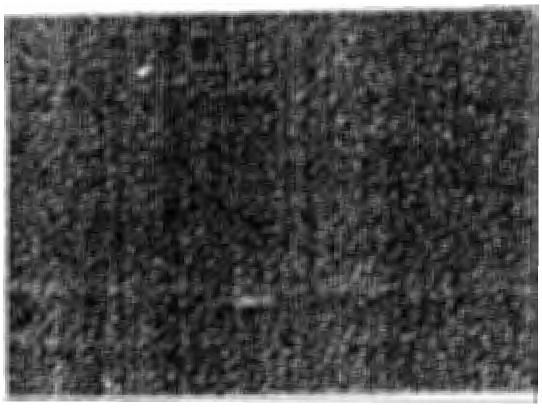


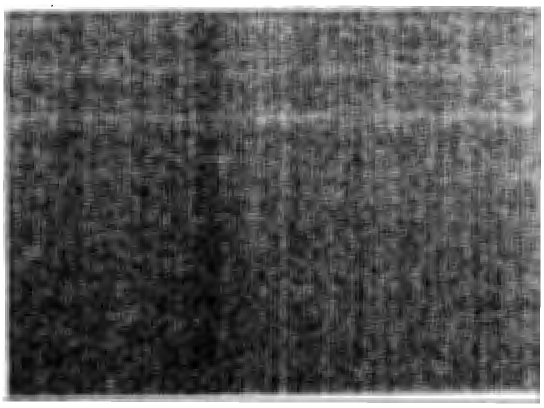
Figure 5: The structure of Single Quantum Well sample using in this set of experiments.



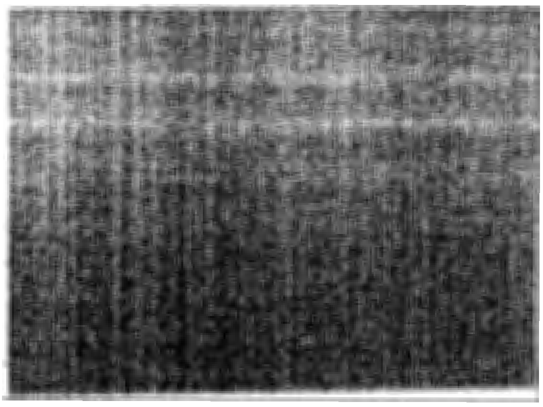
(a)



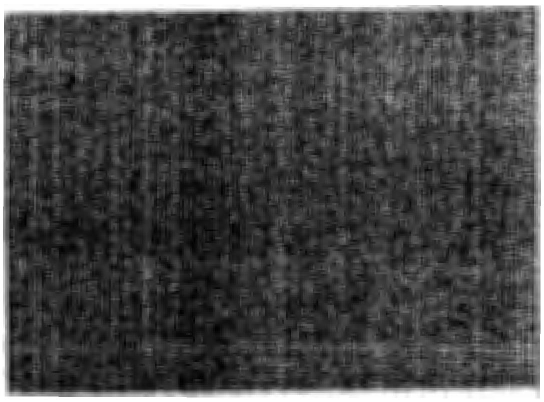
(d)



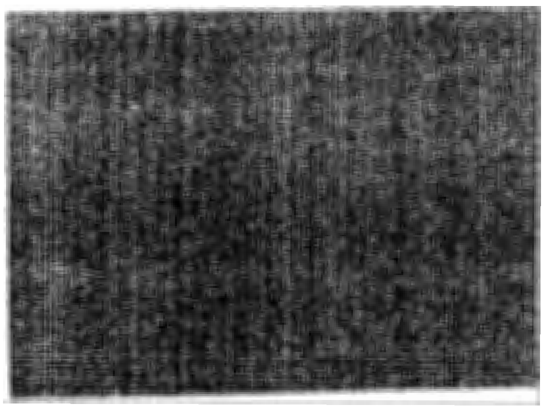
(b)



(e)



(c)



(f)

Figure 6: Normaski Interference Micrographs of samples grown on GaAs(111)A. (a), (b) and (c) were grown at under a V:III ratio of 2:1, 5:1 and 10:1 respectively at substrate temperatures of 400°C. Similarly , (d), (e) and (f) were grown under V:III ratios of 2:1, 5:1 and 10;1, but at a substrate temperature of 520°C.

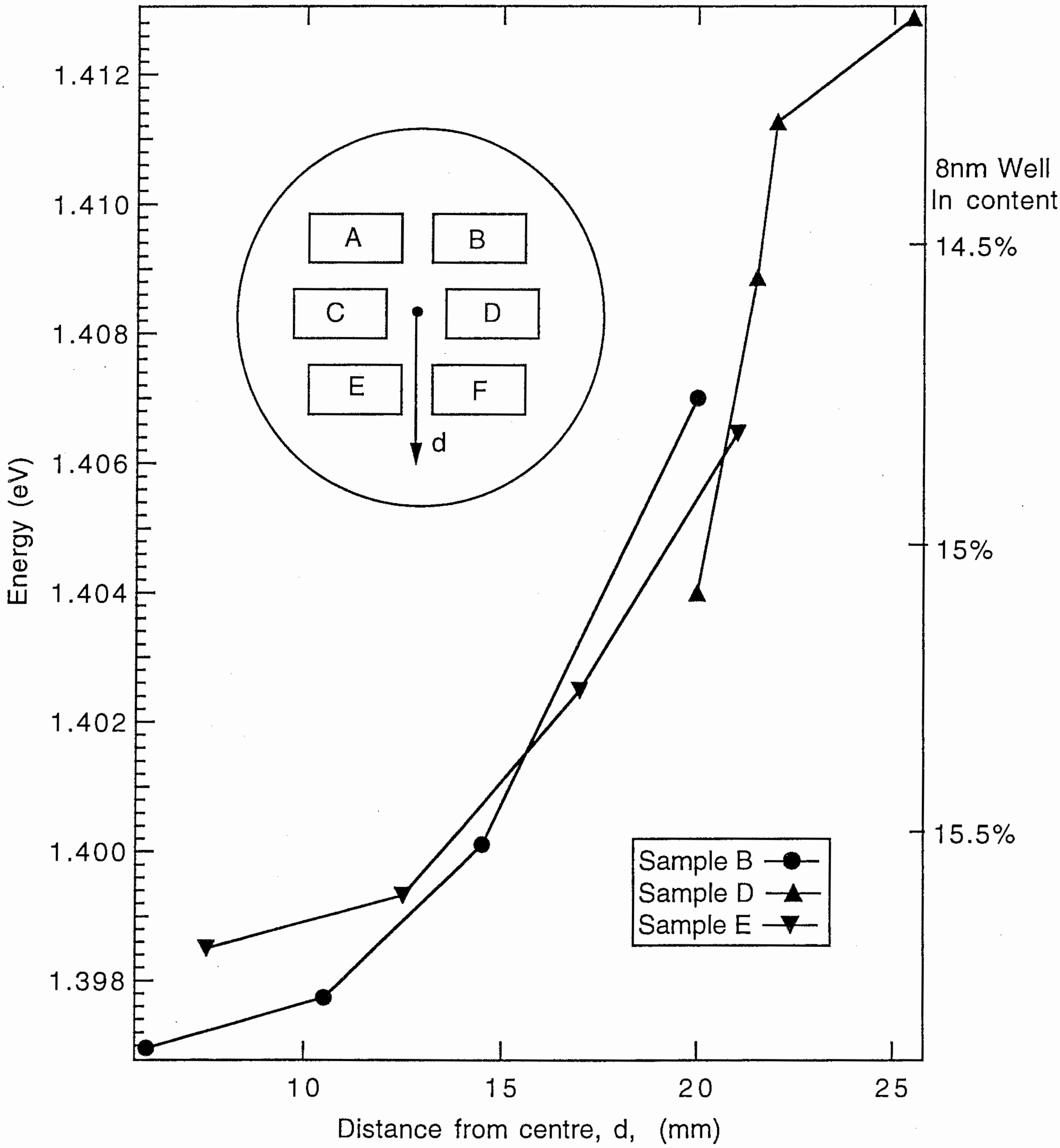


Figure 7: PL peak position from a nominally 80A, 15% InGaAs single quantum well grown on GaAs(001). The figure also shows calculated In content assuming a well thickness of 80A.

