Reduced threshold current dilute nitride Ga(NAsP)/GaP quantum well lasers grown by MOVPE

N. Hossain, S.J. Sweeney, S. Rogowsky, R. Ostendorf, J. Wagner, S. Liebich, M. Zimprich, K. Volz, B. Kunert and W. Stolz

Recent significant improvements in Ga(NAsP)/GaP quantum well lasers grown by metal organic vapour phase epitaxy on a GaP substrate are reported. At room temperature, the devices show a threshold current density of 4.0 kAcm^{-2} at a lasing wavelength of 981 nm for a cavity length of 1 mm and a characteristic temperature of 58 K in the temperature region of 220–295 K. These improvements further verify the possible application for the novel III/V Ga(NAsP)/GaP material system to integrate long-term stable laser diodes in a standard CMOS-compatible electronic chip.

Introduction: An efficient light source monolithically integrated on a silicon substrate is one of the key components to combine the advantages of optical data processing with mature silicon microelectronics technology. The obstacle to progress is in developing a reliable integrated laser diode compatible with current silicon CMOS fabrication techniques. Unlike optically efficient direct bandgap III-V semiconductors such as GaAs and InP, the indirect bandgap of silicon causes inefficient light emission and gain has been difficult to achieve. Growth of conventional direct bandgap III-V compound semiconductors directly onto Si is very difficult owing to the formation of threading dislocations as a result of the large lattice mismatch, which inhibits laser performance [1]. However, it has been shown that the incorporation of a small percentage of boron or nitrogen into GaP allows lattice matched deposition of GaP-based active materials on silicon [2, 3]. GaP is itself an indirect bandgap semiconductor, but a Ga(NAsP) alloy with high As fractions of more than 75% and dilute N fractions (of 4–7%) can form a direct bandgap material approximately lattice matched to GaP and Si [4]. We earlier reported lasing operation near room temperature (RT) in Ga(NAsP) quantum well (QW) lasers on a GaP substrate [5]. However, the very large threshold current density (J_{th}) $\sim 42 \text{ kAcm}^{-2}$ [5] and strong non-radiative recombination processes [6] in the devices necessitated further optimisation to improve device performance. In this Letter, we report on substantial improvements in the lasing characteristics under electrical injection for broad-area Ga(NAsP)/GaP single quantum well (SQW) laser structures at RT.

Experimental setup: The devices in this study were grown in a commercial metal organic vapour phase epitaxy (MOVPE) horizontal reactor system (Aix 200) on exactly oriented n-(100) GaP:S substrates. Owing to the metastable character of the specific low temperature (575°C) MOVPE growth conditions for Ga(NAsP) the more efficiently decomposing group-V-sources tertiarybutyl arsine (TBAs), tertiarybutyl phosphine (TBP) and 1,1-dimethyl hydrazine (UDMHy) in combination with the group-III-sources triethyl gallium (TEGa), and trimethyl aluminium (TMAI) were applied. The active region consists of a 6.2 nm Ga(NAsP) SQW within two 200 nm-thick undoped GaP separate confinement heterostructure (SCH) layers and embedded in between 1.5 μm -thick n-(Al_{0.23}Ga_{0.77})P:Te and p-(Al_{0.23}Ga_{0.77})P:Zn layers which were deposited at 725 and 675°C, respectively. In addition, 300 nm-thick n-GaP:Te and 100 nm-thick p⁺-GaP:Zn layers were grown as buffer and contact layers, respectively. Further details of the MOVPE growth process can be found elsewhere [7]. 100 μm -wide Au/Cr metal stripes on the p-contact layer and Au/Ni/AuGe-based back contacts have been used to form broad-area laser structures. Laser facets were formed by standard cleaving techniques into cavity lengths of 1000 μm . The devices were measured as-cleaved under pulsed operation (500ns-long pulses at a 0.5% duty cycle) in order to reduce current heating effects. RT measurements were carried out on a probe station, where the facet emission was detected with a large area InGaAs detector. Temperature dependent measurements over the range of 60–295 K were performed in a closed cycle cryostat. For the cryostat measurements, the emission was collected using an optical fibre and measured either directly with an optical power meter or spectrally with an optical spectrum analyser.

