Journal of the European Optical Society - Rapid Publications 5, 10049s (2010) www.jeos.org

$(InP)_5/(Ga_{0.47}In_{0.53}As)_5$ superlattice confined 1.5 μm multiquantum well laser grown by all-solid source atomic layer molecular beam epitaxy.

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Room temperature laser emission near 1.55 μm is obtained in compressive strained multiquantum well separate confinement heterostructure grown at 340°C by solid source Atomic Layer Molecular Beam Epitaxy , where $(InP)_5/(Ga_{0.47}In_{0.53}As)_5$, lattice-matched short period superlattices have been used as pseudoquaternary barrier to confine $Ga_{0.27}In_{0.73}As$ wells . These preliminary results show that solid source Atomic Layer Molecular Beam Epitaxy is well adapted to fabricate advanced optoelectronic components including pseudoquaternary material. [DOI: 10.2971/jeos.2010.10049s]

Keywords: ultra short light pulses, mode locking, intensity correlation, nonlinear optics

1 INTRODUCTION

This paper was written in 1993. It was accepted with minor revision in Applied Physics Letters but the corrected version was not finally submitted. The results describe the fabrication for the first time of InGaAsP laser diodes with emission in 1.5 μm, at low growth temperature to facilitate its monolithic integration on chips, using all solid-source molecular beam epitaxy including phosphorous (P_2). For its time, the results were very relevant, especially for the Spanish incipient optoelectronic industry that funded the project. Today, many optoelectronic devices and lasers are grown by molecular beam epitaxy technique thanks to the P_2 solid source, which prototype was developed and tested by the authors of this paper at their laboratory in Madrid. Furthermore, the monolithic integration of active and passive devices is still a hot topic in present optoelectronic technology. The original paper starts in the next paragraph and some updated conclusions have been added at the end.

The growth of useful GalnAsP by solid source molecular beam epitaxy (MBE) is inhibited by the difficulty in maintaining precise composition control due to As/P competition for incorporation [1]. It requires controlling very accurately all growth parameters, such as flux from both effusion cells and substrate temperature. The use of pseudoquaternary GaInAsP semiconductors can conveniently replace conventional $Ga_xIn_{1-x}As_yP_{1-y}$ alloy in a variety of device applications [2, 3]. Ginty et al. [4] have reported laser emission at 1.64 μm in separate confinement SCH multiquantum well lasers grown at 625°C by metal organic vapour phase epitaxy (MOVPE), where InP/lnGaAs superlattices were used for optical confinement and barrier layers. We have reported [5] that these short period superlattices (SPSL) of binary InP and ternary $Ga_{0.47}In_{0.53}$ As grown at low temperature by atomic layer molecular beam epitaxy (ALMBE) [6] have been used to confine GalnAs multiquantum well (MQW) in a separate confinement heterostructure (SCH) of GaInAs/GaInAsP/lnP.

We have overcome the problem of high residual doping in InP grown at low temperature [7]. By adequate control of P_2 beam pulses during ALMBE, it is possible to obtain low residual doping ($n \sim 1 \times 10^{16}$ cm^{-3}) and consequently to grow p-type InP doped with Be , with low compensation and good optical properties [8]. We have employed reflection high energy electron diffraction RHEED to monitor surface reconstruction during growth. Under optimized InP growth conditions, diffraction pattern alternates from a P-stabilized surface (2×1) during P_2 pulse, to an In-stabilized surface (2×4) shortly after P_2 pulse is turned off.

In this letter, we report the first successful fabrication by solid source ALMBE at low substrate temperature of GalnAs SCH-MQW lasers emitting at 1.55 μm where $(InP)_5/(Ga_{0.47}In_{0.53}As)_5$, lattice matched SPSL have been used as pseudoquaternary material to confine strained $Ga_{0.3}In_{0.7}As$ wells.