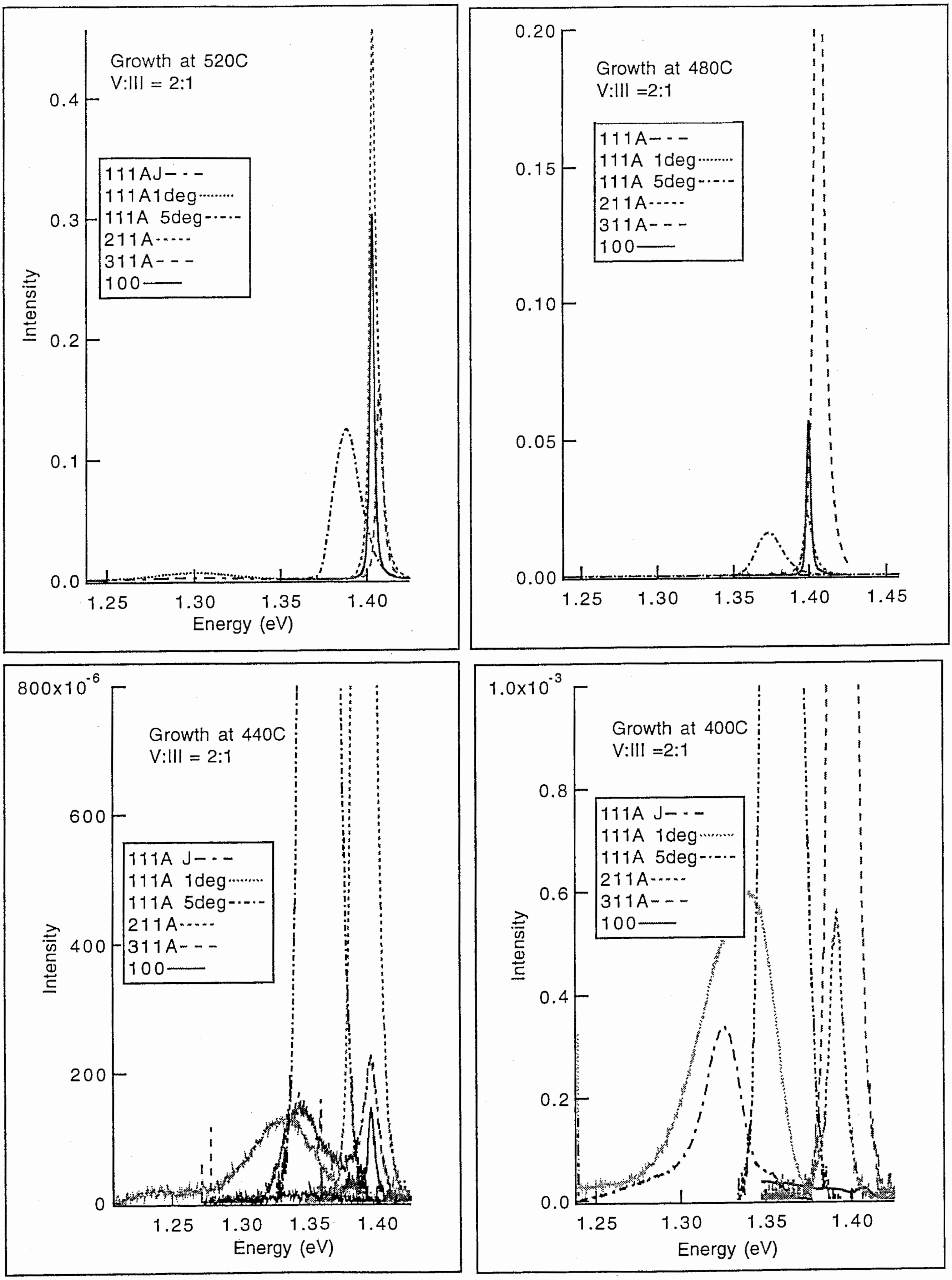


Figure 8; PL spectra for samples grown at a V:III ratio of 2:1 at growth temperatures of 400, 440, 480 and 520C

