Extended Abstracts of the 1993 International Conference on Solid State Devices and Materials, Makuhari, 1993, pp. 8-10 **A-0-3**

Invited

Recent Progress in Quantized Electronic Structures

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Recent experimental and theoretical results on low-dimensional quantum structures will be reviewed. The current status of so-called Serpentine Superlattices will be described, as well as fabrication techniques utilizing patterning or template formation, either before or after epitaxial growth. Finally, novel spectroscopic techniques will be described that are expected to prove useful for future investigation of quantum wires and dots.

1. WHAT'S NEW IN SERPENTINE SUPERLATTICES?

The conception and development of Serpentine Superlattice (SSL) quantum wires has been a major activity at QUEST.[1)] These structures are grown by molecular beam epitaxy (MBE) or metal-organic chemical vapor deposition (MOCVD) on vicinal substrates misoriented by a few degrees, providing periodicity of the order of 100 Å, and hence are suitable for quantum confinement. The "serpentine" structure results from periodically varying the fraction of a monolayer of two constituents grown in each cycle from less than to more than a single monolayer. Much work has been done on SSL formation in the AlGaAs/GaAs compound semiconductor system,[2-4)] including detailed optical polarization, magneto-optical, and time-dependent luminescence measurements, and the situation is now quite clear: uniform quantum wires are obtained but carrier confinement is weaker than desired. Holes are weakly confined in two dimensions but the electrons are confined only in one; i.e., they behave as in a quantum well. The weak confinement is a result of intermixing of Al and Ga in the superlattice (SL) layers. Original estimates of this intermixing showed that approximately 30% of the Al intended for the barrier ended up in the well; more recent studies suggest that this number might be slightly high (i.e., it should be closer to 25%), but the intermixing is nevertheless severe.

The origin of this mixing is now felt to be understood, arising from a vertical exchange reaction between Al and Ga. This was first noted by observing the formation of a self-organizing lateral SL — the deposition of alternate complete monolayers of GaAs and AlAs should result in $(AlAs)_1(GaAs)_1$ short period SLs in the growth direction, with no lateral compositional modulation. An unexpected lateral modulation was nevertheless observed, and was explained by a model that includes an anisotropic Al-Ga vertical exchange reaction under ideal step-flow growth; i.e., Al exchanges with Ga, but not vice versa. Computer simulations have confirmed this effect.

Despite this intermixing, we have been able to fabricate double heterostructure (DH) lasers whose active layer consists of a SSL, and we have studied the behavior of such lasers for cases where the SSL quantum wires were either parallel or perpendicular to the laser axis. A theoretical treatment of the case where the wires are parallel to the laser cavity shows that the TM laser mode should have higher gain, and this has been observed, indicating that 2-D confinement is indeed affecting the lasing characteristics.

Increased segregation has been obtained for two variations of the SL growth described above: (1) growth on (110)-misoriented substrates rather than (100), and (2) growth of AlGaSb/GaSb SSLs. In the former case, severe step-bunching is observed, which results in faceting of the resulting SLs[5)]. However, in the latter case, greatly improved segregation of Al and Ga results, particularly when SSLs are grown on GaSb substrates.[6] These results may have important application to very long wavelength devices, such as infrared lasers and detectors.

2. GROWTH ON PATTERNED TEMPLATES

Holographically patterned GaAs substrates have been used to grow InGaAs multi-quantum wires with high luminescence efficiency and polarized emission.[7] The technique used here, referred to as AMBE, is to alternate the beams of the group III species and As. This results in significantly increased surface migration lengths compared to the usual case with simultaneous beams present, so that the quantum wires formed in the bottom of the substrate grooves are more uniform in cross section. Another important procedure used is to stop the growth after deposition of the InGaAs layer. This results in additional migration of the InGaAs from the quantum wells which develop on the sidewalls of the substrate grooves, to the quantum wires formed in the bottom of the grooves, reducing the lateral dimension of the quantum wire, and increasing the lateral confinement. Photoluminescence (PL) efficiency of the wire increased by a factor of ≈ 3 using this technique, and the PL showed a polarization ratio of $\approx 21\%$.

