Laser operation of Ga(NAsP) lattice-matched to (001) silicon substrate

S. Liebich, M. Zimprich, A. Beyer, C. Lange, D. J. Franzbach et al.

Citation: *Appl. Phys. Lett.* **99**, 071109 (2011); doi: 10.1063/1.3624927

View online: <http://dx.doi.org/10.1063/1.3624927>

View Table of Contents: <http://apl.aip.org/resource/1/APPLAB/v99/i7>

Published by the [American Institute of Physics](#).

Related Articles

In-well pumping of InGaN/GaN vertical-external-cavity surface-emitting lasers

Appl. Phys. Lett. **99**, 201109 (2011)

Near-field dynamics of broad area diode laser at very high pump levels

AIP Advances **1**, 042148 (2011)

Photonic bandstructure engineering of THz quantum-cascade lasers

Appl. Phys. Lett. **99**, 201103 (2011)

Simulation of quantum cascade lasers

J. Appl. Phys. **110**, 093109 (2011)

Ultra-broadband heterogeneous quantum cascade laser emitting from 2.2 to 3.2 THz

Appl. Phys. Lett. **99**, 191104 (2011)

Additional information on *Appl. Phys. Lett.*

Journal Homepage: <http://apl.aip.org/>

Journal Information: http://apl.aip.org/about/about_the_journal

Top downloads: http://apl.aip.org/features/most_downloaded

Information for Authors: <http://apl.aip.org/authors>

ADVERTISEMENT

The logo for AIP Advances features the text 'AIPAdvances' in a blue and green font. Above the text is a decorative graphic of several orange circles of varying sizes, some of which are connected by a dotted line.

Submit Now

**Explore AIP's new
open-access journal**

- **Article-level metrics
now available**
- **Join the conversation!
Rate & comment on articles**

Laser operation of Ga(NAsP) lattice-matched to (001) silicon substrate

S. Liebich,¹ M. Zimprich,¹ A. Beyer,¹ C. Lange,^{2,a)} D. J. Franzbach,² S. Chatterjee,² N. Hossain,³ S. J. Sweeney,³ K. Volz,¹ B. Kunert,^{4,b)} and W. Stolz¹

¹Material Sciences Center and Faculty of Physics, Philipps-University Marburg, Marburg, Germany

²Faculty of Physics, Philipps-University Marburg, Marburg, Germany

³Advanced Technology Institute and Department of Physics, University of Surrey, Surrey, United Kingdom

⁴NAsP III/V GmbH, Marburg, Germany

(Received 17 June 2011; accepted 19 July 2011; published online 17 August 2011)

The lattice-matched growth of the direct band gap material Ga(NAsP) is a seminal concept for the monolithic integration of III/V laser on a silicon substrate. Here, we report on the growth, characterization, and lasing properties of Ga(NAsP)/(BGa)(AsP) multi quantum well heterostructures embedded in (BGa)P cladding layers which were deposited on an exactly oriented (001) Si substrate. Structural investigations confirm a high crystal quality without any indication for misfit or threading dislocation formation. Laser operation between 800 nm and 900 nm of these broad area device structures was achieved under optical pumping as well as electrical injection for temperatures up to 150 K. This “proof of principle” points to the enormous potential of Ga(NAsP) as an optical complement to Si microelectronics. © 2011 American Institute of Physics. [doi:10.1063/1.3624927]

The monolithic integration of III/V compound materials with Si microelectronics and integrated circuits (ICs) allows for the combination of the advantageous material properties of both semiconductor classes, opening up completely new device concepts. For example, the application of III/V material systems for n-channels with high electron mobility offers huge potential for device improvement.¹ The most significant benefits of III/Vs over Si are their superior optoelectronic properties. The successful and cost-efficient integration of a reliable, long-lifetime III/V laser diode on silicon will enable chip-to-chip and on-chip optical functionalities with all of the advantages of high bandwidth, low latency, and low power optical data communication.

The monolithic growth of standard III/V laser materials such as common alloys of GaAs and InP on Si inevitably leads to the formation of a high density of misfit and threading dislocations due to the large differences in lattice constants relative to Si. Such dislocation defects act as non-radiative recombination centers limiting device performance and shortening device lifetime.² In order to gain control over the formation of threading and misfit dislocations, various growth techniques have been explored.^{3–6} To date, some notable progress has been made in reducing the dislocation density. However, the remaining defect density in the range of 10^5 – 10^6 dislocations/cm² still precludes long-term stable operation of laser diodes.