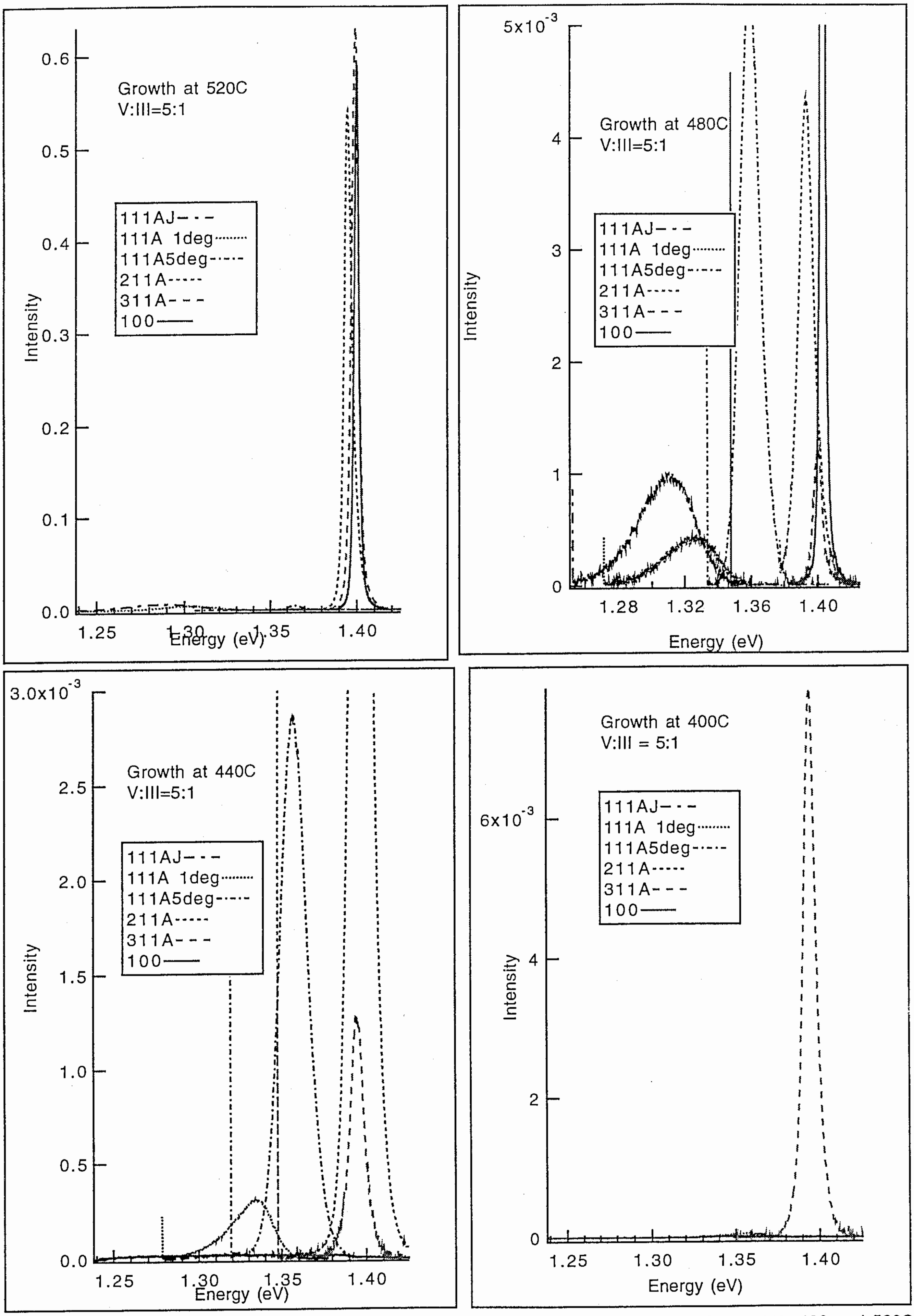


Figure 9; Pl spectra for samples grown at a V:III ratio of 5:1, at growth temperatures of 400, 440, 480 and 520C

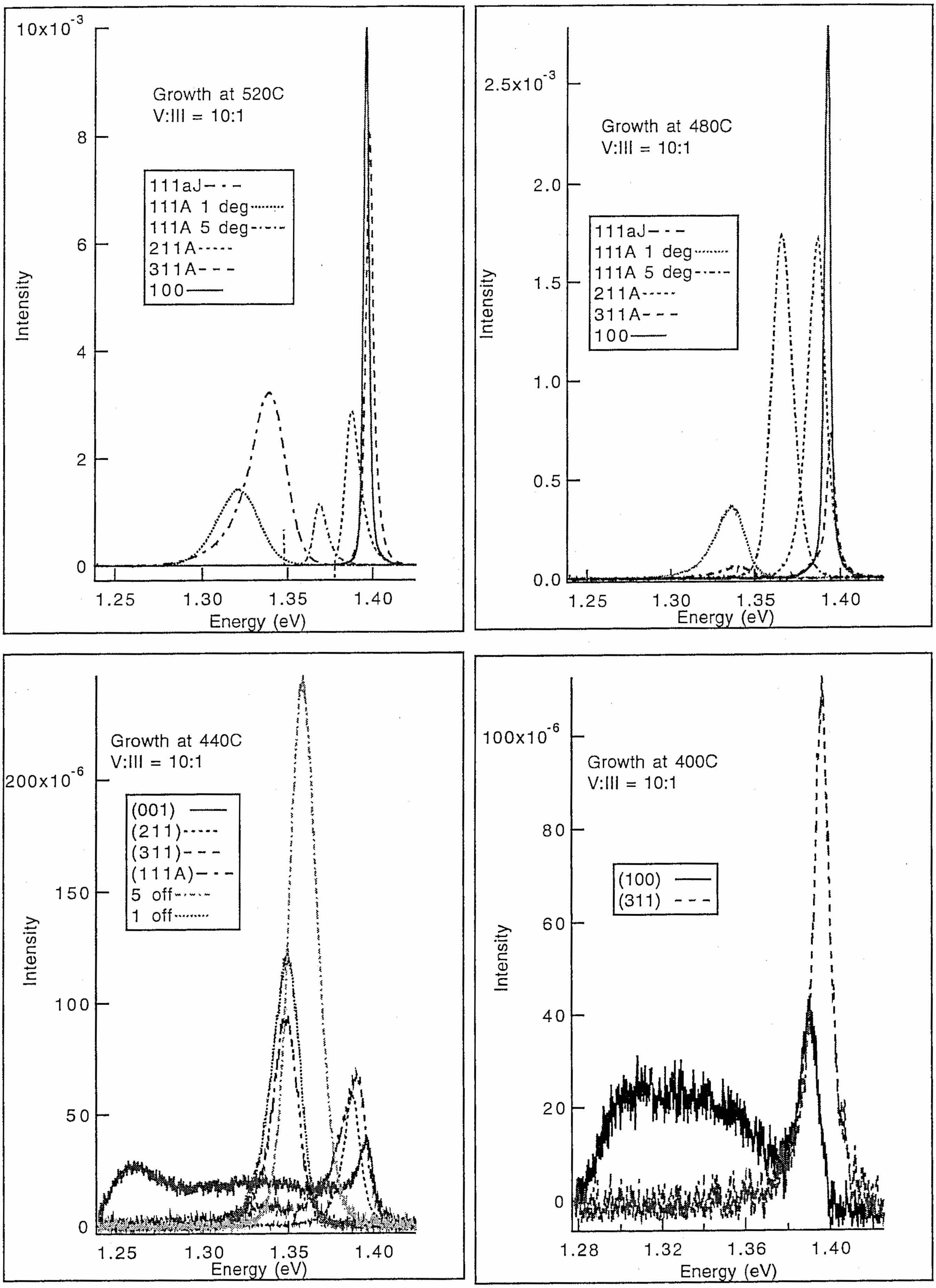


Figure 10: PL spectra for samples grown at a V:III ratio of 10:1, at growth temperatures of 400, 440, 480 and 520C