Results: The L - I curve and the laser spectrum recorded at an injection current of $\sim 1.1J_{th}$ (inset) at RT is shown in Fig. 1. The J_{th} of the device is measured to be $4.0 \pm 0.2 \text{ kAcm}^{-2}$ with a lasing wavelength of $\sim 981 \text{ nm}$ at RT. J_{th} is an order of magnitude lower than the previously reported value of $\sim 42 \text{ kAcm}^{-2}$ (emitting at $\sim 943 \text{ nm}$ at 278 K) [5]. This indicates a significant improvement in device quality. For the current devices, the growth temperature of the GaP SCH region was increased to 675°C (originally 575°C) resulting in a higher P/Ga-ratio in the MOVPE gas phase due to more efficient decomposition of the TBP at higher temperature. The clear device improvement could indicate a reduction in non-radiative recombination centres in the barrier material. However, the precise character of these defects is still unclear and could be group-V-vacancy or carbon-related. The composition of the active material Ga(NAsP) with about 5% N and 92% As has been also slightly changed. Compared to the former device in [5] the N-concentration is increased by approximate 1%, which leads to red-shift in emission wavelength. Finally, the Zn- and Te-doping concentration of the cladding layers close to the centred waveguide structure has been reduced to decrease losses caused by free carrier absorption.

Fig. 1 L - I curve for $100 \times 1000 \mu\text{m}$ laser diode at room temperature
Inset: Corresponding lasing spectrum

The natural logarithm of J_{th} against the inverse of the cavity length (L) is depicted in Fig. 2. The current density for infinite cavity length J_{∞} is determined to be $3.2 \pm 0.3 \text{ kAcm}^{-2}$. Fig. 3 shows the measured temperature dependence of the threshold current yielding the characteristic temperature T_0 (derived from $1/T_0 = d \ln J_{th} / dT$). Values for T_0 of 103 and of 58 K are deduced in the temperature regions of 40–200 and 220–295 K, respectively. These results emphasise that the device shows improved temperature stability compared to the previously reported devices [6]. Because of the high intrinsic material gain, predicted theoretically for the novel Ga(NAsP)/GaP-material system [8], future improvements of the laser performance can be anticipated by careful optimisation of the MOVPE growth conditions as well as the design of the laser layer sequence.

Fig. 2 Natural logarithm of J_{th} against inverse of cavity length

Fig. 3 Temperature dependence of threshold current density

Conclusion: Improved lasing characteristics in broad-area GaP-based Ga(NAsP)/GaP SQW laser structures operated under pulsed electrical injection have been observed. A reduced J_{th} of 4.0 kAcm^{-2} at RT indicates significant improvement in device quality compared to previous devices. Despite the clear reduction in threshold current the high value of J_{∞} suggests that further improvement in the devices are required. Improvements in laser characteristics are expected by further careful optimisation of the MOVPE growth conditions of the barriers and SCH material systems as well as of the novel Ga(NAsP) QW and the design of the laser layer sequence to optimise optical and electrical confinement.

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N. Hossain and S.J. Sweeney (*Advanced Technology Institute and Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom*)

E-mail: s.sweeney@surrey.ac.uk

S. Liebich, M. Zimprich, K. Volz and W. Stolz (*Material Sciences Center and Faculty of Physics, Philipps-University, Marburg 35032, Germany*)

B. Kunert (*NAsP III/V GmbH, Am Knechtacker 19, Marburg 35041, Germany*)

S. Rogowsky, R. Ostendorf and J. Wagner (*Fraunhofer Institute for Applied Solid State Physics IAF, Tullastraße 72, Freiburg 79108, Germany*)

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