AIP Applied Physics Letters

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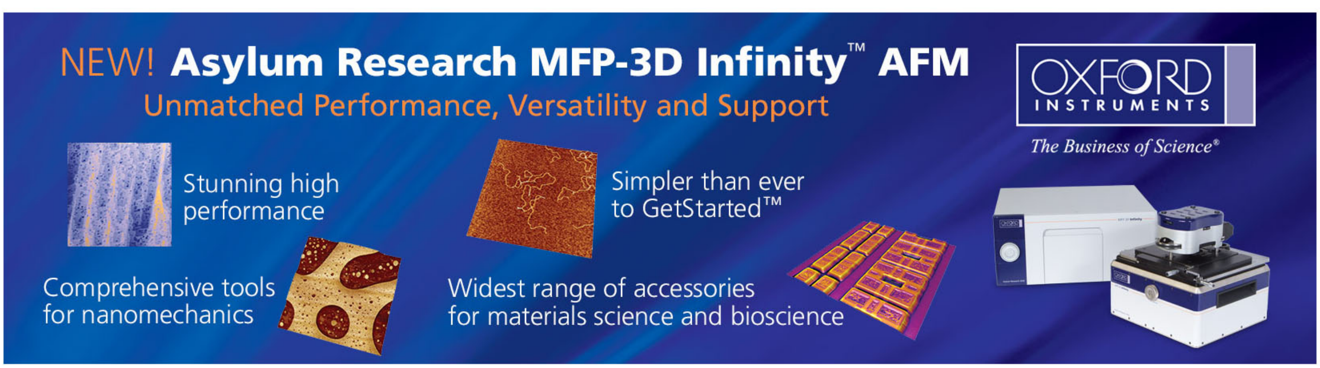
Citation: Applied Physics Letters **77**, 821 (2000); doi: 10.1063/1.1306648
View online: http://dx.doi.org/10.1063/1.1306648
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/77/6?ver=pdfcov
Published by the AIP Publishing



Effects of tensile and compressive strain on the luminescence properties of AlInGaN/InGaN quantum well structures

M. E. Aumer,[a)] S. F. LeBoeuf, and S. M. Bedair[b)]
Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina 27695-7911

M. Smith, J. Y. Lin, and H. X. Jiang
Department of Physics, Kansas State University, Manhattan, Kansas 66506

(Received 3 April 2000; accepted for publication 9 June 2000)

We report on the luminescence properties of AlInGaN/$In_{0.08}Ga_{0.92}N$ quantum wells (QWs) subjected to a variable amount of lattice mismatch induced strain, including wells with zero strain, compressive strain, and tensile strain. The primary peak emission energy of a 3 nm $In_{0.08}Ga_{0.92}N$ QW was redshifted by 236 meV as the stress in the well was changed from −0.86% (compressive) to 0.25% (tensile). It was also found that the photoluminescence intensity of quantum wells decreased with increasing strain. A lattice matched 9 nm QW exhibited a luminescence intensity that is three times greater than its highly strained counterpart. The potential applications of this strain engineering will be discussed. © *2000 American Institute of Physics.*
[S0003-6951(00)01732-0]

The vast potential of GaN, AlN, InN, and their alloys for ultraviolet to far-red optoelectronic devices, high frequency devices, and power applications has been established.[1–3] However, many issues involving important materials properties remain unresolved. The large lattice mismatch of the nitrides can result in device active layers experiencing significant biaxial stress, especially for AlGaN/InGaN or GaN/InGaN heterostructures. Furthermore, the III nitrides also possess large piezoelectric constants, which produce an additional class of strain-related phenomena for these compounds.

Many studies have analyzed the optical properties of InGaN quantum wells (QWs).[4–8] Motivations for these investigations involve the unusual optical properties for InGaN QWs. First of all, InGaN layers are very efficient emitters despite the presence of defect densities that would destroy radiative recombination in other III–V compounds. Also, an energy shift between absorption and emission spectra is frequently observed for InGaN-based layers, and several investigators have reported a blueshift in emission energy as carrier injection levels are increased in InGaN QWs.