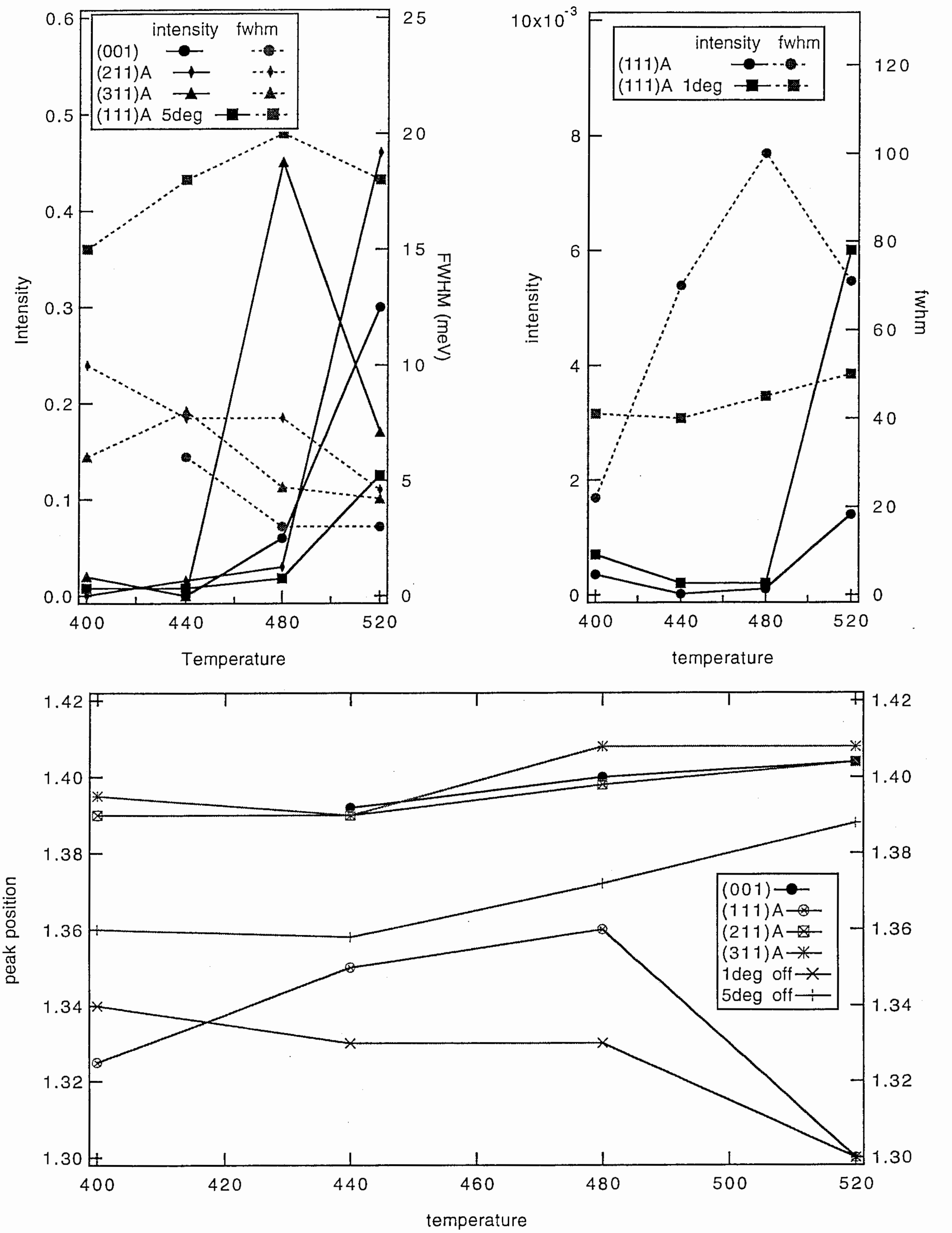


Figure 11: Summary of PL data as a function of growth temperature for samples grown under a V:III ratio of 2:1

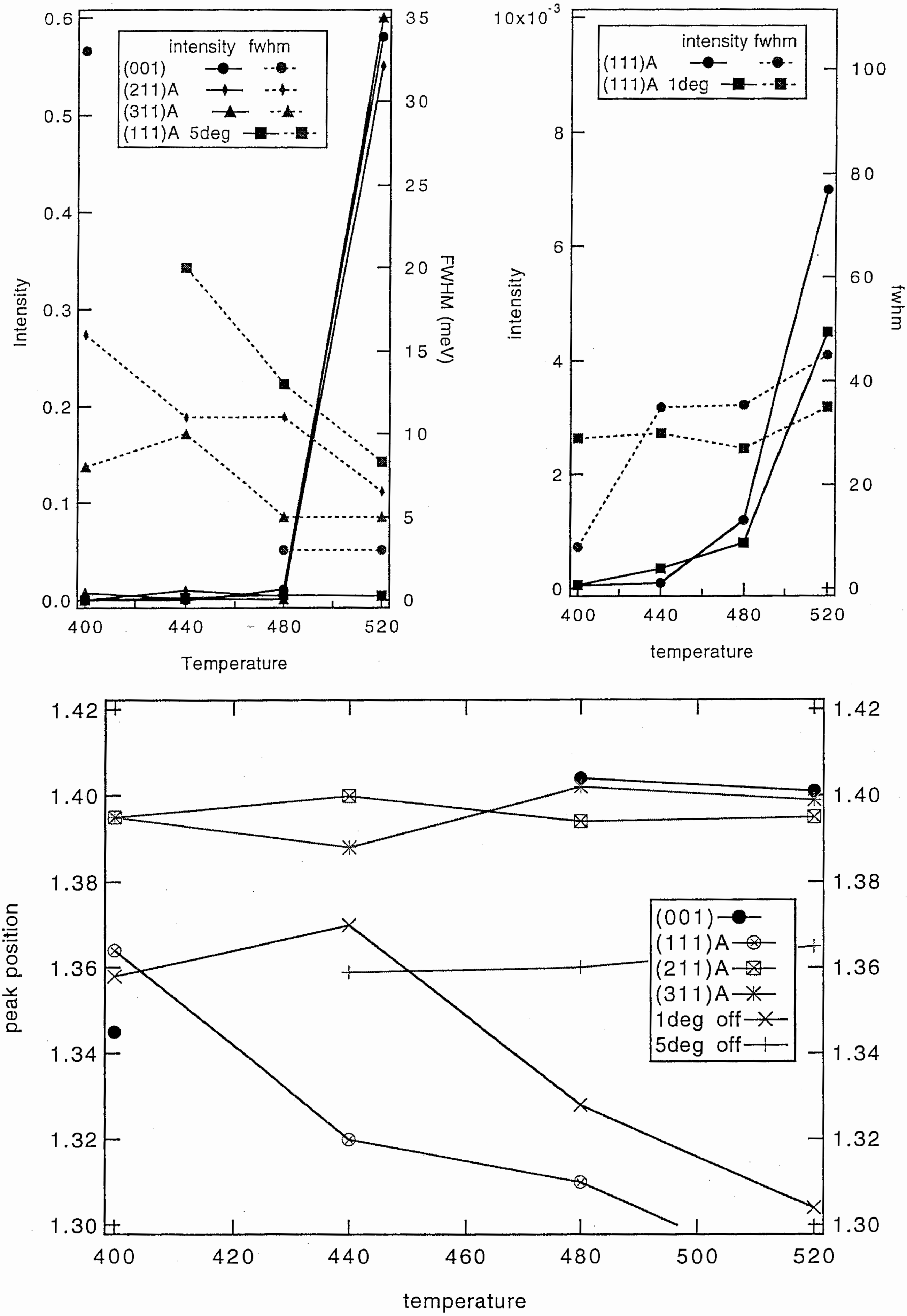


Figure 12 Summary of PI data as a function of growth temperature for samples grown under a V:III ratio of 5:1

