



## Intermixing of InP-based multiple quantum wells for integrated optoelectronic devices

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### ABSTRACT

The intermixing characteristics of three widely used combinations of InP-based quantum wells (QW) are investigated using the impurity-free vacancy disordering (IFVD) technique. We demonstrate that the bandgap energy shift is highly dependent on the concentration gradient of the as-grown wells and barriers, as well as the thickness of the well, with thinner wells more susceptible to interdiffusion at the interface between the barrier and well. According to our results, the InGaAsP/InGaAsP and InGaAs/InP are well suited for applications requiring a wide range of bandgap values within the same wafer. In the case of the InGaAs/InGaAsP system, its use is limited due to the significant broadening of the photoluminescence spectrum that was observed. The effect of the top InGaAs layer over the InP cladding is also investigated, which leads to a simple way to obtain three different bandgaps in a single intermixing step.

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### 1. Introduction

A key factor for the development of photonic integrated circuits (PICs) is its ability to selectively control the bandgap across a semiconductor wafer. Since the semiconductor bandgap can be easily controlled during the growth, the use of selective epitaxial growth, or etching and regrowth, has been extensively studied for different semiconductor platforms. However, due to the multiple epitaxial processing the process becomes quite expensive. A simpler and more cost-effective approach for bandgap tuning is the post-growth quantum well intermixing (QWI). Over the years different QWI techniques have been developed, such as impurity-induced disordering (IID) [1,2], photoabsorption-induced disordering (PAID) [3] and impurity-free vacancy disordering (IFVD) [4,5]. Among these, the IFVD has proven to be a very reliable process with lower optical losses as compared to the other techniques. IFVD has been widely used for the GaAs/AlGaAs system, and some photonic devices have been demonstrated [6]. Nevertheless, in the case of InP-based materials we have a variety of compositions to form quantum wells (QW), since we can easily grow lattice matched QW with InP, InGaAs, and InGaAsP. Therefore, knowledge of the intermixing behavior for each system is important from the device perspective.

In this work, the intermixing characteristics of QW with compositions of InGaAsP/InGaAsP, InGaAs/InGaAsP, and InP/InGaAs are investigated. We show that the amount of bandgap tuning is strongly correlated to the material composition of the wells and barriers, and also to the thickness of the wells. Our experimental results demonstrate that the InGaAsP/InGaAsP and InGaAs/InP are ideal for applications requiring a wide bandgap tuning range, while the InGaAs/InGaAsP system was limited due to the significant broadening of the photoluminescence spectrum that was observed. Based on our results the more appropriate system for defining up to three different bandgaps would be the InGaAs/InP.

### 2. Impurity-free vacancy disordering

The IFVD is a relatively simple technique for the post-growth modification of the QW bandgap. Typically the sample is capped with a 200 nm SiO<sub>2</sub> layer, and then the sample is annealed to temperatures beyond 900 °C in the case of GaAs systems. At these temperatures Ga has a very high diffusion coefficient in SiO<sub>2</sub>, and vacancies can then be created at the dielectric–semiconductor interface due to the out-diffusion of Ga atoms from the semiconductor layer to the dielectric. As these vacancies diffuse through the structure, the Ga vacancies promote the diffusion of Ga into the AlGaAs barrier and Al into the GaAs QW, thus modifying the QW bandgap.

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In the case of InP-based QW systems, the intermixing is slightly more complicated. Most InP-based QW have a top InGaAs layer which is required to fabricate ohmic contacts. As a result, vacancy generation is achieved using a similar IFVD process. However, we also have a thermal effect to consider since at elevated temperatures the vapor pressure is dominated by the more volatile group V elements, mainly phosphorous and also arsenic in this case. As a consequence, we should require a lower temperature in order to achieve intermixing for an InP-based QW. The samples were prepared by covering half of the sample with SiO<sub>2</sub> and the other half is uncovered. This was accomplished by growing SiO<sub>2</sub> over the whole sample using a PECVD system, and then removing half of SiO<sub>2</sub> capping layer by etching with a diluted buffered oxide (BOE) solution. After the intermixing the SiO<sub>2</sub> layer is removed and the photoluminescence of the samples is used to observe any bandgap shift.

### 3. IFVD on InP-based MQW systems

The intermixing experiments were performed on the three QW systems using the process we just described. The annealing time in all cases was set at 40 s leaving the temperature as the only variable in the experiments, which was changed from 750 to 850 °C. Shown in Fig. 1 are the photoluminescence results for the InGaAsP/InGaAsP QW system. As can be observed, intermixing started around 750 °C, which in fact confirms group V intermixing mechanism previously explained. As shown in Fig. 1, we can easily see a clear blue-shift of the QW bandgap, which is dependent of the annealing temperature. Similar results were also obtained for the remaining QW systems.