The approach presented here overcomes this fundamental limitation by completely eliminating the threading dislocation issue. The dilute nitride material Ga(NAsP) based on GaP has been developed specifically for the lattice-matched and defect-free integration of an optically efficient direct band gap semiconductor on Si. The high As concentration of the quaternary compound material guarantees the direct band gap whereas the incorporation of N enables the adjustment of the lattice constant of Ga(NAsP) towards that of Si.⁷ Based on GaP substrates, room temperature gain⁸ and elec-

trically pumped laser operation⁹ of Ga(NAsP) devices structure was demonstrated underlining the promising optical properties of this emerging material system.

In this letter, we describe the successful transfer of the GaP-based active material technology to the Si platform through monolithic deposition of a complete III/V laser structure by metal organic vapor phase epitaxy (MOVPE) on exactly oriented (001) Si substrates. The active material system is Ga(NAsP) while the boron containing material systems (BGa)P and (BGa)(AsP) form the cladding layers and the separate confinement hetero-structures (SCHs), respectively. X-ray diffraction (XRD) and transmission electron microscopy (TEM) confirm that this integration approach suppresses the formation of misfit or threading dislocations. Laser operation of Ga(NAsP) device structures on Si was demonstrated at low temperature under optical excitation as well as electrical injection. The material growths as well as the structural and optical investigations were carried out in Marburg whereas the characterization of the electrical injection lasers was done at the University of Surrey.

All III/V laser device structures under investigation were grown in a commercial horizontal reactor system (AIX 200-GFR) by MOVPE using hydrogen carrier gas at low reactor pressure. Specific GaP/Si-templates were employed as substrates, which consist of a 50–100 nm thick GaP layer nucleated on (001) exactly oriented Si substrate. Details about the defect-free nucleation of GaP on Si are described in Refs. 10 and 11. Due to the metastability of the dilute nitride Ga(NAsP) layers, low growth temperatures of 575 °C were required where the more efficiently decomposing group-V sources tertiarybutylarsine, tertiarybutylphosphine, and 1,1-dimethylhydrazine in combination with the group-III-sources triethylgallium and triethylboron were utilized. For the p- and n-doping, the precursors diethylzinc and diethyltellurium were chosen, respectively.

The compositions of the different III/V layers were adjusted by the gas phase ratio of the metal organic precursors. XRD measurements allow for a precise identification of the composition of ternary alloys. The composition of the quaternary material systems of the device was estimated by the

^{a)}Present address: Department of Physics, University of Toronto, Toronto, Canada

^{b)}Electronic mail: bernardette.kunert@nasp.de.

strain state in line with various test structures investigating the incorporation behavior of the different elements in MOVPE. Additional information about the epitaxial growth conditions of the active material and the importance of the correct strain-adjustment at growth temperature are published elsewhere.¹² All device structures were annealed after growth in the MOVPE chamber for 30 min at 800 °C to 850 °C in order to improve the optical properties according to previous publications about dilute nitrides based on GaP and GaAs substrates.^{13,14} X-ray diffractometry was carried out with an *X'Pert Pro MDR* diffractometer from PANalytical. For the TEM study, [010] and [110] cross sections of the sample were prepared. The (002) dark field (DF) images were obtained in a *Jeol JEM3010* at an acceleration voltage of 300 kV.

A conventional approach to verify laser operation is the realization of an undoped laser structure for optical pumping. A four-fold repeating Ga(NAsP)/(BGa)(AsP) multi-quantum well (MQW) heterostructure, embedded in undoped (BGa)P cladding layers was deposited on a GaP/Si template. The boron concentration of the 1 μm thick bottom and top (BGa)P cladding layers was 3.0%. The QW and barrier thicknesses were 4.3 nm and 65.7 nm, respectively. Hence, the total thickness of the MQW-structure in the SCH-region was about 350 nm. The direct band gap material Ga(NAsP) with 6%–7.5% N and 75%–81% As is compressively strained, which is beneficial in reducing the density of states at the top of the valence band, while the (BGa)(AsP) barriers with 6%–7% B and 10%–14% As are under tension to ensure strain-compensation. The incorporation of As into (BGa)(AsP) induces a band gap reduction compared to (BGa)P, which leads to a better carrier and light field confinement. The entire thickness of this first laser structure is about 2.5 μm .

The crystal quality was verified in detail by XRD and TEM investigations. The excellent agreement of the experimental XRD data with a modeled simulation proves the high crystalline quality of the device stack and verifies the abruptness of the respective hetero-interfaces. The XRD profile of this thick device is comparable to previous published measurements of basic MQW structures with a pronounced crystal quality in Refs. 12 and 15. Diffraction patterns from all of the layers are clearly visible and can be distinguished according to their respective strain. The integral strain of the entire device stack has to be carefully adjusted in order to mitigate against defect formation, such as dislocations and/or cracks, resulting from the different thermal expansion coefficients of the III/V compound layers and the Si substrate. There is no evidence of dislocation formation or related inhomogeneous strain relaxation as also explored by TEM.