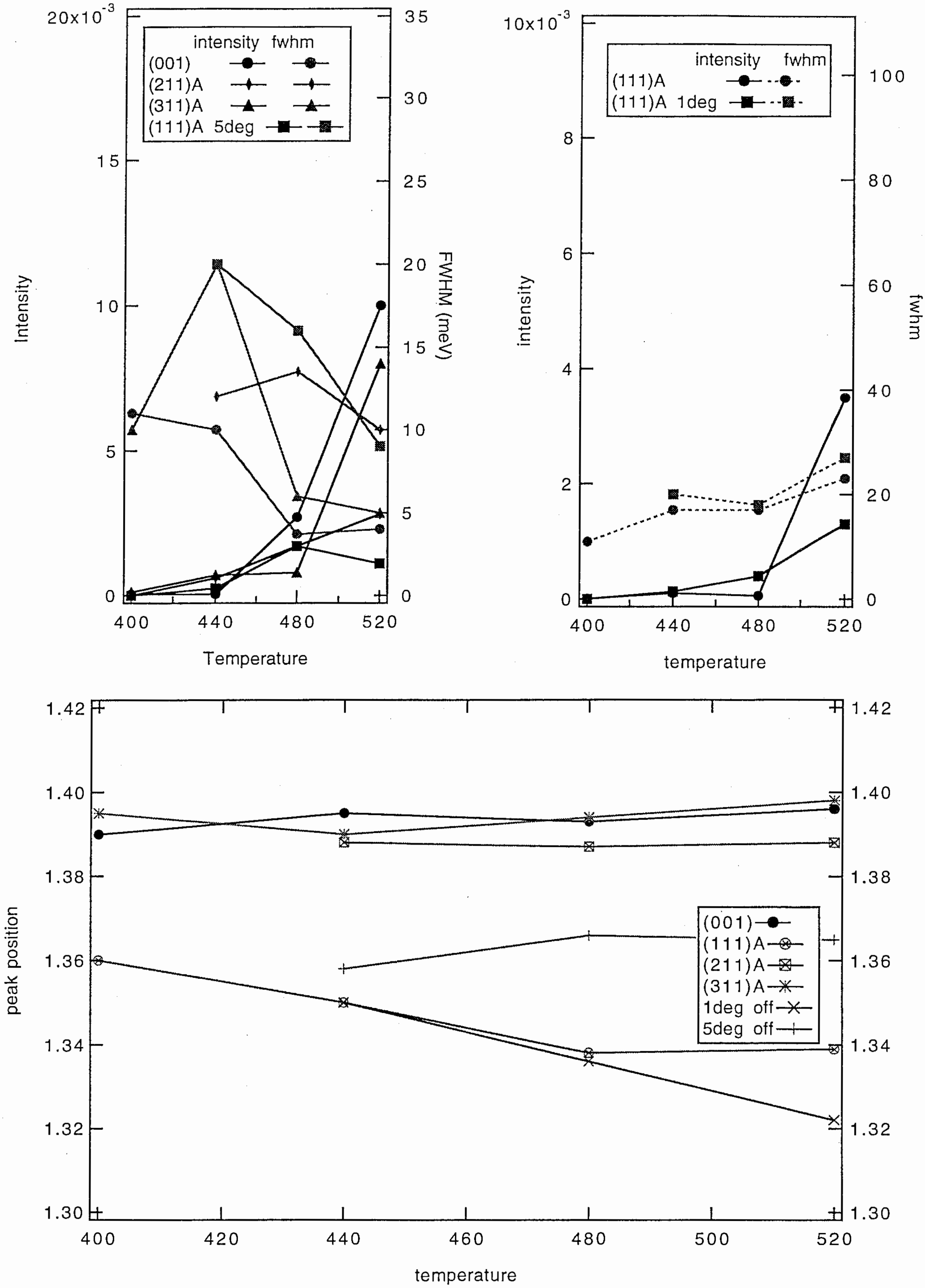


Figure 13 Summary of PL data as a function of grwoth temperature for samples grown under a V:III ratio of 10:1

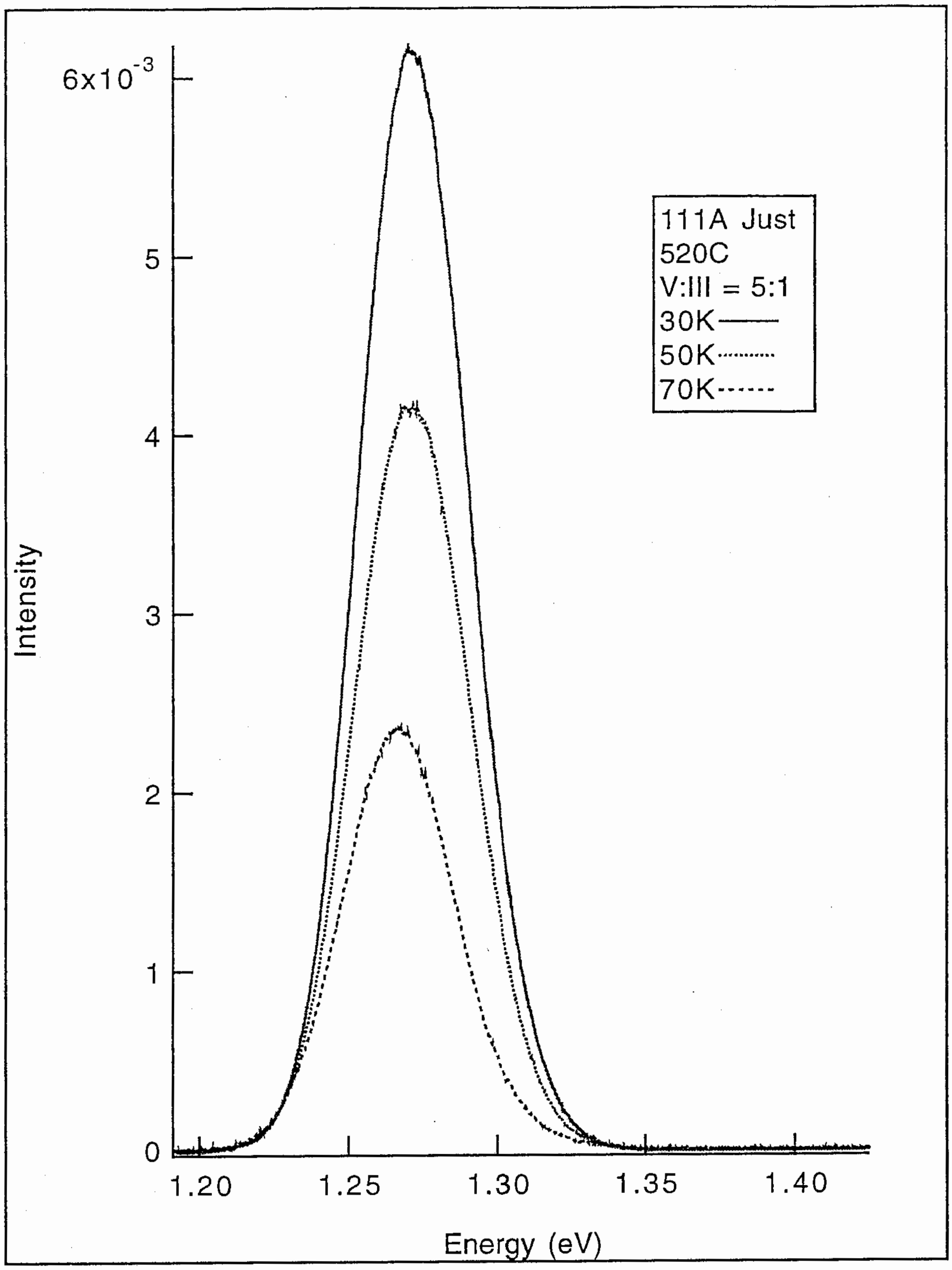


Figure 14: Temperature dependence of PL spectra for SQW grown on GaAs(111)A at 520C under a V:III ratio of 5:1

