Determination of the microscopic quality of InGaAs-InAlAs interfaces by photoluminescence—Role of interrupted molecular beam epitaxial growth

F-Y. Juang, P. K. Bhattacharya, and J. Singh
Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, Michigan 48109

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Photoluminescence (PL) studies have been carried out on 120 Å InGaAs/InAlAs single quantum well structures grown by molecular beam epitaxy. Three types of samples were grown with the growth being interrupted before interface formation. The interruption times were 0, 2, and 3 min. The corresponding linewidth of the main excitonic transition associated with the quantum well was found to be 20, 16, and 10 meV, respectively, while the PL intensity changed by the ratio 1:0.4:0.1. We believe this behavior is due to a steady improvement in the interface quality due to interruption accompanied by impurity accumulation during the interruption. Analysis of the 10 meV linewidth, which is among the smallest ever reported, suggests that the InAlAs/InGaAs interface can be described by two-dimensional InAlAs and InGaAs islands which have a height of two monolayers and a lateral extent of about 100 Å.

The GaInAs/AlInAs quantum well system lattice matched to InP has emerged as an important material for use in long wavelength optoelectronic devices. Although near perfect interfaces have been obtained in the GaAs/AlGaAs interface,[1,2] due to a variety of reasons a similar level of perfection has not been reached in the InAlAs/InGaAs system. Photoluminescence (PL) of InGaAs/InAlAs single quantum well (SQW) structures has been investigated and reported by Welch *et al.*[3,4] and Stolz *et al.*[5] In particular the former group of authors has concluded that high electron density in the barrier regions, poor interfacial quality, and well thickness variations are important extrinsic factors which can limit the photoluminescence linewidth (FWHM) to ~20–80 meV depending on well thickness. An important reason for this deviation from ideality is the difficulty associated with growing high quality interfaces from components having very different bond strengths. Thus the large difference in the In–As and Al–As bond strengths produces very different cation migration rates during growth, thereby making it difficult to control the interface quality. These difficulties may be overcome by novel growth approaches such as interrupting the growth before the interface formation and use of thin smoothening layers.[6] In this letter we report studies on the quality of InAlAs/InGaAs interfaces grown with and without interruption and show evidence of the improvement in the interface quality.

The SQW heterostructures were grown in a three-chamber RIBER 2300 system. System preparation for the growth of high-quality crystals has been described by us earlier.[2] 7N purity In, 8N Ga, 6N Al, and 7N As were used as sources to grow the undoped quantum well structures. The substrate was heated to 540–560 °C under As_4 flux prior to commencement of growth. Typical substrate temperature for the growth of the entire structure was 480–490 °C as set in the temperature controller. The growth rates were ~1.3 μm/h for both compounds. Growth was done under As-stabilized condition, as evidenced from the reflection high-energy electron diffraction (RHEED) pattern. Three types of samples were grown for the present study. Samples of type A were grown continuously through the heterointerfaces. Samples of types B and C were grown under identical conditions, but with 2 min and 3 min interruptions, respectively, at the two interfaces of the quantum well. All samples consist of 120 Å InGaAs wells and 0.2 μm AlInAs barriers grown on InP substrates with a suitable buffer.

Photoluminescence measurements were done at 10 K and higher temperatures and with variable excitation intensity. The luminescence was excited with a 6328-Å He-Ne laser and was analyzed with a 1-m Jarell–Ash spectrometer. A typical photoluminescence spectrum for sample C is seen in Fig. 1. The spectrum is dominated by an intense peak at 0.81 eV which is probably due to donor bound exciton transitions. A weak shoulder at lower energies to the main peak is observed and is believed to be due to donor or acceptor bound excitons. The weak transition at 0.79 eV is probably due to acceptor bound excitons. These latter two transitions have not been observed earlier in the photoluminescence spectrum of InGaAs/InAlAs SQW's. Very weak peaks are observed to higher energies from the main peak. Deep traps in the InAlAs barriers could give rise to such transitions and a similar observation has been made by Stolz *et al.*[5]

The temperature and excitation dependence of the intensity of these peaks were measured. The excitation dependence exhibits a linear to superlinear behavior. All the transitions are quenched with increase of temperature, as expected. At 40 °C a single dominant transition with a linewidth of 10 meV is observed and is shown in the inset of Fig. 1. If this value for the FWHM is extrapolated to 2 K, a value of ~7–8 meV can be expected.

