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Electrical injection Ga(AsBi)/(AlGa)As single quantum well laser

P. Ludewig,¹ N. Knaub,¹ N. Hossain,² S. Reinhard,¹ L. Nattermann,¹ I. P. Marko,² S. R. Jin,² K. Hild,² S. Chatterjee,¹ W. Stolz,¹ S. J. Sweeney,² and K. Volz^{1,a)}

¹Material Sciences Center and Faculty of Physics, Philipps-Universität Marburg, 35032 Marburg, Germany

²Advanced Technology Institute and Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom

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The Ga(AsBi) material system opens opportunities in the field of high efficiency infrared laser diodes. We report on the growth, structural investigations, and lasing properties of dilute bismide Ga(AsBi)/(AlGa)As single quantum well lasers with 2.2% Bi grown by metal organic vapor phase epitaxy on GaAs (001) substrates. Electrically injected laser operation at room temperature is achieved with a threshold current density of 1.56 kA/cm² at an emission wavelength of ~947 nm. These results from broad area devices show great promise for developing efficient IR laser diodes based on this emerging materials system. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4811736>]

Dilute bismide Ga(AsBi) based lasers diodes are promising candidates for high efficiency infrared (IR) light sources. The incorporation of only a small amount of Bi into GaAs causes a large reduction in the band gap due to valence band anti-crossing¹ and, in addition, decreases the temperature sensitivity of the emission wavelength compared to conventional III/V semiconductors,² making temperature stabilization more straightforward. Furthermore, for Bi fractions above approximately 10%, the spin-orbit splitting becomes larger than the bandgap.^{3–6} Under such conditions it is expected that troublesome hot-hole generating Auger recombination and inter-valence band absorption (IVBA) processes may be suppressed leading to higher efficiencies and more temperature stable power output of lasers for optical communications applications.^{6–8} Ga(AsBi) light-emitting diodes (LEDs)^{9,10} and optically pumped laser diodes¹¹ have been demonstrated with promising optical material qualities. In order to exploit the beneficial properties of this metastable material system, which has to be grown under highly non-equilibrium growth conditions, it is however necessary to demonstrate that electrically pumped lasing at room temperature can be achieved.

In this work we will present an electrically pumped Ga(AsBi)/(AlGa)As laser with a Bi fraction of 2.2% in the active material. Single quantum well (SQW) laser devices as well as Ga(AsBi)/(AlGa)As multi QW test structures were grown by metal organic vapor phase epitaxy (MOVPE) on exact GaAs (001) substrates. A commercially available AIX 200-GFR reactor system with Pd-purified H₂ as carrier gas at a reduced reactor pressure of 50 mbar was used. Trimethylaluminum (TMAI) and triethylgallium (TEGa) were used as group III precursors, tertiarybutylarsine (TBAs), and trimethylbismuth (TMBi) as group V precursors since low growth temperatures were required. Diethyl tellurium (DETe) and diethyl zinc (DEZn) were used as n- and p-type dopants, respectively. Furthermore p-type doping with carbon was realized by a reduced V/III ratio in the p-contact (AlGa)As layer.

Adding Bi to GaAs mainly affects the valence band and for low Bi concentration, the conduction band (CB) offset is

small; we estimate the e1-CB(GaAs)-separation to be 12 meV. Therefore, to provide a suitable electron confinement (AlGa)As barriers were used. Adding Al into the barriers improves the electron confinement; however, this leads to a lower refractive index contrast relative to the cladding and hence causes poorer optical confinement. A reasonable compromise was found to be to use 20% Al in the barriers which significantly increases e1-CB(Al_{0.2}Ga_{0.8}As) to approximately 144 meV. The quantum well was selected to be thick enough to avoid inhomogeneity effects. A schematic of the layer structure of the laser diode grown on n⁺ substrate is given in Figure 1. The 6.4 nm thick Ga(AsBi_{0.022}) QW is embedded between 150 nm thick (Al_{0.2}Ga)As barriers for electrical confinement in the active region. The 1.4 μm thick (Al_{0.4}Ga)As:Te and (Al_{0.4}Ga)As:C layers serve as waveguides as well as n and p contact layers, respectively. 250 nm of highly p-doped GaAs:Zn were grown on top of the structure to improve the metal-semiconductor contact. All (AlGa)As and GaAs layers were grown at 625 °C, adjusting the Al fraction by the ratio of the group III vapor pressures. In contrast, the Ga(AsBi_{0.022}) QW was deposited at 400 °C using a pulsed growth mode where group III and group V precursors were alternately supplied to the reactor for 1 s without any pause in between. Subsequently, TEGa and TBAs were supplied for a few seconds with continuous precursor flow in order to consume the segregated Bi. This growth methodology of Ga(AsBi) QW structures using MOVPE was described earlier in more detail.¹² The temperature changes applied before and after the growth of the QW were performed during TBAs stabilized growth interruptions. It is assumed that the segregated Bi that is left at the surface after the QW growth is stopped gets evaporated during the heating to 625 °C. So far no influence of segregated Bi on the growth of the (AlGa)As barrier was found which supports this assumption.

To form broad area laser structures, 50 μm and 100 μm wide Au/Cr metal stripes were deposited on the top contact, and an Au/AuGe/Cr-based contact was deposited on the substrate backside. The sample was alloyed at 400 °C for ohmic contact formation. To avoid current spreading the GaAs:Zn-contact layer was etched-off using the metal stripes as mask. Since the device was grown on GaAs-substrates the laser

^{a)}E-mail: kerstin.volz@physik.uni-marburg.de

FIG. 1. Schematic view of the electrically pumped Ga(AsBi_{0.022})/(AlGa)As SQW laser diode.

facets were cleaved using standard techniques with a cavity length of 1 mm. The devices were measured *as-cleaved*.