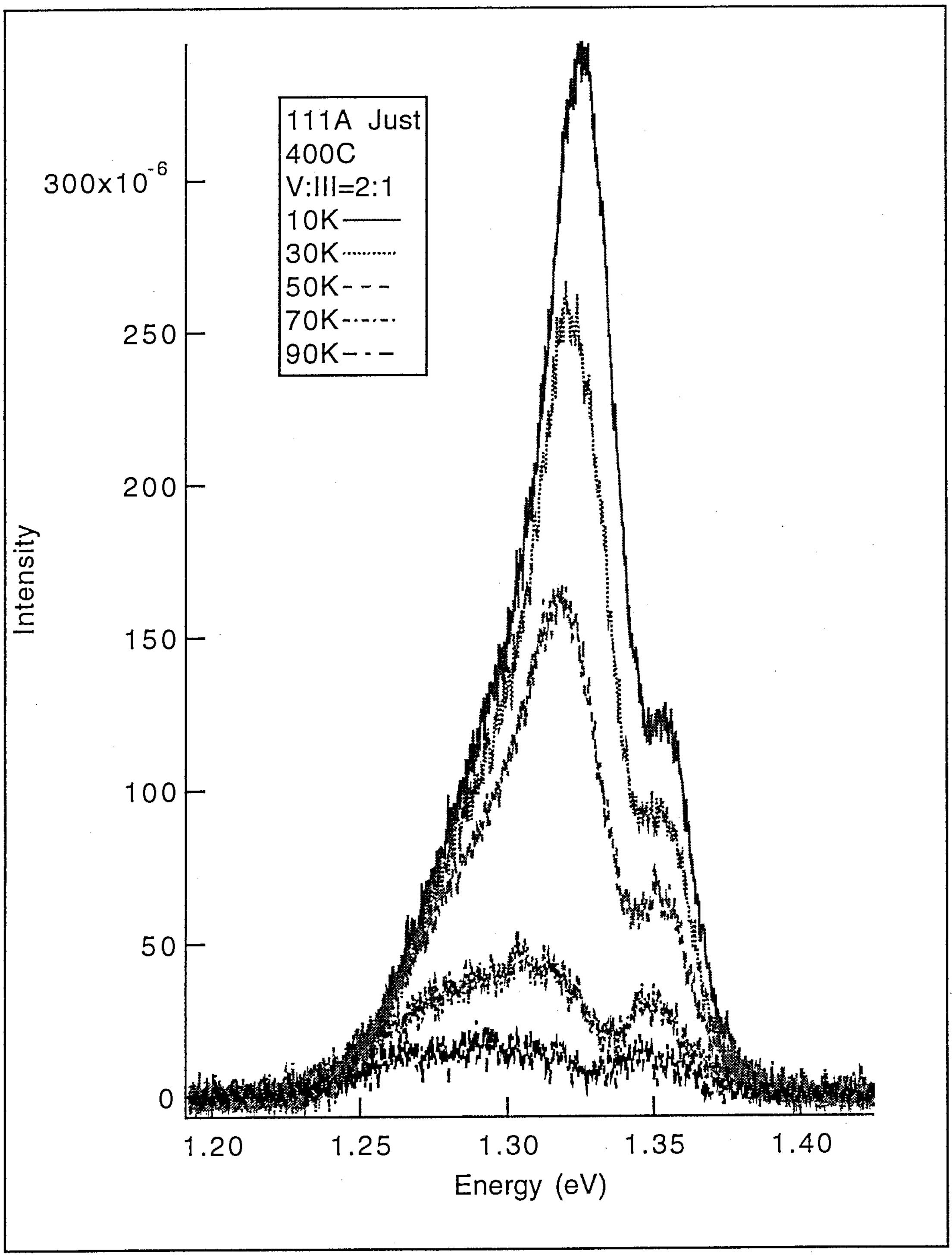


Figure 15; Temperature dependence of the PL spectra for the sample grown on GaAs(111)A at 400C under a V:III ratio of 2:1

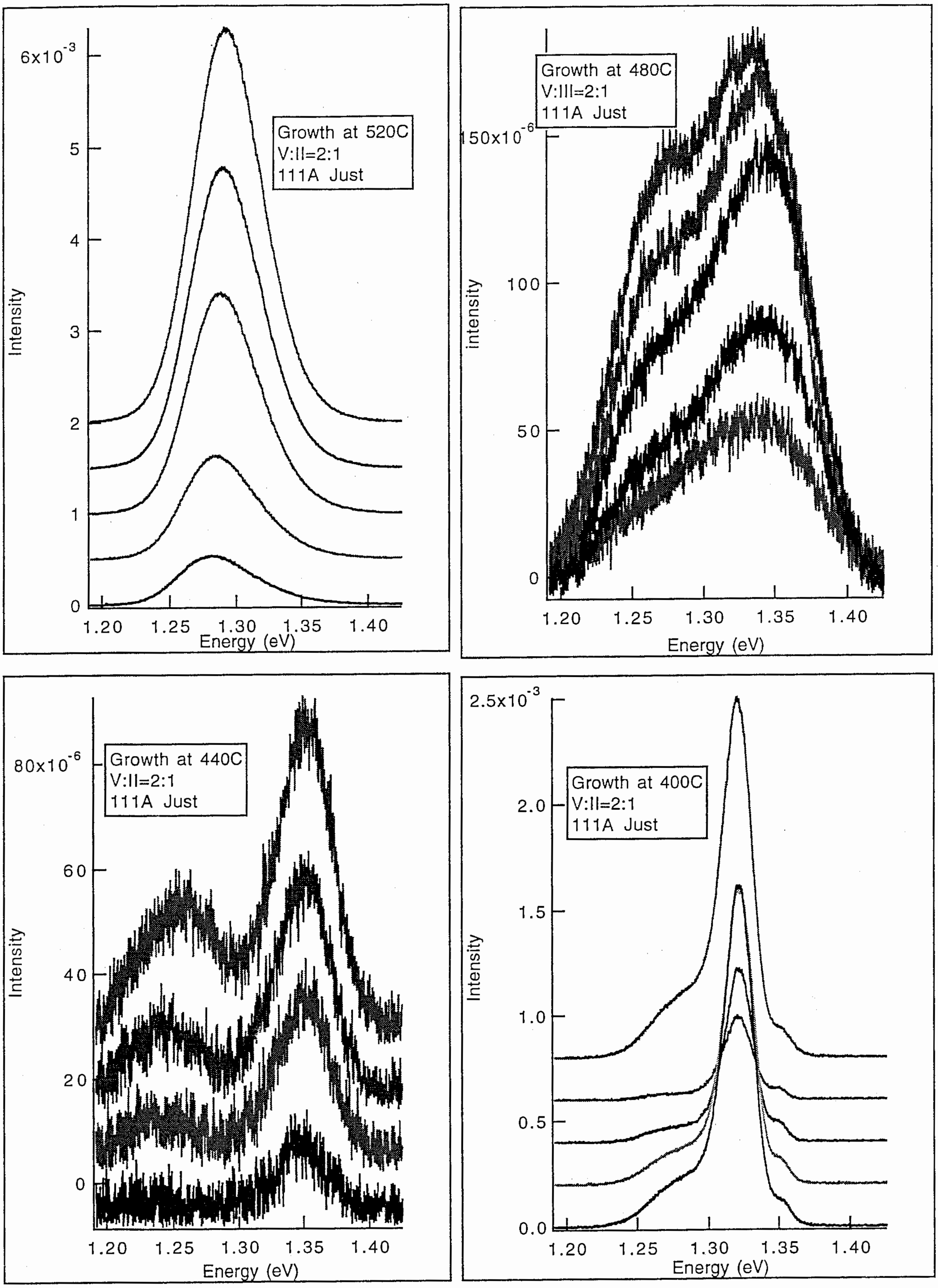


Figure 16; Laser Intensity dependence (15mW-100mW) of PL spectra for GaAs(111)A samples grown at a V:III ratio of 2:1.