#### 3.1. InGaAsP/InGaAsP system

The composition and thickness of this system is In<sub>0.58</sub>Ga<sub>0.42</sub>As<sub>0.89</sub>P<sub>0.11</sub>/In<sub>0.79</sub>Ga<sub>0.21</sub>As<sub>0.45</sub>P<sub>0.55</sub> and 10/10 nm, respectively. As shown in Fig. 2, the QW bandgap can be tuned for about 100 nm. In this case, intermixing is primarily due to As moving from the quantum well into the barrier and P diffusing into the well from the barrier. However, since we have small concentration gradients of the constituents, thermal effects are very slow at low temperatures. We can notice that beyond 825 °C, the intermixing rate increases which might be due to improved

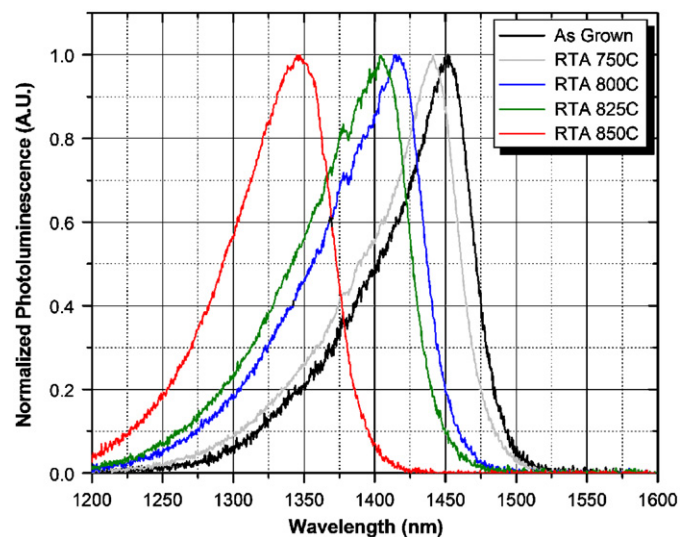


Fig. 1. Normalized photoluminescence results for the InGaAsP/InGaAsP system at different temperatures for an annealing time of 40 s.

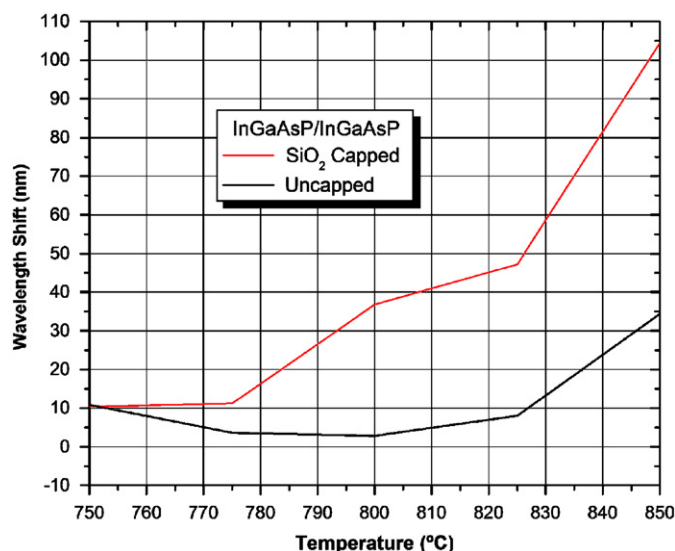


Fig. 2. Temperature dependence of the blue-shift for the InGaAsP/InGaAsP system.

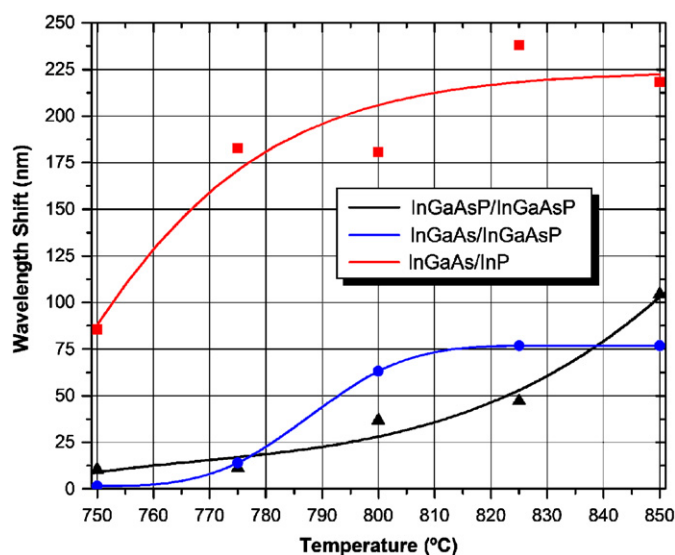


Fig. 3. Temperature dependence of the blue-shift for the InGaAsP/InGaAsP, InGaAs/InGaAsP, and InGaAs/InP systems.

vacancy generation at higher temperatures. There is also a slight shift from the uncovered section, which will be due mainly to thermal effects. It is important to notice that a similar behavior for the uncovered regions was observed in all the samples.