The Si substrate was mechanically thinned to a thickness of approximately 120 μm to improve the quality of the facets when cleaving the sample into bars. Laser bars with a resonator length of 0.3 mm to 5 mm were mounted into a variable temperature helium flow cryostat. A Ti:Sapphire regenerative amplifier emitting 100 fs pulses at 1 kHz repetition rate was tuned to 800 nm central wavelength for excitation of the Ga(NAsP) quantum wells only. The laser beam was focused to a thin stripe across the laser bars.

A clear threshold behavior of the facet emission intensity over the pump intensity in line with a pronounced mode spectrum verify laser activity of this III/V laser diode lattice

FIG. 1. (Color online) The left graph displays the integrated emission intensity versus the pump intensity of a $\sim 300 \mu\text{m}$ long MQW laser bar at 10 K. The right graph shows the emission spectrum of a $\sim 480 \mu\text{m}$ long laser bar above threshold at 10 K.

matched to (001) Si substrate as shown in Fig. 1. The mode spacing of 0.26 nm around 878 nm at 13 K matches the cavity length of about 480 μm , assuming an average refractive index of 3.1. A maximum modal gain of 6 cm^{-1} was extracted according to the method of Hakki and Paoli.¹⁶ Thus, laser operation was observed up to 150 K with an emission wavelength of about 900 nm for this nominally undoped device generation.

After this proof of optical gain and optically pumped lasing, we focused on the growth of devices for electrical current injection since the electrically pumped laser diode is the final key component required for optoelectronic ICs. The (BGa)P cladding layers were doped with zinc and tellurium and the thickness was slightly increased to alleviate the contact processing (n-doped bottom layer: 1.7 μm , p-doped top layer: 1.2 μm). In contrast to the optically pumped device structure, where the QWs were homogeneously distributed, three QWs were placed in the center of the 350 nm thick SCH to improve the overlap of the gain medium with the confined light field. The triple QW stack consists of 4.7 nm thick Ga(N_{6-7%}As_{82-77%}P) QWs embedded in 20 nm thick (B_{6-7%}Ga)(As_{8-12%}P) barriers. The electron injection into the MQWs is also supported by the growth of a GRINSCH (graded-index SCH)-waveguide structure through a As and B composition gradient.

This laser structure was also extensively investigated applying TEM and XRD analysis. The corresponding XRD pattern indicates the same crystal quality as discussed above. Two DF-TEM images of the device structure for current injection are given as examples in Fig. 2, clearly confirming the absence of a defect network. No signs of misfit and threading dislocation formation were found. The three Ga(NAsP)-QWs can be identified in the upper TEM image. The lower image shows the region around the GaP/Si interface. The triangle-shaped dark structures in the GaP nucleation layer are anti-phase domains self-annihilating after the deposition of about 40 nm of GaP.^{10,11}

Broad area lasers were processed for electrical carrier injection. The p-contact stripes have a width of 50 μm and are placed on the top surface. These metal stripes also serve as a mask for the wet-chemical etch process of the mesa. Electrons are injected via a lateral n-contact into the Te-doped III/V layer positioned next to the etched laser mesa. The Si substrate was thinned before cleaving. Laser bars with cavity lengths of ~ 1.0 mm were mounted in a closed cycle cryostat for temperature

FIG. 2. Dark field TEM images of the Ga(NAsP)/(BGa)(AsP) triple quantum laser device. The upper image shows the SCH containing the QWs (cross section in [010]) whereas the lower image shows the region around the GaP/Si interface (cross section in [110]).

dependent measurements. The devices were driven under pulsed operation with 500 ns long pulses at a repetition rate of 10 kHz in order to minimize Joule heating effects.

The facet emission intensity as a function of drive current reveals a clear threshold behavior for low temperature up to 120 K as shown in Fig. 3. This threshold behavior also corresponds to a pronounced spectral narrowing of the facet emission above threshold providing further verification of laser action. Laser operation from single QW devices was also observed. The emission wavelength is in the region of 800 nm to 850 nm at 40 K. The measured threshold current density is 4.4 kA/cm² (1.7 kA/cm²) for the triple QW device at 120 K (40 K). These initial results are very encouraging for this leadoff laser generation.

Due to the early stage of material development, this integration concept still has much room for improvement. The MOVPE growth conditions and the post-growth annealing treatment provide many parameters to optimize material quality. In particular, the current-voltage characteristics of these devices indicate a high series resistance across the contact p-n-junction and/or waveguide layers. Present research is focusing on the improvement of current injection to minimize heating effects and carrier leakage currents. The devices described here utilize simple as-cleaved facets. Ongoing process development of ridge waveguide lasers with etched facets is underway and is expected to lead to improved device performance.