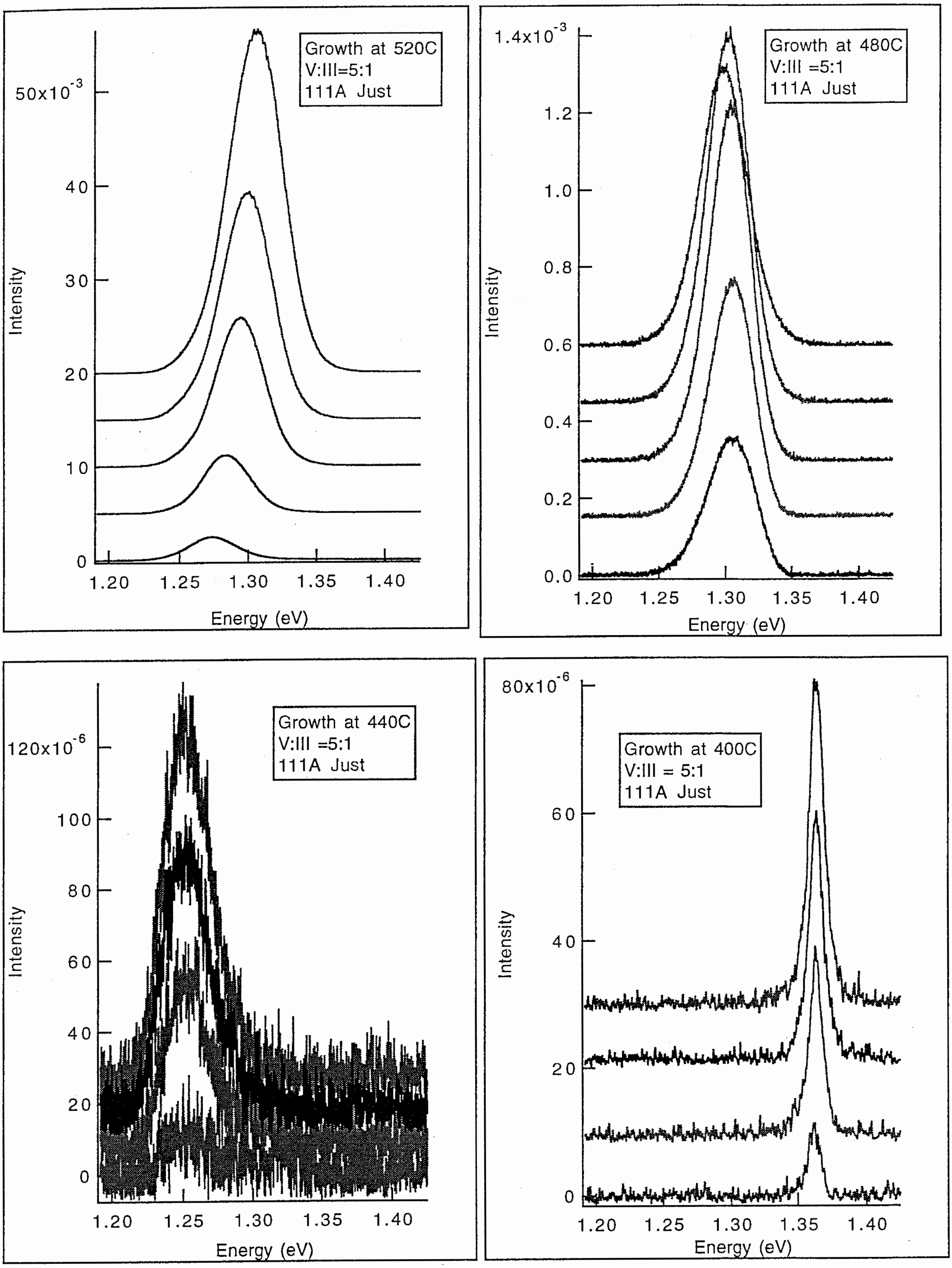


Figure 17; Laser Intensity dependence (15mW-100mW) of PL for samples grown on GaAs(111)A under a V:III ratio of 5:1

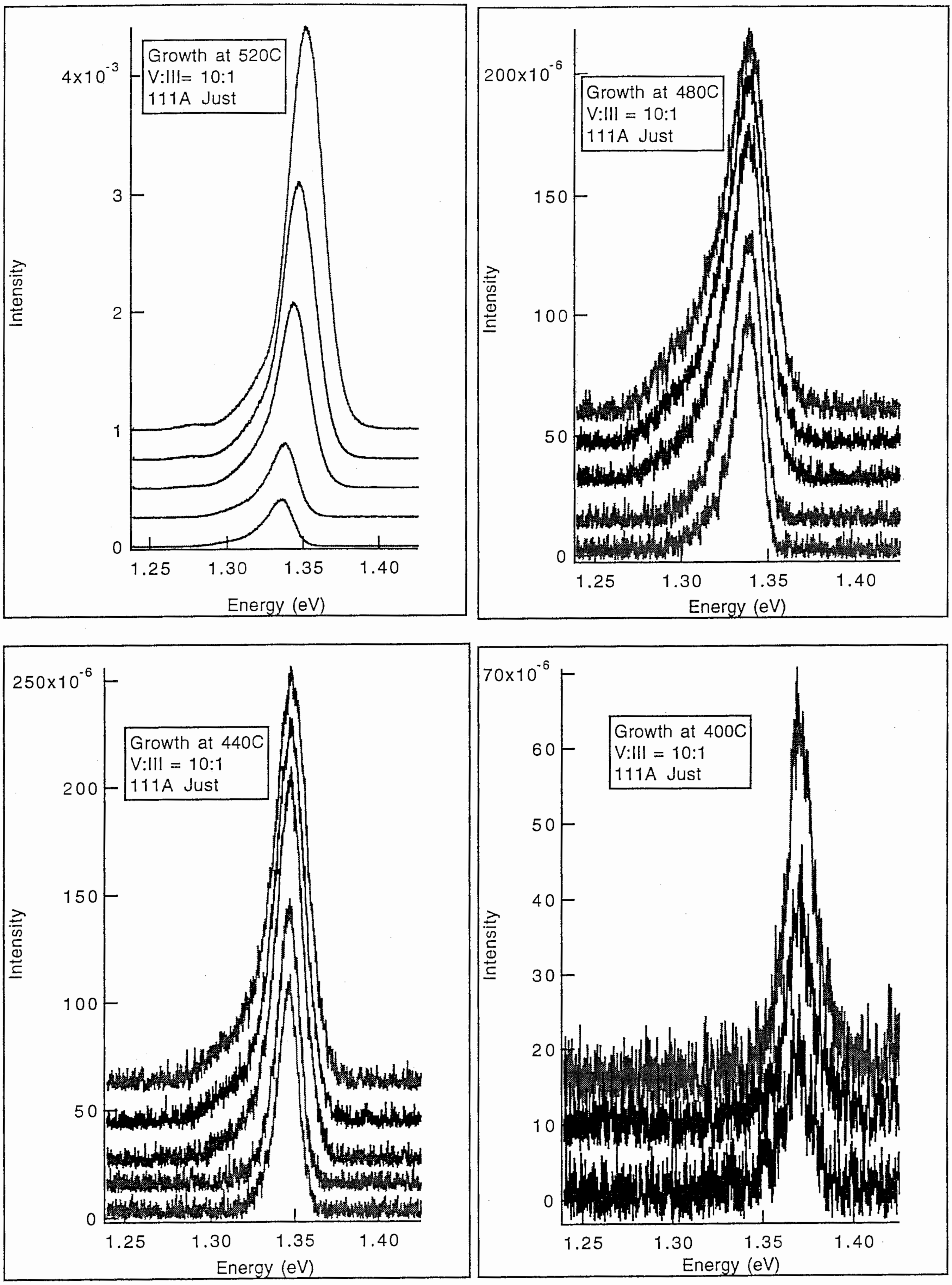
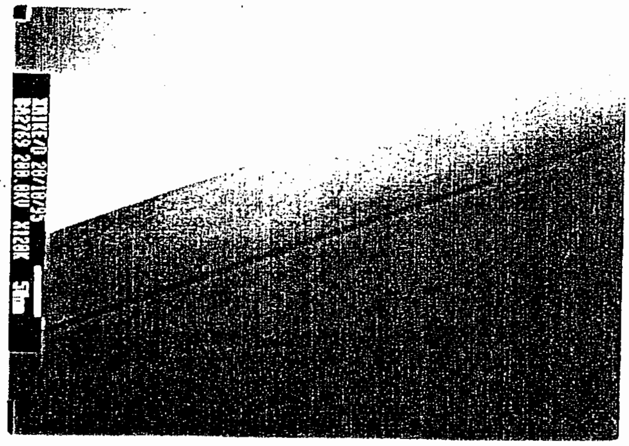
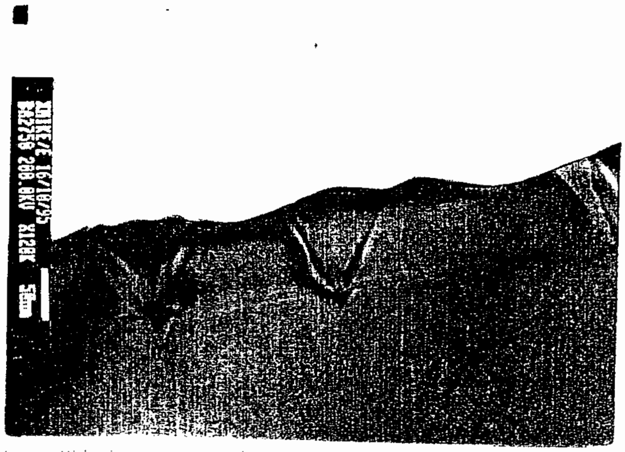