Previous studies have been performed using GaN/InGaN or AlGaN/InGaN QWs. In this scheme, the InGaN well layer is subjected to compressive stress. In order to develop a better understanding of InGaN QWs, measurements of structures in which the well experiences tensile stress and zero stress are highly desirable. This can be achieved with the use of the quaternary alloy AlInGaN. Use of a quaternary film as the barrier for an InGaN QW allows independent control of the barrier height and lattice constant. This flexibility allows the lattice strain experienced by the InGaN QW layer to be varied between compressive, zero, and tensile strain. Progress in the epitaxial growth of $Al_xIn_yGa_{1-x-y}N$ has resulted in films with good optical properties for compositions of $0<x<0.26$ and $0<y<0.11$.[9] This range allows the growth of AlInGaN/$In_{0.08}Ga_{0.92}N$ QWs for which the band gap of the barrier is equal to 3.4 eV and the a-axis lattice constant is nearly equal to that of strain-relaxed $In_{0.08}Ga_{0.92}N$. In this letter, we report on the effects of strain on the optical properties of AlInGaN/InGaN QW structures grown by metalorganic chemical vapor deposition (MOCVD).

Samples were grown on c-face sapphire in a vertical reactor MOCVD system. First, a low temperature AlN buffer layer is deposited. This step is followed by the deposition of 2 μm of GaN. A 0.45 μm layer of $In_xGa_{1-x}N$ is then grown to serve as the new growth template. For the indium content used, this thickness exceeds the critical layer thickness, indicating the film is relaxed.[10] The lattice constant of the template is varied by changing x. On top of the InGaN template, the AlInGaN/$In_{0.08}Ga_{0.92}N$/AlInGaN QW structure is grown (Fig. 1). Details of quaternary growth can be found elsewhere.[9] The widths of the AlInGaN barriers are 150 and 30 nm for the bottom and cap layer, respectively. Thus, the total thickness of the double heterostructure is less than the expected critical layer thickness for AlInGaN on $In_xGa_{1-x}N$ for the compositional ranges investigated assuming the quaternary has similar elastic properties as InGaN.[10] The strain in the QW structure is determined by the lattice parameter of the $In_xGa_{1-x}N$ template. If $x=0.08$, the QW is unstrained. If $x>0.08$, tensile stress exists in the well, and compressive stress is created when $x<0.08$. The composition of the AlInGaN barrier is chosen such that the band gap is equal to 3.4 eV, and the unstrained lattice parameter is nearly equal to that of unstrained $In_{0.08}Ga_{0.92}N$.

An alternative scheme to achieve the same strain conditions in the QW would utilize very thick AlInGaN layers grown directly on GaN. For this case, defect generation would originate in the quaternary layer as opposed to the InGaN template. Samples grown with a thick quaternary layer but without the InGaN template demonstrated poorer optical properties related to interface roughness than did

a)Electronic mail: meaumer@eos.ncsu.edu
b)Electronic mail: bedair@eos.ncsu.edu

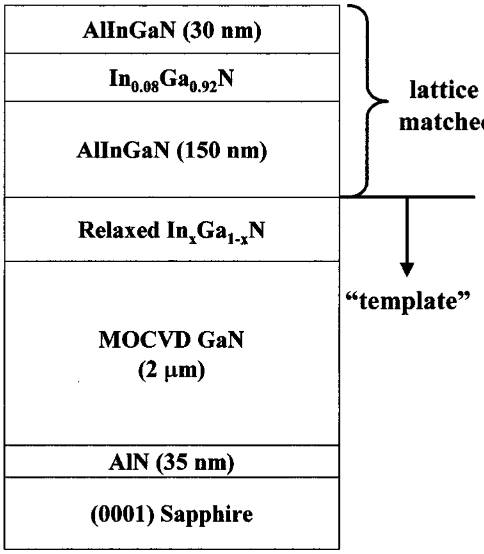


FIG. 1. Cross section of test structure grown. $In_{0.08}Ga_{0.92}N$ QW and AlInGaN cladding are pseudomorphic to the relaxed InGaN layer. Strain is varied by changing x.