The verification of laser action from a III/V active region grown dislocation-free on (001) Si substrate provides a “proof of principle” for this lattice-matched integration concept and opens the door to realize long term stable lasers on silicon with high yields. In particular, this lattice-matched approach allows for overgrowth with Si to completely embed the III/V components into Si reducing any risk of cross-contamination. The overgrowth of doped Si layers also permits the application of standard CMOS metallization. All these integration aspects underline the high compatibility of this approach to current CMOS processes.

In summary, we have introduced a promising concept for the realization of optoelectronic functionalities integrated monolithically onto (001) Si substrates. The approach is based

FIG. 3. (Color online) The left graph shows the integrated emission intensity versus drive current of an electrical pumped triple QW laser for different temperatures. The right graph contains the emission spectrum of a single and triple QW laser for a drive current above threshold.

on the defect-free nucleation of thin GaP-layers on an exactly oriented (001) Si-substrate, onto which the dilute nitride material system Ga(NAsP) is epitaxially grown by MOVPE. Laser structures were realized for optical pumping as well as electrical current injection. Detailed structural analysis indicates high crystalline quality of the III/V structure with no evidence of misfit and threading dislocations or cracks. The successful verification of laser operation under optical pumping and electrical injection was shown at low temperature. These first results are very promising for the development of a truly monolithically integrated efficient laser on silicon. Improvements in material quality, structural design, and device fabrication are currently under investigation.

We gratefully acknowledge the German Science Foundation (DFG), the German ministry for education and research (BMBF), EPSRC (UK) and the Royal Academy of Engineering (UK) for supporting this work.

¹M. Radosavljevic, G. Dewey, J. M. Fastenau, J. Kavalieros, R. Kotlyar, B. Chu-Kung, W. K. Liu, D. Lubyshv, M. Metz, K. Millard, N. Mukherjee, L. Pan, R. Pillarisetty, W. Rachmady, U. Shah, and R. Chau, International Electron Devices Meeting 6–8 December 2010, San Francisco, USA.

²P. Petroff, W. D. Johnston, and R. L. Hartmann, *Appl. Phys. Lett.* **25**, 226 (1974).

³N. Hayafuji, S. Ochi, M. Miyashita, M. Tsugami, T. Murotani, and A. Kawagishi, *J. Cryst. Growth* **93**, 494 (1988).

⁴Z. T. Mi, J. Yang, P. Bhattacharya, G. X. Qin, and Z. Q. Ma, *Proc. IEEE* **97**, 1239 (2009).

⁵E. A. Fitzgerald, P. D. Kirchner, R. Proano, G. D. Pettit, J. M. Woodall, and D. G. Ast, *Appl. Phys. Lett.* **52**, 1496 (1988).

⁶J. Z. Li, J. Bai, C. Major, M. Carroll, A. Lochtefeld, and Z. Shellenbarger, *J. Appl. Phys.* **103**, 106102 (2008).

⁷B. Kunert, K. Volz, J. Koch, and W. Stolz, *Appl. Phys. Lett.* **88**, 182108 (2006).

⁸S. Borck, S. Chatterjee, B. Kunert, K. Volz, W. Stolz, J. Heber, W. W. Ruehle, N. C. Gerhardt, and M. R. Hofmann, *Appl. Phys. Lett.* **89**, 031102 (2006).

⁹B. Kunert, A. Klehr, S. Reinhard, K. Volz, and W. Stolz, *Electron Lett.* **42**, 601 (2006).

¹⁰K. Volz, A. Beyer, W. Witte, J. Ohlmann, I. Németh, B. Kunert, and W. Stolz, *J. Cryst. Growth* **315**, 37 (2010).

¹¹I. Németh, B. Kunert, W. Stolz, and K. Volz, *J. Cryst. Growth* **310**, 1595 (2008).

¹²B. Kunert, S. Zinnkann, K. Volz, and W. Stolz, *J. Cryst. Growth* **310**, 4776 (2008).

¹³K. Volz, J. Koch, B. Kunert, I. Németh, and W. Stolz, *J. Cryst. Growth* **298**, 126 (2007).

¹⁴B. Kunert, D. F. Trusheim, V. Vossebuenger, K. Volz, and W. Stolz, *Phys. Status Solidi A* **205**, 114 (2008).

¹⁵W. Stolz, *Compound Semicond.* **14**, 21 (2008).

¹⁶B. W. Hakki and T. L. Paoli, *J. Appl. Phys.* **44**, 4113 (1973).