Received May 25, 2010; published September 23, 2010 ISSN 1990-2573

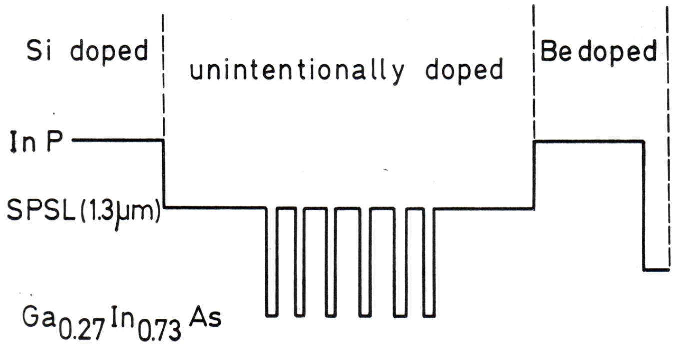

FIG. 1 Layout of the conduction band of the SCH-MQW laser, where the pseudoquaternary Q (1.3 μm) material is grown from $(InP)_3/(Ga_{0.47}In_{0.53}As)_5$ short period superlattices.

Growth was carried out at 340°C by ALMBE in a standard MBE system except for As and P effusion cells, which were designed to operate in a pulse mode by incorporating fast acting valves. Notice that only group V beams are modulated in ALMBE. If τ is the time period needed to supply one monolayer of InP (or GalnAs), during ALMBE operation phosphorus (or arsenic) valve are open only a fraction of τ, just after a group III stabilized surface has been reached on each period under continuous supply of In or GaIn. Beams of As_4 and P_2 were used. It should be noted also that under ALMBE growth conditions P_2 beam does not increase the base pressure of the growth chamber, which remains at 2×10^{-9} torr when P_2 valve is turned off.

Laser structures were grown on S-doped (100) InP substrate. Figure 1 shows the MQW active layer, which consists of six $Ga_{0.3}In_{0.7}As$ quantum wells (11 monolayers (ml) $\approx$ 32 Å each) and five barriers (176 Å each) made of the Q (1.3 μm) pseudoquaternary material, and Q (1.3 μm) separate confinement layers (1000 Å at each side of the MQW active zone) . These layers were not intentionally doped. The InP cladding layers (1 μm each) were Si doped ($n \approx 1 \times 10^{18}$ cm^{-3}) and Be doped ($p \approx 1 \times 10^{18}$ cm^{-3}) respectively. A 2000 Å thick $Ga_{0.47}In_{0.53}As$:Be cap layer was grown on top of the whole structure. There was a growth interruption of 120 s before and after the growth of each strained well in order to modify the In cell temperature to change the $Ga_xIn_{1-x}As$ composition from $x = 0.47$ (Iattice-matched) in the superlattices to $x = 0.27$ (compressive strained) in the wells. InP claddings were grown at 0.75 monolayers per second (ml/s), with phosphorus pulses of 0.8 s. In the SPSL, growth rates were 0.53 ml/s for InP (P_2 pulse of 1.1 s) and 1 ml/s for $Ga_{0.47}In_{0.53}As$ (As_4 pulses of 0.4 s). The $Ga_{0.27}In_{0.73}As$ wells were grown at 1.75 ml/s (As_4 pulses of 0.2 s). Values of beam equivalent pressure for P_2 and As_4 were 1.6×10^{-6} torr and 5.5×10^{-6} torr respectively. Broad area lasers (stripe width 40 μm) [9] were fabricated to evaluate the threshold current and lasing spectrum at room temperature. Cavities of 270 μm were formed by cleaving. The lasing threshold was determinate by measuring the light-current characteristic with a GaInAs detector under pulsed operation (100 ns–1 μs, 1–7 kHz).