It is important to point out that the linewidth measured here is the narrowest being reported. Since the PL linewidth is a representation of the quality of the heterostructure, we believe the quantum wells grown and measured by us are of very high quality. The structural quality of the InAlAs/InGaAs system can be described by the three components: (i) InAlAs alloy quality, (ii) InGaAs alloy quality, and (iii) InAlAs/InGaAs interface quality. All three of these components contribute to the line broadening mechanism.

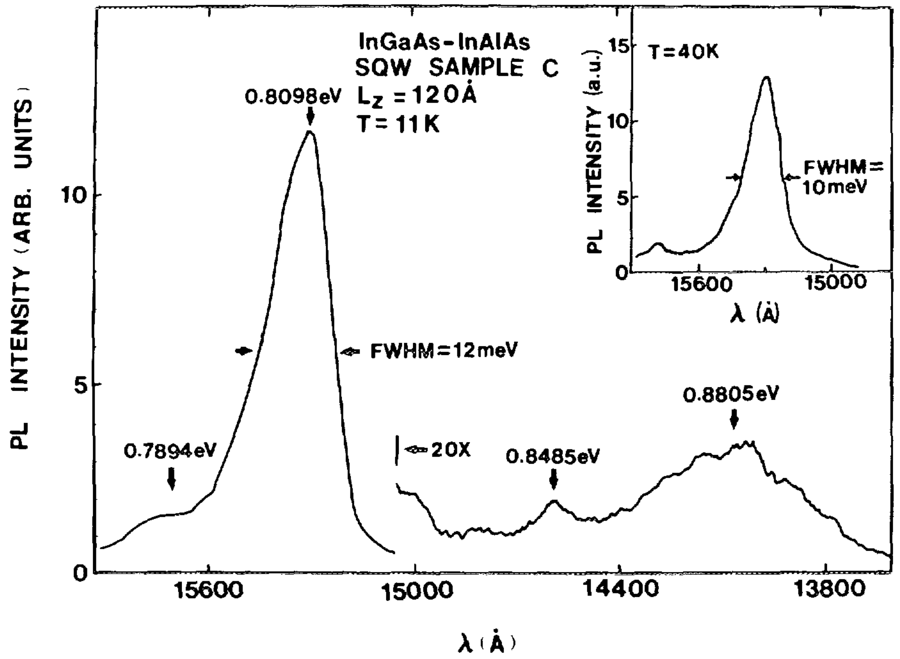

FIG. 1. Measured photoluminescence from 120 Å $In_{0.53}Ga_{0.47}As$ single quantum well with $In_{0.52}Al_{0.48}As$ barriers. The main peak and shoulders in the lower energy side are attributed to bound exciton transitions. Inset shows the photoluminescence spectrum at 40 K. The measured FWHM is 10 meV.

The linewidth due to the alloy broadening is given by[7]

$$\sigma^a = \sqrt{\sigma_1^2 + \sigma_2^2}, \tag{1}$$

where

$$\sigma_1 = \sigma_{B1}^a \frac{\Delta_{QW}}{\Delta_{B1}} \frac{1}{\sqrt{P_0^{ex}}}, \tag{2}$$

$$\sigma_2 = \sigma_{B2}^a \frac{\Delta_{QW}}{\Delta_{B2}} \frac{1}{\sqrt{1 - P_0^{ex}}}. \tag{3}$$

Here σ_{B1}^a and σ_{B2}^a represent the PL linewidth in the InAlAs and InGaAs respectively, Δ_{QW} represents the variation of the electron-hole subband energy difference with variation in the alloy composition, and W_B's represent the variation in the band gap of the material with alloy composition. P_0^{ex} is the exciton fraction in the barrier. In addition to σ^a, the fluctuations due to the interface roughness also affect the linewidth. The interface roughness can be described by two-dimensional islands (or valleys) of height δ_1 and lateral radius δ_2. The linewidth is dependent upon both δ_1 and δ_2. Its dependence on δ_2 is much more complicated [e.g., see Eq. (12) of Ref. 7].