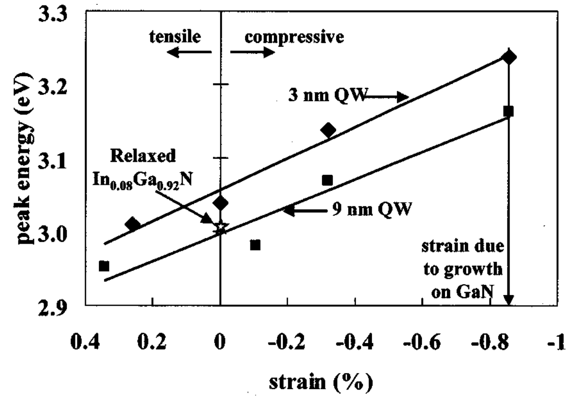


FIG. 3. PL peak energy vs strain for $In_{0.08}Ga_{0.92}N$ QWs. (Diamonds) 3 nm QWs. (Squares) 9 nm QWs. The star indicates the band gap for fully relaxed $In_{0.08}Ga_{0.92}N$. The strain equivalent of growth on GaN occurs at 0.86% compressive stress.

samples with the InGaN template. The reason for improved quaternary quality when grown on an InGaN buffer with the identical in-plane lattice constant is still under investigation.

Two sets of samples were grown for this study. The InGaN QW width was either 3 or 9 nm, and the strain in the QW was varied from 0.4% tensile stress to 0.86% compressive stress. The latter number corresponds to the strain equivalent of pseudomorphic growth of $In_{0.08}Ga_{0.92}N$ on a thick layer of GaN. The stress was calculated using the relationship $\sigma_{xx} = a_s / a_f - 1$, where a_s and a_f are the a-axis lattice constant for the substrate and film, respectively. In our samples, the InGaN template is the substrate and the $In_{0.08}Ga_{0.92}N$ well is the film. Values of the lattice parameters were obtained by x-ray diffraction measurements of thick, relaxed films grown under identical conditions. The films were characterized using photoluminescence (PL) and capacitance–voltage measurements ($C-V$).

The optical properties of these films are demonstrated by the room temperature PL for the 3 nm QWs (Fig. 2). Since narrow wells are particularly sensitive to surface roughness, the narrow peaks and subdued deep level emission indicate the presence of a good interface between the AlInGaN barrier and the InGaN well layer. As expected, the peak emission energy of the QWs increased due to compressive stress and decreased when subjected to tensile stress (Fig. 3). For the 3 nm QW, the peak energy shifts by 206 meV when the compressive strain is eliminated. The peak energy is reduced another 30 meV when the InGaN is subjected to 0.25% tensile stress. The peak energy trend is very similar for the case of the 9 nm QWs. Reducing the strain from 0.86% compressive to 0.34% tensile results in a redshift of the PL peak energy by 211 meV. The peak energy positions for the 3 nm QWs are uniformly higher than the peak energy for a 9 nm well subjected to the same stress. Quantum size effects can account for this behavior which, due to the large effective masses in the nitrides, are not usually significant for thick wells.

The strain dependence of PL peak position illustrates one possible application for strain engineering. Long wavelength emitters can be obtained with relatively low indium compositions in the active layer. This is significant because the solid solubility of indium in GaN is predicted to be about 8% at our growth temperature of 875 °C.[11] To emit light at 420 nm, the indium content required in the active layer of a 9 nm InGaN QW clad by GaN is 13%. Such a film is more

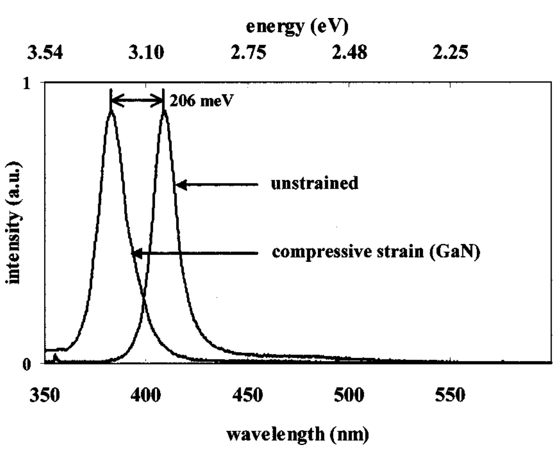


FIG. 2. Room temperature PL of 3 nm QWs under compressive and zero strain. Peak energy shifts by 206 meV going from compressive to zero strain.

