MOVPE growth and characterization of Ga(NAsP) laser structures monolithically integrated on Si (001) substrates

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Laser structures containing the dilute nitride material Ga(NAsP) can be grown lattice matched on silicon substrates with high crystal quality and low defect density. Lasing operation from broad area lasers up to 120K is verified.

The implementation of an efficient light source on silicon is the key technology for optical data communication on chip level. Our approach to realize CMOS-compatible laser structures on Si is the monolithic integration of the novel direct band gap material Ga(NAsP) which can be grown lattice matched on Si [1]. Its unique band structure can be explained in the framework of the band anti-crossing model (BAC) [2, 3]. Lasing from a Ga(NAsP) laser on GaP under electrical injection was previously demonstrated [4]. The integration of the laser material on Si is more crucial. In particular, the defect-free nucleation of GaP on Si is essential to allow the growth of the active material and thick laser waveguide/barrier layers of (BGa)P or (BGa)(AsP) without introducing defects and cracking. In this work we focus on the MOVPE growth of Ga(NAsP) laser structures for electrical current injection lattice matched on exactly orientated Si substrates and their structural characterization.

The MOVPE growth took place in a commercially available Aixtron AIX 200-GFR reactor system at a reduced pressure of 50 mbar using Pd-purified H₂ as carrier gas. The laser structures were grown at a reactor temperature of 575°C applying all-liquid precursors. Tertiarybutyl phosphine (TBP), tertiarybutyl arsine (TBAs), unsymmetric dimethyl hydrazine (UDMH₂), triethyl gallium (TEGa) and triethyl boron (TEB) were used as sources for P, As, N, Ga and B, respectively. For the doping of the contact layers diethyl zinc (DEZn) and diethyl tellurium (DETe) were chosen as sources for Zn and Te as p- and n-dopants, respectively. Fig. 1 shows a schematic of the realized multi-quantum well (QW) laser structure.

The first step for defect-free III/V integration on exactly oriented Si (001) is the nucleation of GaP. Due to the different crystal structure of Si and III/V compound materials a double-stepped Si surface is necessary which can be achieved under special annealing conditions [5]. The nucleation of 3nm GaP at a low temperature of 450°C and an overgrowth with 55nm GaP at a higher temperature of 675°C allows for defect-free III/V growth and the self-annihilation of any formed anti-phase domains within the GaP crystal after a few tens of nanometers, respectively.

Because of the different thermal expansion coefficients of Si and the III/V material, the (BGa)P contact layers must be lattice matched at the growth temperature to avoid initialization of defects, which is realized by the incorporation of about 3% B. Precise overall strain-management allows the growth of a several-μm-thick III/V device structure without cracking. Doping levels of the p- and n-contacts, which is also crucial for optimal current injection, were adjusted via Hall measurements and secondary ion mass spectroscopy (SIMS) on test samples on GaP and Si substrates, respectively.

The active material Ga(N_{~7%}As_{~80%}P) of the 3QW structure is surrounded by 3nm thick GaP layers to prevent the formation of strong B-N bonds and 20nm thick (B_{5.5%}Ga)(As_{11%}P) barriers for strain compensation of the highly compressively strained QW material. This active region is embedded in a separate confinement heterostructure (SCH) consisting of a 100nm (BGa)(AsP) linear grading and 50nm (B_{5.5%}Ga)(As_{11%}P).

The QW-photoluminescence (PL) can be increased by applying optimal post-growth annealing conditions to the sample. Investigations of the PL intensity and line width show a clear dependency on annealing temperature, time and also on the composition of the SCH and barrier material, as will be discussed. For structural investigations high-resolution X-ray diffraction (XRD) around the (004) reflection of Si were performed together with dynamical simulation of this XRD pattern (fig. 3). The well-resolved satellite peaks even at high diffraction angles and the good agreement of measurement and simulation indicate sharp interfaces within the structure and the high crystal quality of this III/V laser on Si.

Additional transmission electron microscopy and SIMS analysis validate the defect-free growth and the well-adjusted doping profile, respectively, and will be discussed in more detail at the conference. From this structure broad area laser were fabricated. The light emission as a function of applied current for different temperatures shows a clear threshold behavior (fig. 4) verifying lasing operation under electrical injection. Lasing up to 120K with a threshold current density J_{th} per QW of 1.47kA/cm^2 and an emission wavelength of about 835nm could be observed. For the first time electrically pumped lasing from Ga(NAsP) broad area laser devices lattice matched on Si (001) substrate is reported.

Fig. 1: Schematic structure of the Ga(NAsP)-3QW laser on Si substrate.

Fig. 2: Integrated PL-intensity at 300 K vs. annealing temperature for three different Ga(NAsP) multi-QW structures on Si (001).

Fig. 3: High-resolution X-ray diffraction measurement of the Ga(NAsP)-3QW laser on Si around the (004)-reflection of Si.

Fig. 4: Light-current curves from 40K to 120K for a (50 x 1000)μm Ga(NAsP)-3QW broad area laser.

References:

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