Figure 2 shows high resolution X-ray diffraction (HR-XRD) omega-2theta scans around the GaAs (004) reflection, which were performed to investigate a Ga(AsBi)/(AlGa)As 5 × QW test structure that was grown under the same growth conditions as the active region of the device. Dynamical modeling of the experimental pattern allowed the determination of the Bi-fraction to 2.2% and layer thickness of 6.4 nm of the QW assuming GaBi lattice constant of 6.33 Å.¹³

Cross-sectional [-110] scanning transmission electron microscopy (STEM) high angle annular dark field (HAADF) images were taken in order to investigate the crystalline quality, the homogeneity of the composition, as well as the

FIG. 2. HR-XRD (004) pattern of a Ga(AsBi)/(AlGa)As 5 × QW. The diffraction pattern is in good agreement with the dynamical simulation of a 5 × QW structure with a Bi fraction of 2.2 and a Ga(AsBi) layer thickness of 6.4 nm. The (AlGa)As barriers contain about 20% Al with a thickness of 22 nm, the sample is capped by a 7 nm thin GaAs layer.

layer thicknesses of the laser in more detail. Imaging took place with a JEOL JEM 2200 FS, which was operated at 200 keV using an aberration corrector for the probe. Figure 3 shows an overview HAADF [-110] STEM image of the laser device (a) as well as a high resolution image of the Ga(AsBi) QW (b). Since the contrast in the STEM HAADF mode is highly sensitive to the chemical composition of the layer (Z-contrast) a very high chemical homogeneity of the quantum well can be concluded from these investigations. In addition, the Ga(AsBi)/(AlGa)As transition can be clearly seen, indicating good control of the growth process. Furthermore, it is obvious that there is no degradation of the crystalline structure occurring during the TBAs stabilized growth interruptions that were applied during changes of the growth temperature.

Room temperature photoluminescence (PL) spectroscopy was performed using a continuous-wave (cw) 100 mW Ar-ion laser at a wavelength of 514 nm for excitation. The PL signal was dispersed in a 1 m grating monochromator (THR 1000, Jobin-Yvon) and collected by a cooled germanium detector applying standard lock-in techniques. The PL spectra of two 5 × QWs samples with Ga(AsBi) QW grown under the same growth conditions are shown in Figure 4. In contrast to the laser test structure with (AlGa)As barriers (black line), the sample with GaAs barriers was completely grown at 400 °C (grey line). The blue shift of the PL signal is explained by a thinner QW thickness using (Al_{0.2}Ga)As barriers since the growth is interrupted and the sample heated to (Al_{0.2}Ga)As growth temperature before all segregated Bi is consumed. Furthermore the higher confinement of the (Al_{0.2}Ga)As barriers compared to GaAs lead to a blue shift.

FIG. 3. (a) STEM HAADF overview image of the laser structure. (b) High resolution STEM image of the Ga(AsBi) QW showing smooth interfaces and a high chemical homogeneity.

FIG. 4. Photoluminescence spectra of a Ga(AsBi)/GaAs and a Ga(AsBi)/(AlGa)As $5 \times$ QW as test structure for the SQW laser diode.

FIG. 5. L-I curve for a $50 \times 1000 \mu\text{m}$ Ga(AsBi)/(AlGa)As SQW laser diode at room temperature and corresponding lasing spectrum (inset).

The integrated PL intensity is increased by a factor of 20 using $(\text{Al}_{0.2}\text{Ga})\text{As}$ barriers. This is most likely due to improved carrier confinement and an annealing effect of the Ga(AsBi) QW due to the higher growth temperature of the $(\text{Al}_{0.2}\text{Ga})\text{As}$ barrier. The relatively large full width at half maximum (FWHM) of about 120 meV might be related to disorder within the QW; however, comparable values were observed before in the Ga(AsBi) material system.^{13,14}

The devices were measured as-cleaved under pulsed operation (200 ns long pulses at a frequency of 10 kHz) 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 (InGa)As detector. Figure 5 shows the light-current (L-I) characteristic and the laser

emission spectrum (inset) recorded at an injection current of $\sim 1.1 J_{\text{th}}$ (where J_{th} is the threshold current density) at RT. Clear threshold behavior of the integrated emission intensity as a function of drive current is observed at RT as shown in Figure 5. This threshold behavior also corresponds to a pronounced spectral narrowing of the facet emission above threshold (as shown in the inset of Figure 5) providing further verification of laser action. J_{th} for the broad area SQW devices was measured to be $\sim 1.56 \text{ kA/cm}^2$ with a lasing wavelength of 947 nm at RT. The voltage drop across devices at threshold was measured to be approximately 2 V. The J_{th} of these devices is relatively high compared to the standard (InGa)As lasers. However, we believe that room temperature lasing in such a complex material system, for which only one quantum well provides optical gain, is encouraging. This shows great promise for developing efficient IR lasers with this materials system. Investigations are currently underway to determine the cause of the high threshold currents; however, we expect that the device performance is affected by non-radiative defect-related recombination due to unoptimised low temperature growth.

In summary, we have developed high optical quality Ga(AsBi) (2.2% Bi) quantum well material using the MOVPE growth technique. Based upon this material development we have gone on to demonstrate electrically pumped lasing at room temperature with a threshold current density of 1.56 kA/cm^2 at an emission wavelength of 947 nm. These initial results show great promise for this material in laser applications, and further research is now focused on demonstrating longer wavelength lasers where higher bismuth fractions are expected to eliminate some of the major losses plaguing lasers in the near-infrared.

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