Growth and Characterization of MBE Parametric Variations Upon
Polarization Independent Strained Films

FINAL REPORT

For the Period of July 1, 2001-August 31, 2003

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April 2003

U.S. Department of Energy
Award No. DE-FG02-97ER45648

Overview

This project was designed to comprehensively investigate the effects of molecular beam epitaxy (MBE) growth variations upon tensile-strained films. Using two dimensional (2-D) structures, such as quantum wells of variable configurations, we worked to observe the electro-optical response of polarization independence. The latter had been studied for compressively strained systems. However, the proof of principle for the feasibility of tensile-strained single and double quantum wells, particularly in the GaAs as opposed to the InP material system, had been much less investigated by comparison. In fact, tensile-strain, unlike compressive strain, provides an opportunity to modulate the heavy-hole/light-hole juxtaposition of subbands in the valence band (VB) of a given 2-D configuration and to therefore alter the photon polarization of in-plane optical transitions simply by changes in the well width and the degree of strain. Although theoretical calculations in the literature indicated that the in-plane effective mass for a tensile-strained/light hole (lh) subband, uppermost in the VB, would be greater than that for the like strained yet heavy hole (hh) subband uppermost configuration, the flexibility of design and phenomena provided by a VB subband engineered system, we believed, was not to be overlooked. Moreover, current literature had few yet promising examples of how the incorporation of tensile-strain could reduce the threshold current density of quantum well lasers. However, the aforementioned devices were based in multiple quantum well designs with additional complexities, thereby overwhelming one's understanding of the potentially very interesting physics involved the manipulation of polarization sensitivities and similar electro-optical responses. Hence, in our study, which involved at most double quantum well systems, we have been able to tap into the parameters needed and mechanisms involved where tensile-strain is employed.

In turn, we sought to push the limits of our characterization techniques which were used to examine the strained systems. Some interesting results, to be discussed later, were obtained and will require further examination. Yet, as per our original goals, noteworthy progress was made in the direction of finding evidence to support the use of phenomena observed in, for example, next-generation high-speed and communication devices. In effect, putting together a study of essentially electronic materials, physics, and electrical engineering provided a fertile test-bed upon which to probe for electro-optical mechanisms which have yet to be fully exploited.

The significance of this project, from a **Basic Energy Sciences** perspective, has been in its contribution to the understanding of how MBE parameters and sample design effect the physics of strained materials which themselves have been tailored to react with polarization insensitivity. Fundamental issues of materials structure control, growth parameter modifications, and characterization methods were investigated. Both single and double quantum well systems were used with both symmetric and asymmetric well widths for the latter. Thus, coupling effects were considered. Along with the bandgap phenomena necessary to pursue our basic goal of better understanding how MBE could be used to monitor these strained systems, these quantum wells provided a launching point for our current and future work in low-dimensional structures (i.e.-quantum wires/dots). Therefore, in this work, we essentially investigated both the growth of and potential applications for quantum based structures that use tensile strain to induce polarization independence.

1. Project Goals

As this report pertains to years 1 and 2 of our proposed research, the primary goals for these time periods were as follows: 1) MBE growth of GaAs/In_xAl_{1-x}As tensile-strained layers, and 2) Characterization studies of test samples with refined MBE growths.

1.1 Year 1: Tasks and Accomplishments

In the first year of our work, as proposed, we made preparations to grow GaAs/InAlAs tensile-strained layers which were fairly complex in terms of parameters such as substrate temperature and flux variations. To monitor our progress, we began a series of characterization studies, mainly using photoluminescence (PL) and high-resolution x-ray diffraction (HRXD).[†] Via an iterative process of growth and characterization, we identified two types of quantum well systems as the most promising for further study. These were the symmetric double quantum well (SDQW) configuration and that of the asymmetric double quantum well (ADQW). Simply, for the SDQW, both well widths in the GaAs/InAlAs structure were approximately equal. For the ADQW structure, the well widths were purposefully non equivalent. In both cases attention was given to the width(s) with respect to the degree of strain to produce a structure with the light hole (lh) subband uppermost. Our starting point for knowledge of the necessary strain-width combinations came from the earlier theoretical studies of our collaborator, McNeil. [1] (Note that we had produced single quantum wells, in conjunction with McNeil's calculations, to test our basic technique prior to the growth of the double well systems described above. [2])

From this effort, a significant highlight emerged in terms of our demonstration of reasonable agreement between theoretical fundamental transition energies in tensile-strained GaAs/InAlAs SDQWs and experimental results. [3] From our earlier calculations,[4] we identified the effects of electric field upon optical absorption that would be valuable for proof of principle of possible device applications. Likewise, we investigated the expected eigenenergies in a double quantum well construct such as our symmetric and asymmetric designs. Coupling effects and the E-field induced changes in eigenstates were calculated using the transfer matrix method as built upon the framework of the Bastard envelope approximation. Interestingly enough, this work showed that theoretically a single quantum well system (sized and strained for a polarization independent response) would exhibit a more straightforward (i.e.-monotonic) response in transition energy to an applied E-field. However, double quantum wells, as in our SDQWs and ADQWs, seemed to exhibit polarization sensitivity over a wider bias range, presumably due to coupling effects. Thus, upon this theoretical basis, we grew tensile-strained double quantum wells that did indeed exhibit reasonable agreement in transition energy to that which had been predicted in our calculations. with one interesting caveat follows: Growth of these tensile-strained structures showed a slightly higher In mole fraction than intended via in-situ reflection high energy electron diffraction (RHEED) and ex-situ high resolution x-ray diffraction (HRXD) measure-