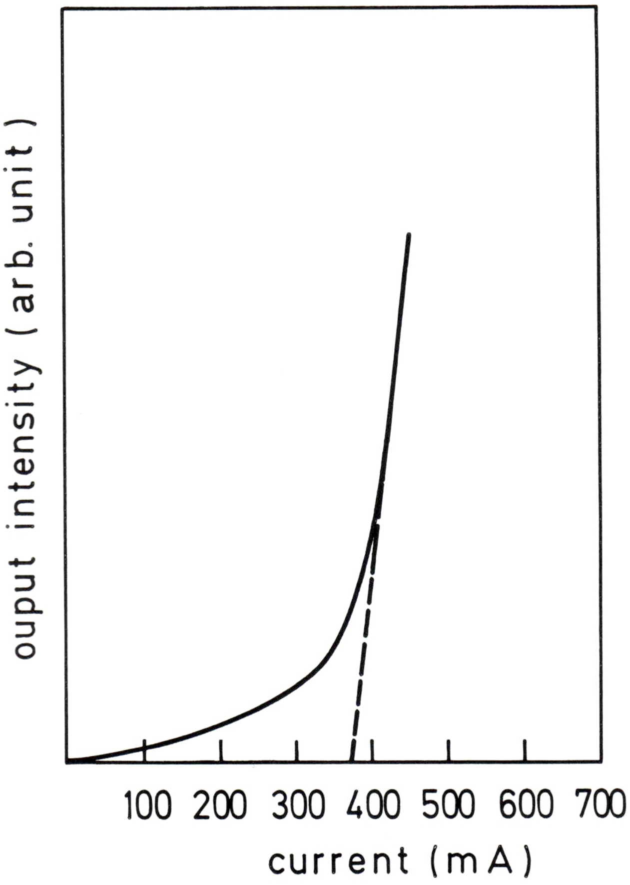

FIG. 2 Light-current characteristic of a 270 μm long laser at 300 K.

Figure 2 shows the light-current characteristic of a 270 μm long laser. Threshold current density is calculated using physical width of metallic stripe. Due to carrier diffusion, the actual threshold current density J_{th} could be lower than the calculated value of 3.5 kA/cm^2. This is a promising result if we take into account the six quantum wells of the structure. For comparison, in a four-strained-quantum well SCH laser with conventional quaternary material, and grown at 625°C by low pressure organometallic chemical vapour deposition (stripe width of 30 μm), a threshold current density of 1.15 kA/cm^2 was measured for 1 mm long cavity, and 1.55 kA/cm^2 for a laser with a cavity of 500 μm [10]. Ginty et aI. [4] obtained threshold current densities of 1.9 kA/cm^2 in a four quantum well SCH structure grown at 625°C by MOVPE (8 μm wide ridge, 400 μm long cavity). Figure 3 shows the spectrum of stimulated emission centred at 1.55 μm, at room temperature and $1.3 \times J_{th}$. This is the first time that MQW-SCH lasers have been fabricated by solid source MBE. The use of valved group V solid sources, with close control of pulse amplitude and duration, and the use of a precise control of stoichiometry and improved surface kinetics at low temperature by the ALMBE technique, allows for growth of GalnAsP and InP of good quality for device applications. In summary, from these experiments low temperature solid source ALMBE appears to be well adapted to fabricate advanced optoelectronic components as MQW-SCH lasers emitting at 1.5 μm, where the quaternary $Ga_xIn_{1-x}As_yP_{1-y}$ material is replaced with SPSL of the binary InP and lattice matched ternary InGaAs.

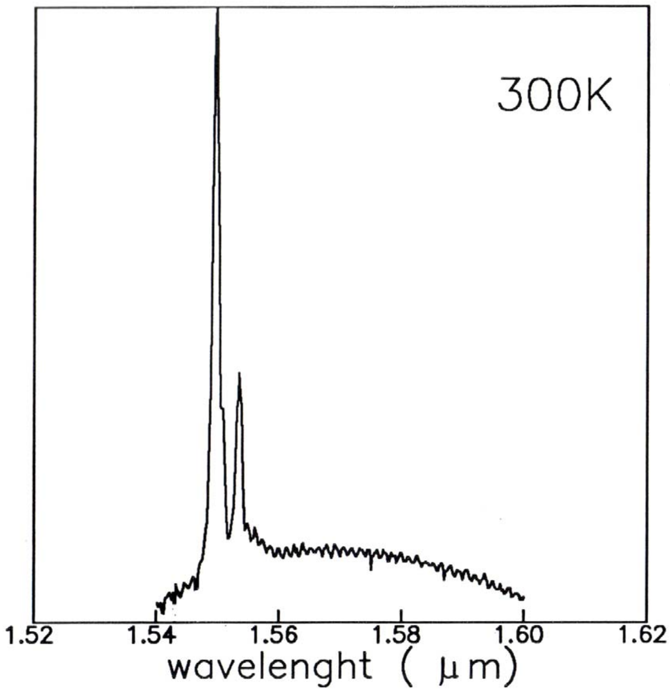

FIG. 3 Room temperature spectrum at 1.3 J_{th} of the laser of Figure 2.

