Extended Abstracts of the 1996 International Conference on Solid State Devices and Materials, Yokohama, 1996, pp. 193-195

Invited

Self-Ordered Quantum Nanostructures Grown on Nonplanar Substrates

Eli KAPON

Laboratory of Nanostructures, IMO-Department of Physics
Swiss Federal Institute of Technology, 1015 Lausanne, Switzerland

Recent progress in the realization of low-dimensional quantum structures formed by self-ordering on nonplanar substrates is reviewed. In particular, GaAs-based vertical quantum wells (VQWs) and quantum wires (QWRs) grown by organometallic chemical vapor deposition on V-grooved substrates are described. Distinct nano-faceting at the growth front results in well defined QWR and VQW structures with lateral dimensions in the sub-10 nm range. Clear subband structure and polarization anisotropy related to the low-dimensionality are exhibited in photoluminescence excitation spectra of these nanostructures. Diode lasers incorporating such self-ordered QWRs and VQWs are also discussed.

1. INTRODUCTION

Self-ordering of nanostructures is an attractive approach for the realization of low-dimensional quantum structures, particularly those with dimensionality lower than two, e.g., quantum wires (QWRs) and quantum dots (QDs). These structured materials show interesting, new optical and electronic properties associated with multi-dimensional quantum confinement and reduced dimensionality, which makes them attractive for applications in novel electronic and optoelectronic devices. However, the extremely small size (<10 nm), high uniformity (on the atomic level) and defect free interfaces required in useful QWRs and QDs present considerable challenges in their fabrication. Conventional, lithography-based techniques are of little use in this context due to limitations in achievable minimum size and uniformity. On the other hand, spontaneous self-ordering processes, which can in principle overcome these limitations, usually lead to a broad distribution of the size of the quantum structures and do not offer a direct control of their positioning.

It has already been demonstrated that organometallic chemical vapor deposition (OMCVD) of AlGaAs in channels oriented along the

defect free, crescent-shaped wires of lateral dimensions in the 10nm range[2]. In addition, segregation of group-III species at the bottom of the grooves leads to the formation of AlGaAs vertical quantum wells (VQWs) at the center of the groove[3]. For both these types of self-ordered quantum structures, the initial channels in the patterned substrate serve as seeds determining the sites of the wires/wells, but the structure and shape of the nanostructures are determined by the composition and growth conditions only[4]. Similar GaAs/AlGaAs, InGaAs/AlGaAs, InGaAsP/InP, SiGe/Si and GaAs/AlGaAs on Si self-ordered QWRs grown by OMCVD or molecular beam epitaxy (MBE), on nonplanar substrates formed by etching or by growth on patterned substrates have been investigated[1,5-13].

In the present review we concentrate on the more recent development of GaAs-based V-groove QWRs and VQWs grown by low-pressure (LP-)OMCVD.

2. STRUCTURE OF SELF-ORDERED VQWS AND QWRS

The GaAs/AlGaAs VQW and QWR structures discussed here were grown at 20 mbar and at temperatures between 650 and 765°C. Figure 1 shows a dark-field TEM cross section of part of a vertically-stacked array of GaAs/AlGaAs QWRs grown in a V-groove[14]. The LP growth results in a nano-faceted, self-limiting surface profile at the bottom of the groove, characterized by a center (100) facet flanked by two {311}A lateral facets. The extent of these facets depends on the Al content, which leads to the formation of a crescent shaped QWR whose size and shape can be controlled by the barrier composition, GaAs thickness, and the growth conditions. In addition to the QWRs, a VQW structure consisting of several branches is formed in the AlGaAs barriers. Each of the VQW branches originates from a different nano-facet, and their convergence to a stable, vertical structure demonstrates the self-limiting nature of the growth process.