[†] We gratefully acknowledge the assistance of our collaborators in this work as follows: Prof. L. E. McNeil of the University of North Carolina, Chapel Hill, for PL measurements, and Prof. W. P. Lowe of Howard University for HRXD.

ments. [5] Since the interplay between degree of strain, as related to In mole fraction, and well width was predicted to be a critical factor in the realization of a polarization independent response, one could interpret this result to mean that the width-strain formulation was more robust and less stringent than originally realized. However, what we found to be more curious was the fact that In deposition, and therefore the mole fraction, was more effected by the strain in the epitaxial layers than had been originally anticipated. To fully understand this aspect of the MBE parameteric effects upon the electro-optical behavior of these structures further study will be needed.

Finally, we were able to broaden our originally proposed study of quantum wells to that of lower dimensional systems, namely quantum wires and quantum dots. This effort was supported by the allocation of supplemental funding from the DOE to our grant so as to enable employment of a postdoctoral research associate. Hence, we explored the growth parameters necessary to produce reproducible structures that might exhibit some degree of polarization independence or at least characteristics amenable to this phenomenon. Our preliminary Year 1 work resulted in a better understanding of how composition, such as spacer layer thickness, and factors such as growth direction would effect low-dimensional morphology in the InAsAs system. [6]

1.2 Year 2: Tasks and Accomplishments

We began Year 2 with a more detailed characterization study, using HRXRD with the Lowe group of Howard University, to look at strain effects in our samples. Comparisons were made between theoretical and experimental rocking curves with respect to the amount of strain as intended from the growth process. Here we investigated MBE grown pseudomorphic versus fully relaxed material in terms of the 1 μ m InAlAs buffer layer which stimulates tensile-strain in the DQW configurations (ref. 5). Evidence emerged to show that this buffer layer would form somewhere between the fully strained to fully relaxed range, thus producing a strained system which was more complex than originally predicted. The level of diffraction analysis necessary to further pursue this point was, at the time, beyond our equipment's capability and actually beyond the scope of the project. Future work may allow for additional investigation. However, the significant and very useful data point of information which emerged from our characterization study was that the DQW structures were more robust than originally realized (i.e.-not as sensitive to the well-width/strain combination) and showed promise for the exhibition of preliminary electro-optical phenomena. This information, along with supportive data from transmission electron microscopy (TEM) measurements and PL verified the work had progressed appropriately.

With respect to the investigation of lower dimensional structures, we continued our growth studies of quantum dots (QD) and quantum wires (QWR). In our Year 1 work, we examined InAs QDs and QWRs as formed on InP substrates. The change to InP from GaAs in this portion of the work was motivated by the fact that, comparatively speaking, significantly fewer studies had been done on the InAs QD/QWR system for the InP substrate. We investigated the formation characteristics of these structures using various matrix layers including an InAlGaAs one which was likewise relatively unique for this system. [7] Atomic force microscopy (AFM), in conjunction with was used to study the surface morphology of each sample. Results at this point indicated that the formation of

either InAs QDs or InAs OWRs depended upon the matrix selected (i.e.- $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$, $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$, and $\text{In}_{0.53}\text{Al}_{0.10}\text{Ga}_{0.37}\text{As}$) to provide the strained template upon which the given nanostructure developed. Moreover, the effects of matrix selection upon the formation of vertically correlated or anticorrelated nanostructures was demonstrated with the (preliminary) conclusion that this structural phenomenon could be ascribed to size of the QDs or QWRs formed. Further investigation would require a numerical analysis that would take into account the interactions between factors such as shape of the nanostructure (i.e.-QDs, elongated QDs, QWRs), In segregation as stimulated by composition modulation, kinetic effects, growth front development, and of course, strain.

2. Future Work

The results given above represent the conclusion of this project as it has been supported through Duke University. The PI has since transferred to another university and now seeks to complete the originally proposed Year 3 work at the new institution. Efforts are underway at the latter to prepare the necessary equipment and personnel to successively continue this project. Thus, intended future work will involve more intensive materials characterization studies. Likewise, data obtained from years 1 and 2 will be correlated in an effort to provide a more formalized understanding of the strained materials and nanostructures studied. From this information, we hope to determine a predictable pattern of MBE parametric effects upon the characteristics of the systems investigated.

Finally, although this investigation has been directed toward the physics and materials science aspects of the samples, it is nonetheless important to realize the potential applications of the results obtained. DQWs exhibit lower electro-optic efficiencies compared to multi-quantum well structures. However, the "simplicity" of the DQW is critical to establishing a manageable model by which to better understand phenomena such as polarization independence. This study, to date, has provided valuable information in terms of both the characteristics and challenges of producing electro-optic interactions as induced by strain. Future energy focused optoelectronic devices will require improved control of the optical response for high speed/high density signal transmission. Thus, continuing progress in this work stands to impact the development of stable low-cost components for next-generation energy technologies.

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