2 CONCLUSIONS

Twenty years ago (around 1990), thin-film growth methods, such as metalorganic chemical vapour deposition (MOCVD), chemical beam epitaxy (CBE), and gas-source molecular beam epitaxy (GSMBE) started to be employed for preparing epitaxial layers of phosphorus compounds and related device structures. All these methods used highly toxic as sources of group-V elements. At the beginning of the 90's the use of phosphorus valved crackers offered an alternative but presented some difficulties in controlling the P_4 vapor pressure when using red phosphorus as a source material [11] . Widespread deployment of valved cracker technology, as a substitute for the more toxic gaseous sources, could only be realized if it was perceived as a viable manufacturing technology. In 1992, we showed that a home made prototype of solid phosphorus source capable of generating P_2 could overcome that problem, allowing for the growth of abrupt SPSL such as GaInAs/GaInP and the fabrication of p-type InP [5, 8], which was critical for a laser diode emitting at 1.55 μm grown by all solid-source MBE. In 1994, the first commercial valved, cracked phosphorus cell [12] paved the way to overcome the problems associated with toxic materials, and offered a competitive and alternative technique to grown state of the art GaInAsP epilayers. Since then, valved cracked phosphorus cells have appeared under different commercial brands, and systematic study about the effects of V/III flux ratio and substrate and cracker temperature on the optical and electrical properties of the layers were reported [13]–[15]; in the middle of the decade improvements in device performance were noted and high electron mobility transistor structures [16] and multiple-quantum well lasers at different wavelengths [17], grown using this technique, were reported. Recently, other structures have been reported like laser based on nanostructures [18] or double heterojunction bipolar transistor technology for high-speed data communication [19, 20] and ultra high quality-factor photonic crystal lasers [21].

References

[1] W. T. Tsang, "Advances in MOVPE, MBE, and CBE" J. Cryst. Growth **120**, 1–24 (1992).

[2] F. Capasso, H. M. Cox, A. L. Hutchinson, N. A. Olsson, and S. G. Hummel, "Pseudo-quaternary GaInAsP semiconductors: A new $Ga_{0.47}In_{0.53}As/InP$ graded gap superlattice and its applications to avalanche photodiodes" Appl. Phys. Lett. **45**, 1193–1195 (1984).

[3] L. M. Dotor, D. Golmayo, and F. Briones, "$(Ga_{0.22}In_{0.78}As)_m/(Ga_{0.22}In_{0.78}P)_m$ superlattices grown by atomic-layer molecular beam epitaxy on InP" J. Cryst. Growth **127**, 619–622 (1993).

[4] A. Ginty, J. D. Lambkin, L. Considine, and W. M. Kelly, "Long wavelength quantum well lasers with InGaAs/InP superlattice optical confinement and barrier layers" Electron. Lett. **29**, 684–685 (1993).

[5] L. M. Dotor, P. Huertas, D. Golmayo, and F. Briones, "$Ga_{0.47}In_{0.53}As$ multiquantum well heterostructures, confined by pseudoquaternary $(InP)_n/(Ga_{0.47}In_{0.53}As)_m$ short period superlattices lattice-matched to InP" Appl. Phys. Lett. **62**, 891–893 (1993).

[6] F. Briones, L. Gonzalez, and A. Ruiz, "Atomic layer molecular beam epitaxy (ALMBE) of III-V compounds: growth modes and applications" Appl. Phys. **A 49**, 7290-7307 (1989).

[7] B. X. Yang, and H. Hasegawa, "Properties of InP grown by migration enhanced epitaxy using polycrystalline InP as phosphorus source" in *Proceedings to the Fifth International Conference on Indium Phosphide and Related Materials*, 271–274 (IEEE, Paris, 1993).