If $\delta_2 \sim R_{ex}$ (where R_{ex} is the exciton radius), the linewidth is given by

$$\sigma_{IR} = \delta_1 \frac{\partial E^{eh}}{\partial W}\bigg|_{W_0}, \tag{4}$$

where E^{eh} is the separation between the electron and hole subbands, W is the well size, and W_0 is the mean well size of the quantum well.

In Fig. 2 we have shown the dependence of σ_{IR} and σ^a for InAlAs/InGaAs quantum wells as a function of well size. In order to interpret the linewidth data reported here we need to know the σ_{B1} and σ_{B2} values. We find that the measured values of σ_{B1} and σ_{B2} for thick InAlAs and InGaAs films grown under similar conditions are 31.0 and 3.0 meV, respectively. While the InGaAs linewidth is close to the theoretical linewidth for a completely random alloy, the large linewidth in InAlAs implies that a certain amount of clustering is present in the system. However, for a 100-Å quantum well, due to the high barrier discontinuities for the InAlAs/InGaAs quantum well, only a very small fraction of the exciton (~ 3%) penetrates and sees the alloy clustering in the InAlAs region. From Eqs. (1)-(3) the linewidth contribution due to the alloy quality of the structure is given by $\sigma^a \cong 3.5$ meV. We therefore estimate that the contribution of the interface roughness is about 5-6 meV to the total linewidth. We note that the linewidth due to a one monolayer fluctuation at the surface with a lateral extension of the fluctuation which is equal to the exciton radius is ~ 3.5 meV

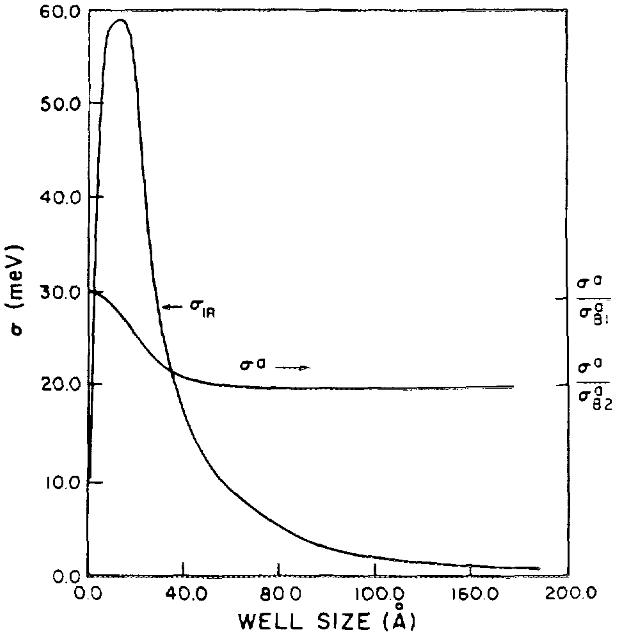

FIG. 2. Calculated photoluminescence linewidth for $In_{0.53}Ga_{0.47}As$-$In_{0.52}Al_{0.48}As$ single quantum well structures. σ_{IR} is the linewidth due to interface roughness with $\delta_1 = 1$ monolayer and $\delta_2 = R_{ex}$ and σ^a is the contribution from the alloy broadening.