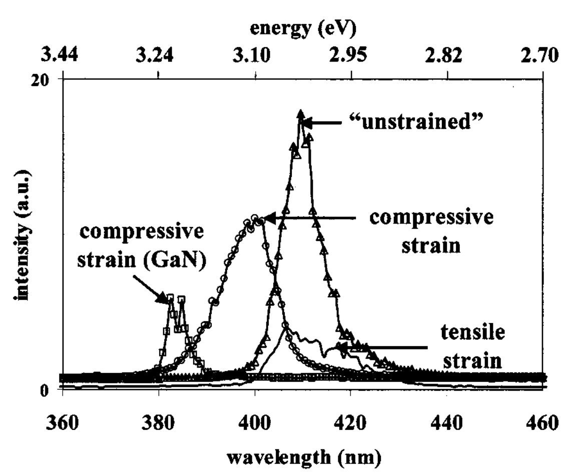


FIG. 4. 10 K PL for 9 nm $In_{0.08}Ga_{0.92}N$ QWs subjected to varying amounts of lattice-mismatch induced strain.

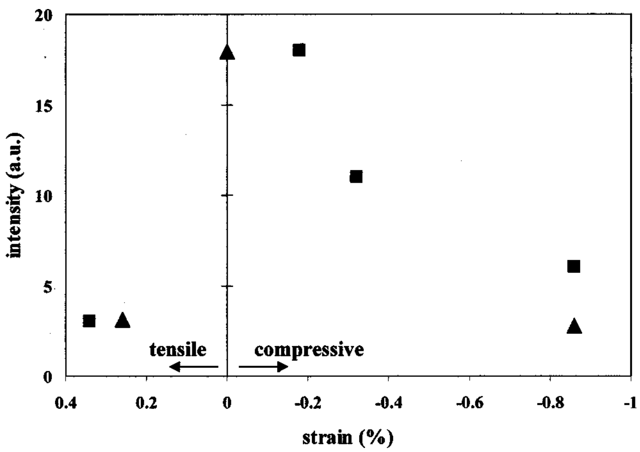


FIG. 5. Peak PL intensity vs strain at 10 K. (Squares) 9 nm QWs. (Triangles) 3 nm QWs. An unstrained QW is three times as intense as its highly strained counterpart.

susceptible to the potentially deleterious effects associated with phase separation, ordering, interface roughness, and compositional fluctuations. However, in our test structure, emission at 420 nm from a 9 nm QW is attainable with 8% InN in the active layer when it is subjected to tensile stress. The emission wavelength of such a QW grown on GaN is only 393 nm.

In Fig. 4, the 10K PL for the set of 9 nm QWs is plotted. The peak energy varies as expected with strain. The highest energy corresponds to the highest level of compressive stress, but the peak intensity also exhibits strain dependence. Plotting peak intensity versus strain emphasizes the relationship (Fig. 5). The intensity is a maximum for the nearly lattice matched QW. If strain is increased, the intensity is reduced for both tensile and compressive cases. One possible explanation of this trend involves the role of piezoelectric fields. For the nearly lattice matched QW, the piezoelectric field is virtually zero. In this well, the electrons and holes are strongly coupled resulting in the highest radiative recombination rate.

For the strained wells, the piezoelectric field will cause spatial separation of electrons and holes thereby reducing the oscillator strength and luminescence intensity. If this effect were present, the electrons would accumulate at one interface for the case of compressive strain and the other interface when tensile strain exists. This shift in electron distribution is observable with $C-V$ profiling by a difference in the electron peak positions.[12] Because the background concentration of the quaternary barrier is almost 10^{18} electrons/cm^{-3}, partial screening of the piezoelectric field in the well is likely due to carrier diffusion. Apparently, this screening is significant enough to reduce the energy redshift due to the quantum confined Stark effect, but not strong enough to completely obscure the effects of field-induced carrier separation.

In summary, $In_{0.08}Ga_{0.92}N$ QWs have been grown subjected to varying amounts of in-plane biaxial strain, including tensile strain and no strain. The strain was found to significantly effect the optical properties of the QW. PL peak intensity is reduced by the existence of strain, and the PL peak position can be shifted hundreds of meV by varying the strain. Thus, strain engineering is a tool to achieve long wavelength emitters when the use of active layers with high indium content is undesirable.

This work is supported by the Army Office of Research. The authors would also like to acknowledge Gregg McIntosh and John Roberts for their professional assistance.

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