A very different but highly controllable type of a template for the formation of quantum wires and dots is represented by the family of "cage" compounds such as the zeolites and mesoporous materials.[8] If a zeolite is used as a host for semiconductor or other technologically interesting materials, it is possible to disperse the material in very small clusters (a few Å to 10 or 15 Å), and assemble those clusters in periodic structures. As an example, Na atoms have been found to donate electrons to the overall material system when they are absorbed in a zeolite cage. The crystallography, band structure, optical absorption and photon-induced ion mobility of these systems have been explored both experimentally and theoretically. Mesoporous materials, such as SiO_2, $Al(Si,P)O_4$, and $Al_xSi_yO_4$, have monosized channels that are somewhat larger than the zeolites, in the range of 14 to 100 Å, which make them very suitable for the formation of quantum wires. Recently, GaAs wires have been deposited inside the cylindrical pores of SiO_2 using MOCVD, and a broad luminescence band has been observed in the visible portion of the spectrum from only those samples loaded with GaAs.

3. POST-GROWTH PATTERNING AND THE FORMATION OF STRESSORS

A variety of post-growth patterning procedures have long been used to make quantum structures. The most obvious of these utilize lithographic techniques (often in concert with high-resolution electron beams or x-ray beams) to produce metal surface electrodes which can be used to deplete carriers from selected regions of quantum wells, forming complicated gate structures for coherent electron transport studies. These investigations will not be reviewed here, for lack of time, though they constitute an important area of research on low-dimensional quantum structures. Instead, we will highlight a few recent examples where post-growth patterning has resulted in lateral modulation of semiconductor bandgaps through Fermi level pinning or lateral stress patterns. A recent example of this is the lateral periodic potentials formed by surface-layer modulation in InAs/AlSb quantum wells.[9] In this work the pinning position of the Fermi level at the surface is demonstrated to shift by 200 meV depending on whether the surface layer is GaSb or InAs, thereby strongly influencing the electron concentration in an InAs quantum well clad by AlSb. The InAs/AlSb DH is covered by thin surface layers of GaSb and InAs, and the top InAs layer is periodically removed, resulting in the modulation of the Fermi level pinning mentioned above. Large anisotropies in the magneto-resistance of these structures have been observed for transport parallel and perpendicular to the InAs surface stripes.

Strained InGaAs structures have also been used to produce quantum wires and dots in buried GaAs/AlGaAs quantum wells through stress-induced local variations in the GaAs bandgap. This is done by etching patterns into InGaAs quantum wells, modulating the strain at the GaAs quantum well. InGaAs "stressors" can be employed near the surface of the sample[10,11] or buried well below GaAs quantum wells, which are regrown over the stressor after patterning.[12] Large subband spacings and confining potentials have been observed. More recently, a very novel effect has been observed by D. Leonard et al at QUEST. It has long been observed that large islands occur when one tries to grow InGaAs surface layers on GaAs, resulting in severe dislocation networks in the GaAs. However, under controlled growth allowing In migration, this process can be utilized to form randomly distributed islands of InGaAs whose size is very uniform, resulting in uniform strain patterns on an underlying GaAs waveguide; that is, an array of uniform quantum dots is produced. Characterization of these dots is underway, and will be reported.

4. NOVEL SPECTROSCOPIES FOR QUANTUM WELLS AND LOWER DIMENSIONS

The conclusion of this talk will briefly describe a number of novel spectroscopic techniques currently being developed to investigate the physics of quantum wells, which will be extremely useful for the study of lower-dimensional structures. These include (1) the use of surface-barrier tunneling studies to investigate surface passivation,[13)] a phenomenon of increasing importance as the structure dimensionality decreases; (2) optically-detected terahertz response of carriers in nanostructures,[14)] and (3) Faraday rotation and spin dynamics in magnetic semiconductor heterostructures.[15)] The significance of each of these novel investigations will be explained.

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