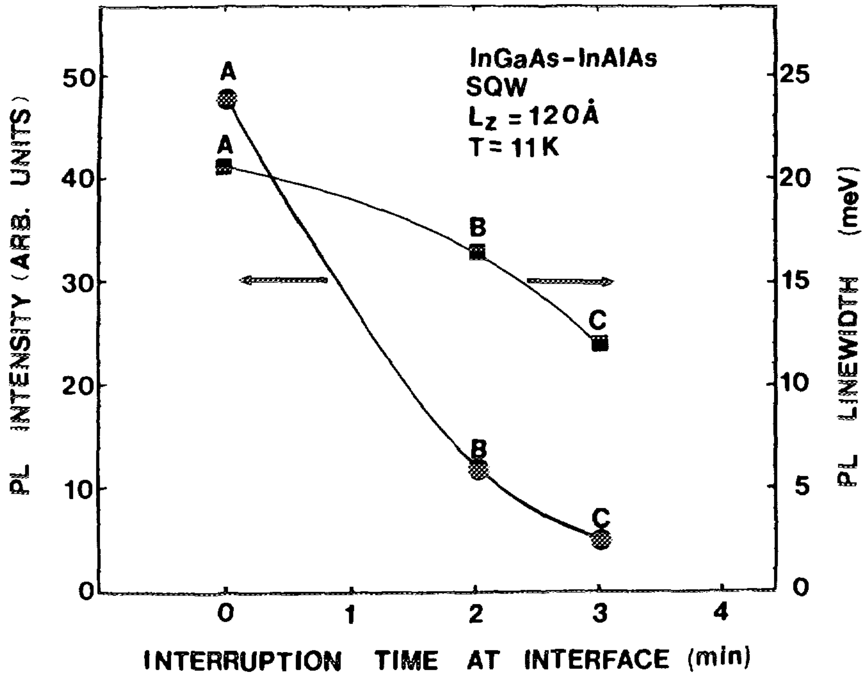

FIG. 3. Dependence of measured luminescence intensity and linewidth (FWHM) on interruption interval during MBE growth of the heterointerfaces in a single quantum well.

for a 100-Å InAlAs/InGaAs quantum well. Based on our calculations we conclude that the interface roughness at the InAlAs/InGaAs interface is described by two-dimensional islands which are two monolayers high (~5.6 Å) with ~100 Å radius laterally. We note that in a quantum well, one has a normal (InAlAs grown on InGaAs) interface as well as the inverted (InGaAs grown on InAlAs) interface. From theoretical studies of molecular beam epitaxial growth mechanisms[8] and from indirect studies based on RHEED measurements during growth,[9] it appears that the normal interface may have a sharper profile compared to the inverted interface. Thus, it is possible that the normal interface has a monolayer roughness. Considering the relatively greater difficulty involved in the growth of the InAlAs/InGaAs system, it is important to note that a quality of the interface structure almost similar to the GaAs/AlGaAs system[7,10] has been obtained. We note, however, that the quality of InAlAs is still quite poor. It is not clear whether the growth conditions necessary for high quality interface also imply that InAlAs quality cannot be very high.

The results and analysis presented above are for sample C, which is representative of quantum wells grown with 3 min interruption at the interfaces during growth. As mentioned earlier, samples A and B were grown with 0 and 2 min interruptions. PL linewidths of 20 and 16 meV at 10 K were measured in samples A and B, respectively. The intensity of the main bound exciton peak also decreased with increase of interruption period. These behaviors are depicted in Fig. 3. These results are of great importance in the understanding of interface formation and show, for the first time, that interrupted growth can result in an improvement in the structural quality of the heterointerface. We believe that the interruption allows a greater time for cation migration and/or reevaporation and consequent smoothening of the surface before the formation of the interface. The decrease in intensity with increasing interruption time is most likely due to a slight accumulation of nonradiative impurities (possibly from the background) during this time.

In summary, we have reported photoluminescence studies on the InAlAs/InGaAs single quantum well grown with interruption at the interfaces. We find that the PL linewidth with 3 min interruption is the narrowest reported so far and gives us considerable information on the structural quality of the quantum well. This information is expected to be useful in studying the charge carrier transport in the InAlAs/InGaAs metal-oxide-diode field-effect transistor structures.

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