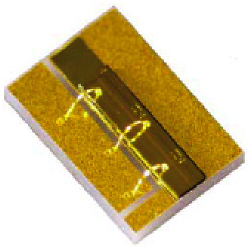
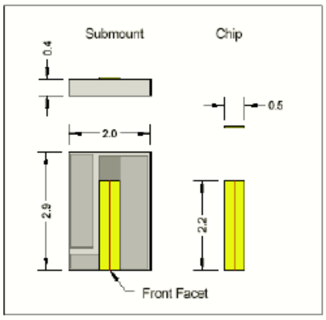
Laser Diodes

Spectral properties of GaAs/AlGaAs/InGaAs quantum well high power lasers with anti-reflection coating

Introduction:
Laser Diodes (LD) consist of semiconducting materials e.g. GaAs or Si, which are doped with electron donors and electron acceptors in different layers. Doping atoms can be Al and In among many others. At the interface between layers with electron depletion and electron excess, electrons and holes can recombine and emit light if a voltage is applied between these layers. Coherent light emission out of the LD is obtained if more light is amplified by recombination than lost through the reflecting outer surfaces of the LD (facets) and by absorption in the LD. The properties of the LD i.e. emission wavelength, linewidth, power, stability, lifetime depend on the dispersion functions of refractive index n and extinction k of all materials of the LD and on the thickness of each layer on the LD. In order to control the quality of the LD those dispersion functions and thickness shall be measured. Especially important for the function of the LD are the optical properties of the anti-reflection coating on the emitting surface of the LD. In a quantum well laser the interface of the light emission is only a few nm thin. Spectroscopic ellipsometry is the ordinary method to measure these optical properties on large semiconducting wafers. Imaging ellipsometry is needed to measure on those tiny LDs, because high lateral resolution of a few µm is necessary.

Samples:
Four different GaAs/AlGaAs/InGaAs quantum well high power lasers (fig.1) labeled A, B, C, D with InGAP anti-reflection coating and one reference laser without coating. It has been specifically designed for applications in low noise broadband Erbium Doped Fiber Amplifiers (EDFA). Lasing occurs between 970 and 985 nm wavelength with 500 mW power. The anti-reflection coating shall have less than 0.5% power-reflectivity. The GaAs (in 110 crystal orientation) has $3*10^{18}$ n-doping of Si.





A B

Fig. 1: A: Top view of the laser, B: Drawing of the laser chip on the submount

Instrumentation:
Spectroscopic Imaging Ellipsometer EP³-SE incl. EP3-View2.31 Software, 10x objective

Tasks:

- Measure the extinction k of the InGaP anti-reflection coating accurately with better than 20µm lateral resolution at the band edge around 800-1000 nm wavelength on the front facet. Measurement 10 µm away from the surface.

- Measure the spectral Reflectivity

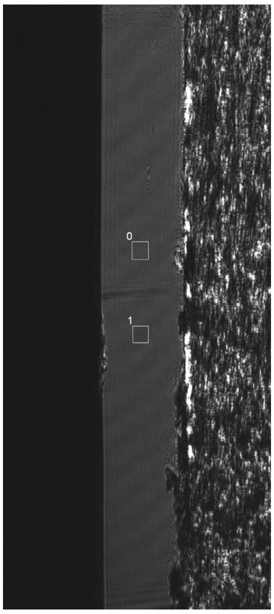


Fig.2: Ellipsometric contrast image (0.4 mm x 0.8 mm) of the front facet of a laser, 70° angle of incidence, 532 nm wavelength

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Measurements:

A spectrum on the reference LD without anti-reflection coating was measured, from which the dispersion function (fig.4) of the GaAs bulk of the LD was determined by direct conversion ("batchprocessing") wavelength by wavelength without dispersion model of the GaAs. The obtained dispersion function of GaAs (fig.4) was used in the following fittings. More spectra, similar to the spectrum of fig.3, were recorded on lasers A-D. The fit parameters were the thickness of the InGaP coating and the InGaP dispersion function parameters. The dispersion function is dominated by a strong oscillator in the near UV and by a constant background refractive index. For an improvement of the fit quality one weak oscillator in the visible spectrum VIS around 730 nm is added. The fitting is most sensitive on the UV-oscillator and the background, less sensitive on the VIS-oscillator. It turns out, that the VIS oscillator has a negative amplitude, which represents light amplification. Due to the superposition of the amplification in the VIS and the absorption of the UV-oscillator, the net amplification is negative without external voltage. Only an applied voltage can effect positive net amplification and lasing. It is obvious from fig.3, that the fit could be further improved by means of additional oscillators at about 650 nm wavelength and in the near infra red (NIR).

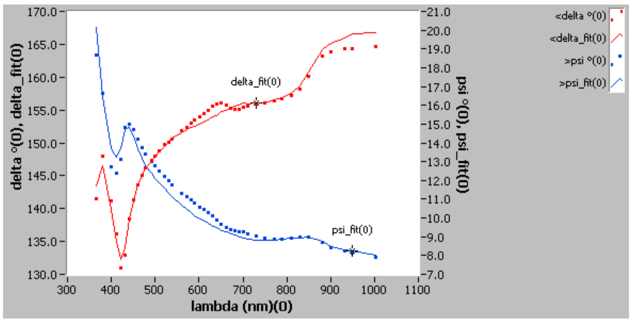

Fig.3: Spectra of Delta/Psi of InGaP coating in ROI 0 on laser D. Fit with the following model parameters: VIS-oscillator: frequency 1.74 ± 0.02, amplitude –0.42 ± 0.07, damping 0.28 ± 0.06, UV-oscillator: frequency 28000 ± 6000 cm-1, amplitude $3.8*10^9$, damping 6200 ± 4000, background: refractive index n = 2.457 ± 0.008 and extinction k = 0, thickness 9.97 ± 0.15, mean square error 10.5