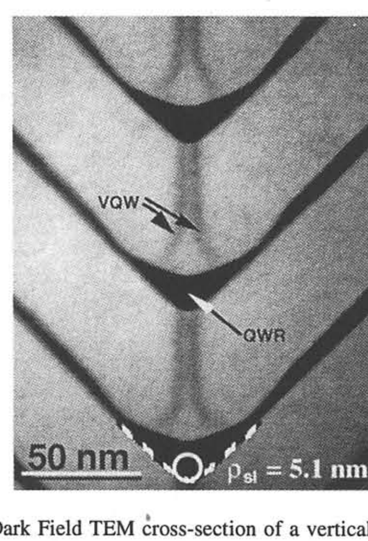

Fig. 1. Dark Field TEM cross-section of a vertically-stacked array of GaAs/AlGaAs QWRs grown by low-pressure OMCVD[14].

A high resolution transmission electron microscope (TEM) cross section of a V-groove QWR structure grown at LP is shown in Fig. 2[14]. The wire interfaces are abrupt within one or two monolayers. Atomic force microscopy of similar (surface) QWRs show that such monolayer-defined interfaces extend along sections of at least a few 100 nm along the wire axis[15].

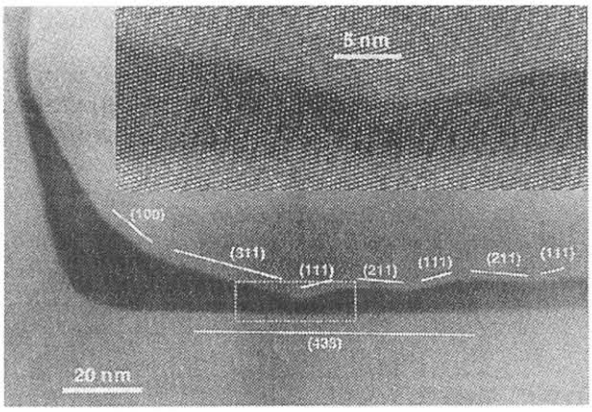

Fig. 2. High resolution TEM of a crescent-shaped QWR grown by low-pressure OMCVD[14]. The inset shows a magnified view of a detail of the wire.

3. OPTICAL PROPERTIES

A low temperature photoluminescence (PL) spectrum of a GaAs/$Al_{0.3}Ga_{0.7}As$ V-groove QWR structure grown on a 0.5 µm-pitch grating by LP-OMCVD is shown in Fig. 3[16]. The PL spectra are typically characterized by an excitonic QWR line at lower energies, and several higher energy lines resulting from recombination in the QW barriers surrounding the wires. Low temperature PL linewidths range from 5.5 to 7 meV for crescent (center) thicknesses of 14 to 4 nm, respectively. These linewidths are considerably narrower than those measured for similar structures grown at atmospheric pressure. Moreover, they are comparable to the PL linewidths of GaAs/AlGaAs QWs of similar thickness, grown by LP-OMCVD on (100)-GaAs planar substrates.

Low temperature PL excitation (PLE) spectra of these QWRs show well resolved peaks due to absorption at their 1D subbands (see Fig. 4)[16]. Detailed investigations of a series of such wires, with different QWR sizes and Al contents in their barriers, indicate good agreement between the observed subband separations and the calculated e-hh 1D transition energies based on a 2D model of the wire potential well[16]. The PLE spectra measured with an exciting beam polarized parallel or perpendicular to the wires show distinct polarization anisotropy associated with valence band mixing. The Stokes shifts at 10K vary between 8 and 4 meV for crescent (center) thickness of 4 to 14 nm. These Stokes shifts arise from potential fluctuations along the wire axis, caused by crescent size fluctuations and Al content variations in the surrounding barriers. The same potential fluctuations are responsible for exciton localization at low temperatures; exciton delocalization at temperatures T_{del} comparable to the potential fluctuations manifests itself in the vanishing of the Stokes shift above T_{del}.[16]

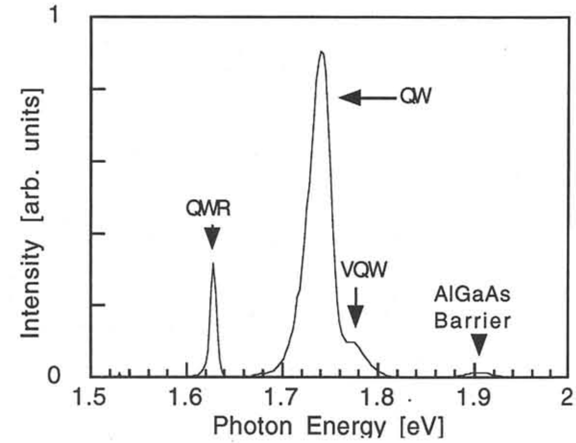

Fig. 3. Low temperature (10K) photoluminescence spectrum of a GaAs/AlGaAs V-groove QWR structure (4 nm center thickness)[16].