Figure 18; Laser Intensity Dependence (15mW - 100mW) of PL spectra for samples grown on GaAs(111)A under a V:III of 10:1

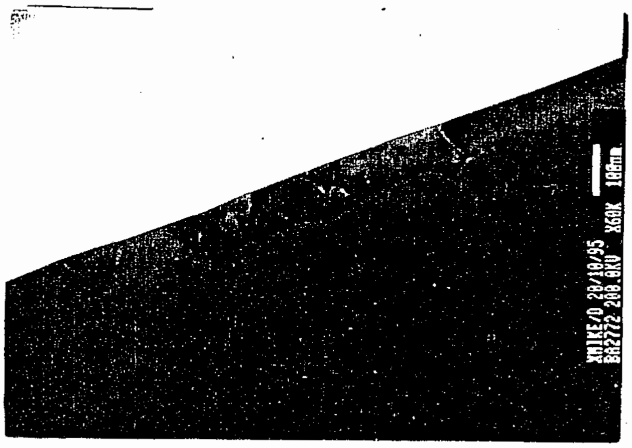


(a)

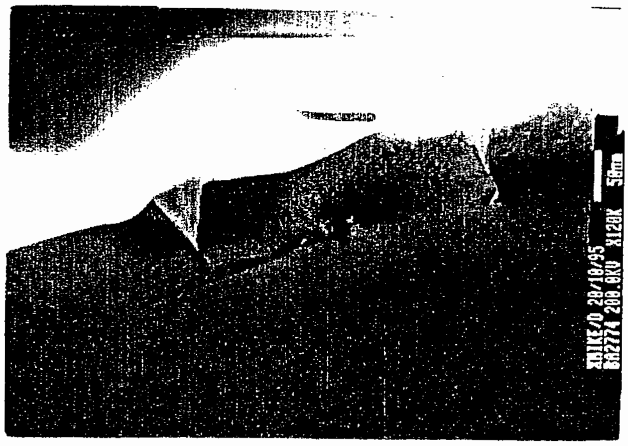
(b)



(c)



(d)



(e)

Figure 19: Transmission Electron Micrographs for a 15%, 80Å InGaAs SQW grown on a) GaAs(001), b,c) GaAs(111)A at 400°C,V:III=5:1 and d,e)GaAs(111)A, at 520°C, V:III=2:1. The upper half of (b) is from an unrelated sample

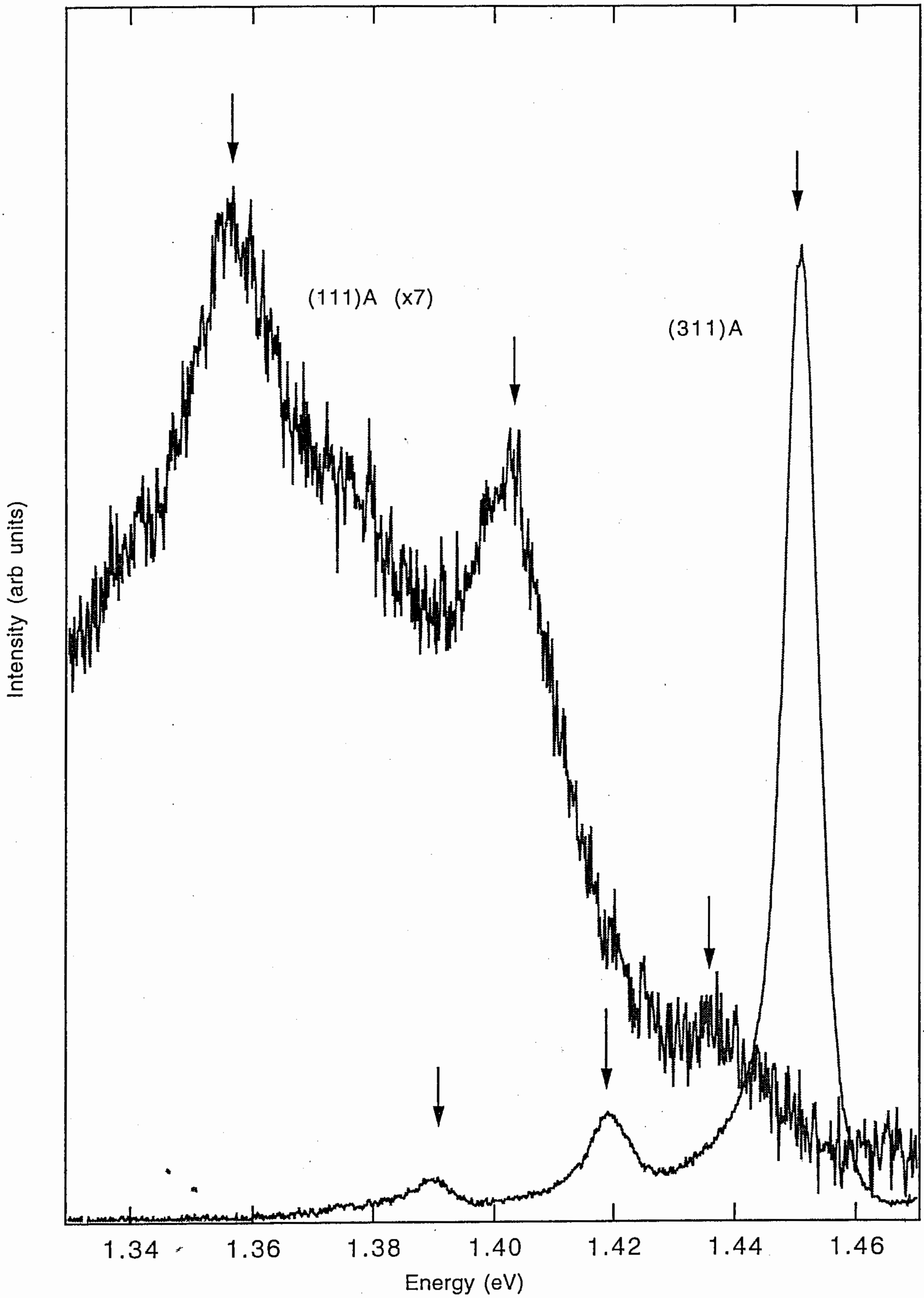


Figure 20: 12K PL spectra from a 3 QW sample grown at 400C at a V:III of 5:1 on (311)A and (111)A substrate. The (001) showed no luminesence.