#### 3.2. InGaAs/InGaAsP system

The composition and thickness of this system is In<sub>0.46</sub>Ga<sub>0.54</sub>As/In<sub>0.8</sub>Ga<sub>0.2</sub>As<sub>0.7</sub>P<sub>0.3</sub> and 7/14 nm, respectively. As in the previous case, intermixing is primarily due to P diffusing into the well and As diffusing out of the well. Although the concentration gradient is similar to the InGaAsP/InGaAsP sample, the quantum wells are much thinner leading to an enhancement of the diffusion effect. The result is a larger initial  $\Delta\lambda$  which is then followed by a much quicker saturation of the blue-shift as a function of annealing temperature, as shown in Fig. 3. The maximum amount of blue-shift was approximately 80 nm. The only drawback in this case is

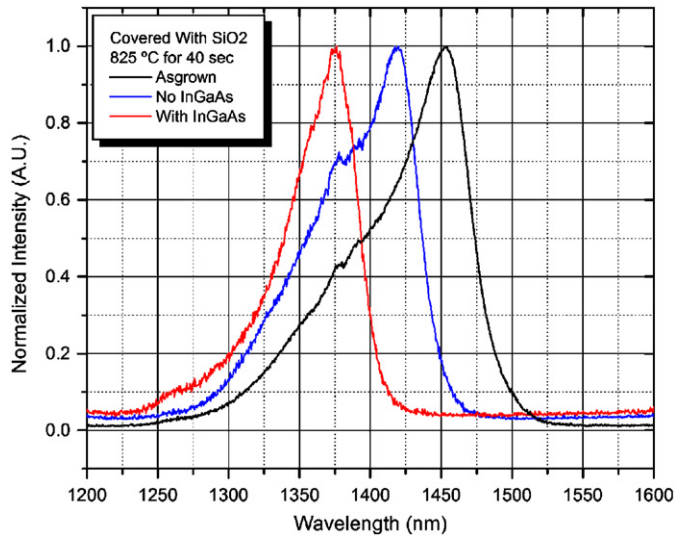


Fig. 4. Spectrum for the InGaAsP/InGaAsP system with and without the InGaAs top layer.

that a significant broadening of the photoluminescence spectrum was observed, and this could limit the use of this material in a real photonic device.

### 3.3. InGaAs/InP system

The composition and thickness of this system is  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$  and 3/5 nm, respectively. As shown in Fig. 3, this system shows the largest bandgap blue-shift as a result of the steep concentration gradient which is a result of the complete absence of P from the quantum well and the absence of As from the barrier. It also has a much thinner quantum well layer which contributes to the large initial shift of the emission peak. The total shift in this case was about 200 nm, which is particularly convenient for defining different bandgaps across a semiconductor wafer. We should also add that the width of the spectrum did not increase as it did for the InGaAs/InGaAsP system.

### 3.4. Effect of top InGaAs layer

As we previously explained, the fact that we have a Ga component at the dielectric–semiconductor interface allows the generation of Ga vacancies. However, depending on the thickness of this layer the number of vacancies generated could be modified and thus the intermixing rate. We prepared a sample (InGaAsP/InGaAsP system) in which the InGaAs top layer was removed from half of the sample. We then covered the whole sample with a 200 nm  $\text{SiO}_2$ , and the sample was annealed at

825 °C for a duration of 40 s. By doing this, we ensured that the intermixing with and without the InGaAs top layer is done under identical conditions. As shown in Fig. 4, there is a drastic change between the photoluminescence from the sample with and without the InGaAs top layer. We believe that removing the Ga component from the dielectric–semiconductor interface inhibits vacancy formation. As shown in Fig. 4, this is an extremely simple way to fabricate three different bandgaps in a single annealing step.

## 4. Conclusions

An experimental study of the intermixing characteristics of InP-based QW using the IFVD disordering technique has been performed. We focused on three combinations of InP-based materials, such as InGaAsP/InGaAsP, InGaAs/InGaAsP, and InP/InGaAs. We demonstrate that the shift of the bandgap energy is highly dependent on the concentration gradient of the as-grown wells and barriers. The well thickness also appears to have a significant effect, with thinner wells more susceptible to interdiffusion at the interface between the barrier and well. According to our results, the InGaAsP/InGaAsP and InGaAs/InP are well suited for applications requiring a wide range of bandgap values within the same wafer, with bandgap shifts of more than 100 and 200 nm, respectively. For the InGaAs/InGaAsP system, a smaller bandgap shift of 80 nm can be obtained, but its use is limited due to the significant broadening of the photoluminescence spectrum that was observed. Even more interesting was the effect of the InGaAs on the intermixing process, since the intermixing is highly dependent on the presence of this layer, and offers a possible approach for obtaining three different bandgaps in a single IFVD step.

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