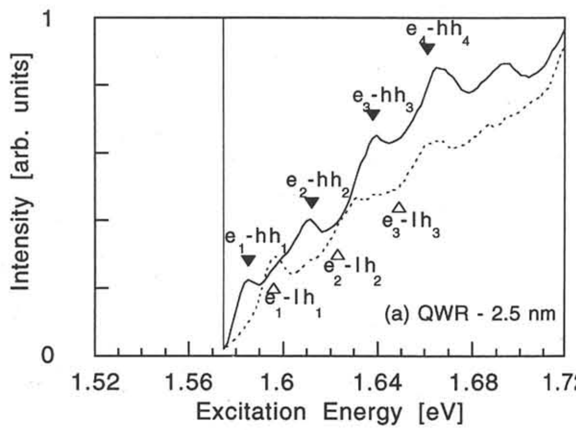

Fig. 4. Low-temperature PL excitation (PLE) spectra of a V-groove QWR structure (9 nm crescent thickness), shown for excitation polarization oriented parallel (solid line) and perpendicular (dashed line) to the wire axis[16].

The observed subband separation generally increases with increasing Al mole fraction in the barriers and with decreasing growth temperature (for fixed crescent thickness). Both effects lead to a decrease in the radius of curvature of the groove profile underneath the crescents and hence to a narrower lateral potential. Figure 5 shows the PLE spectra for the smallest wires investigated so far, for which the measured subband separation is about 45 meV[17]. Further optimization of the structures and the growth conditions are expected to increase the subband separation to 2-3k_BT_{room}.

4. APPLICATION IN DIODE LASERS

Diode lasers incorporating GaAs/AlGaAs V-groove QWRs grown by atmospheric pressure OMCVD operated at room temperature with threshold currents as low as 0.6 mA (high-reflection coated devices)[18]. Strained InGaAs/GaAs V-groove QWR lasers grown by MBE exhibited threshold currents as low as 100 µA (uncoated mirrors) at room temperature[19]. However, both laser types tend to lase from an excited 1D subband at room temperature, due to subband filling. At lower temperatures (typically below 70K for single QWR GaAs/AlGaAs lasers with subband separation of 10-15 meV), lasing at the ground electron and hole 1D states has been observed[20].

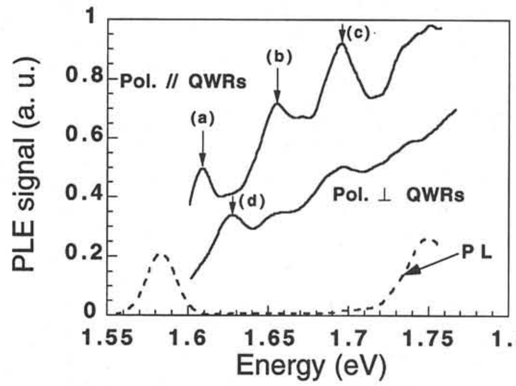

Fig. 5. Low temperature PL and PLE spectra of a GaAs/AlGaAs QWR structure with a large (45 meV) one-dimensional subband separation[17].

The VQW structures are interesting for laser and other optoelectronic device applications both since they assist in carrier capture into adjacent QWRs[21], and because they can serve as an active region as well. Lasing from such VQWs has been observed, with the laser beam polarized in the plan of the VQW, consistent with 1D quantum confinement of the carriers[22]. Intersubband transitions in such doped VQW, observed recently, suggest their use in top illumination infrared devices; unlike conventional, layered QWs, these heterostructures are useful for such applications since their confinement direction lies in the wafer plane[23].