Results:

Fitting of the spectrum (fig.3) in the range 350 – 600 nm is sufficient to yield the thickness in a very good approximation. However the obtained dispersion function of laser A ("dispersionfit-A" in fig.6) cannot resolve the fine structure of the spectra of n and k above 700 nm wavelength. Therefore it is better to fit the Delta/Psi spectra (e.g. in fig.3) in a second step while keeping the thickness constant and while fitting for n and k of the InGaP coating wavelength per wavelength ("batchprocessing"). The dispersion functions obtained on this way (fig. 6), reveal now the desired fine structure at the band edge around 830 nm. There appears one absorption peak at 830 nm (i.e. laser C in fig.6B). The peak is more or less dominant in lasers A, B, C, D, depending on the doping or the production process. The effect of doping increases the extinction k by 0.04 at 830 nm wavelength comparing lasers A and C. The effect of doping is clearly resolved by the ± 0.01 accuracy of the measurement. The overall reflectivity of the laser (fig.5) is calculated out of the Delta/Psi spectrum. The lateral variation of optical parameters of the InGaP has also been studied by comparison of several regions of interest (e.g. fig.2) and by Delta/Psi maps.

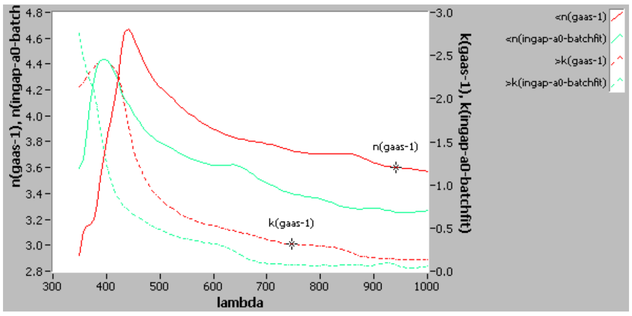

Fig.4: Dispersion functions n and k of GaAs laser bulk and InGaP anti-reflection coating obtained from batchprocessing of Delta/Psi spectra of laser A ROI 0, wavelength lambda in nm

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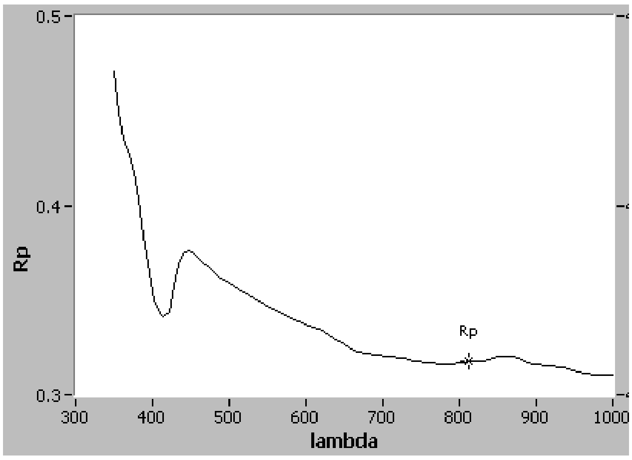
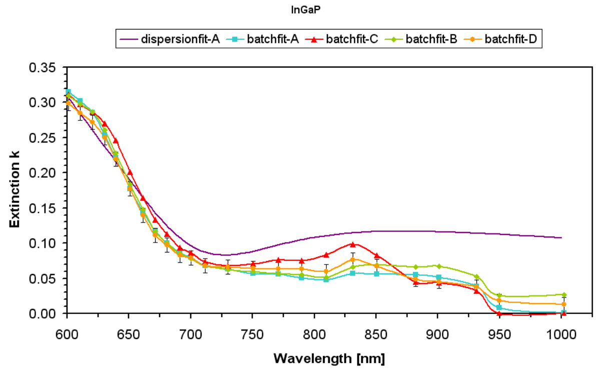
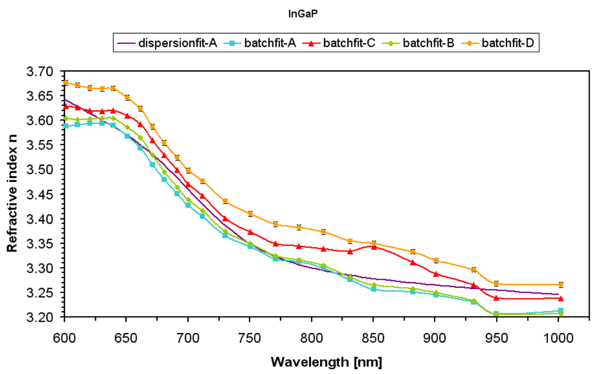


Fig.5: Optical field-reflectivity Rp of the InGaP coated GaAs laser vs. wavelength close to 0° angle of incidence



B

Fig.6: Refractive index n (A) and extinction k (B) of lasers A-D with different doping, comparison with the dispersion function obtained from the fit on the Delta/Psi spectra of laser A



A

Conclusion:

The signature of doping in the InGaP anti-reflection coating on a laser diode has been measured in the extinction spectrum by Nanofilm's spectroscopic imaging-ellipsometer EP3-SE. The imaging ellipsometer is thus a versatile tool for quality control in the production of laser diodes and anti-reflection coatings on laser diodes.

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