[8] L. M. Dotor, P. Huertas, A. P. Postigo, D. Golmayo, and F. Briones, "p-Type InP grown at low temperatures by atomic layer molecular beam epitaxy (ALMBE)" Electron. Lett. **29**, 1270–1271 (1993).

[9] L. M. Dotor, P. Huertas, P. A. Postigo, D. Golmayo, and F. Briones, "Emisión laser en 1.5 μm en una estructura de tipo pozo cuántico múltiple crecida sobre InP por epitaxia de haces moleculares (MBE)" in *Proceedings of the VIII National Symposium of the International Union of Radio Science (URSI)* **2**, 1353–1356 (Universidad Politécnica de Valencia, Spain, 1993).

[10] C. E. Zah, R. Bhat, F. J. Favire, S. G. Menocal, N. C. Andreadakis, K. W. Cheung, D. M. D. Hwang, N. A. Koza, and T. P. Lee, "Low threshold 1.5 pm compressive-strained multiple and single quantum well lasers" IEEE J. Quantum Elect. **27**, 1440–1450 (1991).

[11] G. W. Wicks, M. W. Koch, J. A. Varriano, F. G. Johnson, C. R. Wie, H. M. Kim, and P. Colombo, "Use of a valved, solid phosphorus source for the growth of $Ga_{0.5}In_{0.5}P$ and $Al_{0.5}In_{0.5}P$ by molecular beam epitaxy" Appl. Phys. Lett. **59**, 342–344 (1991).

[12] F. Briones "Phosphorus effusion cell for Molecular Beam Epitaxy" U. S. Patent 5431735 (1995).

[13] S. F. Yoon, H. Q. Zheng, P. H. Zhang, K. W. Mah, and G. I. Ng, "Electrical and optical properties of InP grown by molecular beam epitaxy using a valved phosphorus cracker cell" Thin Solid Films **326**, 233–237 (1998).

[14] J. N. Baillargeon, A. Y. Cho, F. A. Thiel, R. J. Fischer, P. J. Pearrah, and K. Y. Cheng, "Reproducibility studies of lattice matched GaInAsP on (100) InP grown by molecular beam epitaxy using solid phosphorus" Appl. Phys. Lett. **65**, 207–209 (1994).

[15] P. A. Postigo, M. L. Dotor, P. Huertas, D. Golmayo, and F. Briones, "Electrical and optical properties of undoped InP grown at low temperature by atomic layer molecular beam epitaxy" J. Appl.

Phys. **77**, 402–404 (1995).

[16] J. C. Harmand, J. P. Praseuth, E. Idiart-Alhor, R. Palla, J. L. Pelouard, and M. Quillec, "Continuous molecular beam epitaxy of arsenides and phosphides applied to device structures on InP substrates" J. Cryst. Growth **150**, 1292–1296 (1995).

[17] M. Pessa, M. Toivonen, M. Jalonen, P. Savolainen, and A. Salokatve, "All-solid-source molecular beam epitaxy for growth of III-V compound semiconductors" Thin Solid Films **306**, 237–243 (1997).

[18] F. Suarez, D. Fuster, L. Gonzalez, Y. Gonzalez, J. M. Garcia, and M. L. Dotor, "Self-assembled InAs quantum wire lasers on (001)InP at 1.6 μm" Appl. Phys. Lett. **89**, 091123-1-3 (2006).

[19] R. Aidam, R. Lösch, R. Driad, K. Schneider, and R. Makon, "Solid source MBE growth on InP-based DHBTs for high-speed data communication" J. Cryst. Growth **301/302**, 1001–1004 (2007).

[20] S. H. Chen, S. Y. Wang, R. J. Hsieh, and J. I. Chyi, "InGaAsSb/InP double heterojunction bipolar transistors grown by solid-source molecular beam epitaxy" IEEE Electr. Device L. **28**, 679–681 (2007).

[21] L. J. Martínez, B. Alén, I. Prieto, D. Fuster, L. González, Y. González, M. L. Dotor, and P. A. Postigo, "Room temperature continuous wave operation in a photonic crystal microcavity laser with a single layer of InAs/InP self-assembled quantum wires" Opt. Express **17**, 14993–15000 (2009).