5. CONCLUSIONS

Considerable progress has been achieved recently in the realization of self-ordered QWR and VQW structures grown by low-pressure OMCVD on nonplanar substrates. The currently achievable uniformity of these wire and well structures permits the clear observation of 1D and 2D quantum confinement effects. Diode lasers incorporating these self-ordered quantum structures, operating at room temperature, have been demonstrated. Further progress in the optimization of these nanostructures, their use in studies of the physics of 2D and 1D system, and their applications in optoelectronic devices is expected.

ACKNOWLEDGMENT

This work was supported by the Fonds National Suisse de la Recherche Scientifique.

References

1) E. Kapon, in *Epitaxial Microstructures*, A.C. Gosssard, Ed., Semiconductors and Semimetals **40** (Academic Press, New York, 1994), pp. 259-336.
2) E. Kapon, D.M. Hwang and R. Bhat, Phys. Rev. Lett. **63**, (1989) 430.
3) E. Kapon, M. Walther, J. Christen, M. Grundmann, C. Caneau, D.M. Hwang, E. Colas, R. Bhat, G.H. Song and D. Bimberg, Superlattices and Microstructures **12**, (1992) 491.
4) E. Kapon, G. Biasiol, D.M. Hwang and E. Colas, Microelectronics J. **26** (1995) 881.
5) R. Bhat, E. Kapon, J. Werner, D.M. Hwang, N.G. Stoffel and M.A. Koza, Appl. Phys. Lett. **56** (1990) 863.
6) S. Tsukamoto, Y. Nagamune, M. Nishioka and Y. Arakawa, Appl. Phys. Lett. **71** (1992) 533.
7) G. Vermeire, Z.Q. Yu, F. Vermaerke, L. Buydens, P.V. Daele and P. Demeester, J. Crystal Growth 124 (1992) 521.
8) Y. Hasegawa, T. Egawa, T. Jimbo amd M. Umeno, Jpn. J. Appl. Phys. **32** (1993) L997.
9) N. Usami, T. Mine, S. Fukatsu and Y. Shiraki, Appl. Phys. Lett. **63** (1993) 2789.
10) X.Q. Shen, M. Tanaka, K. Wada and T. Nishinaga, J. Crystal Growth **135** (1994) 85.
11) M. Grundmann, J. Christen, D. Bimberg and E. Kapon, J. Nonlinear Optical Physics and Materials **4**, (1995) 99.
12) M. Pfister, M.B. Johnson, S.F. Alvarado, H.W.M. Salemink, U. Marti, D. Martin, F. Morier-Genoud and F.K. Reinhart, Appl. Phys. Lett. **67** (1995) 1459.
13) X.L. Wang, M. Ogura and H. Matsuhata, Appl. Phys. Lett. **66** (1995) 1506.
14) A. Gustafsson, F. Reinhardt, G. Biasiol and E. Kapon, Appl. Phys. Lett. **67** (1995) 3673.
15) F. Reinhardt, G. Biasiol, B. Dwir and E. Kapon, to be published.
16) D. Oberli et al., Il Nuovo Cimento **17D** (1995) 1641.
17) E. Kapon, G. Biasiol, D.M. Hwang, E. Colas, and M. Walther, Solid State Electronics **40** (1996) 815.
18) E. Kapon, OPTOELECTRONICS- Devices and Technologies **8** (1993) 429.
19) S. Tiwari, in *Low Dimensional Structures prepared by Epitaxial Growth or Regrowth on Patterned Substrates*, K. Eberl et al. (eds.), (Kluwer Academic, 1995) 335.
20) N. Chiriotti, Diploma Thesis, EPFL, February 1996.
21) M. Walther, E. Kapon, J. Christen, D.M. Hwang and R. Bhat, Appl. Phys. Lett. **60** (1992) 521.
22) E. Kapon, B. Dwir, H. Pier, A. Gustafsson and J.M. Bonnard, Quantum Electronics Laser Sciences Conference (QELS '95), Baltimore, Maryland, May 1995.
23) V. Berger, G. Vermeire, P. Demeester and C. Weisbuch, Appl. Phys. Lett. **66** (1995) 218.