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Interdiffusion-induced degradation of 1017 nm ridge waveguide laser diodes

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Abstract

Device degradation of GaAs-based AlGaAs/GaInP/GaInAs ridge waveguide (RW) laser diodes is found to lead to peculiarities in the longitudinal mode spectrum. These features give information on the position of inhomogeneities along the laser stripe. Using monochromatic cathodoluminescence (CL), transmission electron microscopy (TEM) and energy dispersive X-ray analysis (EDX) these inhomogeneities are found to be located in the region of the quantum well (QW) and to be caused by interdiffusion of the lattice constituents. This interdiffusion extends over the active region from the interfaces of the GaInP waveguides to the GaAs spacer layers. It is triggered by nonradiative recombination under laser operation. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Interdiffusion; Interface; $A_{III}B_V$ compounds; Laser diodes; Electron beam methods

1. Introduction

The development of new types of laser diodes combining high output power with high reliability has triggered research into the causes of device degradation. Rapid degradation [1–3] stemming from grown-in dislocations and their movement under laser operation has mostly been overcome due to the availability of highly perfect substrate material and the advances in epitaxial growth. But still native defects and other point defects in the epitaxial layer structure can act as deep levels and thus cause nonradiative recombination resulting in a gradual degradation of laser properties. The most important factor limiting the reliability of high-power laser diodes is facet degradation. In earlier work [4] concerning InGaAs/AlGaAs laser diodes we have found, that interdiffusion of Al and In in the active region initiates facet degradation (catastrophic optical damage, COD). The threshold level of COD can be considerably enhanced by facet coating. In this contribution we will show that in InGasAs/GaInP/AlGaAs laser diodes showing no facet damage degradation of the device performance can be related to interdiffusion processes in the bulk of the structure.

2. Experimental procedure

Ridge waveguide laser diodes emitting at 1017 nm have been processed from wafers consisting of 8 nm

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thick $In_{0.23}Ga_{0.77}As$ single quantum well (QW) with 10 nm thick GaAs spacer layers, embedded in 200 nm thick GaInP waveguide and 1800 (1570) nm $Al_{0.62}Ga_{0.38}As$ cladding layers. The structures have been grown on (1 0 0) n-type GaAs substrates by metal organic vapor-phase epitaxy [5]. Dopant elements are zinc for p-type and silicon for n-type. The laser facets were coated with antireflecting Al_2O_3 films on the front facet and highly reflective dielectric mirrors (pairs of Al_2O_3/Si) on the rear facet. Lasers showing untypical high degradation rate during screening tests (40°C, 200 mW output power) were selected to study the reasons of the degradation. By analysing the intensity distribution of the broad longitudinal mode spectrum below laser threshold by fast Fourier transform the longitudinal position of regions with different reflection along the stripe can be identified [6]. After removing the p-metal contact layer monochromatic cathodoluminescence (CL) imaging at 110 K with the emission wavelength of the active region was done with an Oxford Instrument system adapted to a Scanning Electron Microscope JEOL JSM 840A. Transmission electron microscopy (TEM) has been applied to clarify the character of regions of dark contrast in these CL images. TEM investigations of samples prepared as cross-section by focussed ion beam etching were done in a High-Voltage Electron Microscope JEOL JEM 1000 operating at 1000 kV. Energy-dispersive X-ray analysis (EDX) was carried out in a Transmission Electron Microscope CM 20 FEG at 120 kV using the Voyager 2 analysing system. The diameter of the probe of the analysing system was 0.6 nm.

3. Results

The intensity distribution of the broad longitudinal mode spectrum below threshold was measured using a 1.25 m grating monochromator with high resolution of 0.006 nm. On the assumption that each longitudinal mode is a single peak, fast Fourier transform (FFT) can be used to identify irregularities from the overmodulation of the longitudinal mode spectrum [7]. Fig. 1a shows a measured spectrum below the threshold of a 2000 μm RW laser diode after stress testing. On the envelope of the spectrum a ripple behaviour (Fig. 1a) can be seen, which indicates internal irregularities/defects. In the FFT of the spectrum, distinct peaks can be seen (Fig. 1b). The main peak at 2000 μm corresponds to the longitudinal mode distance and correlates to the laser length by the relation

$$\Delta\lambda = \frac{\lambda^2}{L 2 n_g},$$

where $\Delta\lambda$ is the distance between the longitudinal modes, λ the wavelength, L the laser cavity length and n_g the group index. Additional small peaks — marked with arrows — can be seen corresponding to irregularities/defects at the respective positions inside the laser cavity. To clarify the origin of these irregularities and their character *top view* CL images at the wavelength of the active region were taken. In the stripe region dark spots with a diameter of $\leqslant 5$ μm are visible (Fig. 2) at the positions indicated by peaks in the FFT spectrum. The dark spots in Fig. 2 correspond to the peaks shown in the inset of Fig. 1b. From the imaging wavelength we can conclude, that these nonradiative regions are located in the active layer. TEM diffraction contrast analysis of these laser diodes has shown that these dark spots are not related to dislocations or other crystal defects. One dark spot in the CL image correlates to an agglomeration of irregularly bordered regions with a composition different from the original structure (see marker in Fig. 3). From the TEM micrograph the size of these regions is 40–100 nm. The vertical extent of these regions is restricted to the GaAs/InGaAs/GaAs active region including the GaAs/InGaP and GaInP/GaAs interfaces. In images taken with the [2 2 0] diffraction vector which is sensitive to different compositions it can be observed, that the irregularly bordered regions are preferentially located at the GaAs/GaInP rsp. GaInP/GaAs interfaces (Fig. 4). Fig. 4 was taken from another place of the same laser diode.

EDX line scans with P_k and As_k lines were taken across the active region as shown in Fig. 5. The line scan position is marked with arrows in Fig. 5a — line scan 1 across the intact structure, line scan 2 across region of active layer showing changes in TEM contrast. The comparison of the two line scans shows that phosphorus is present down to the

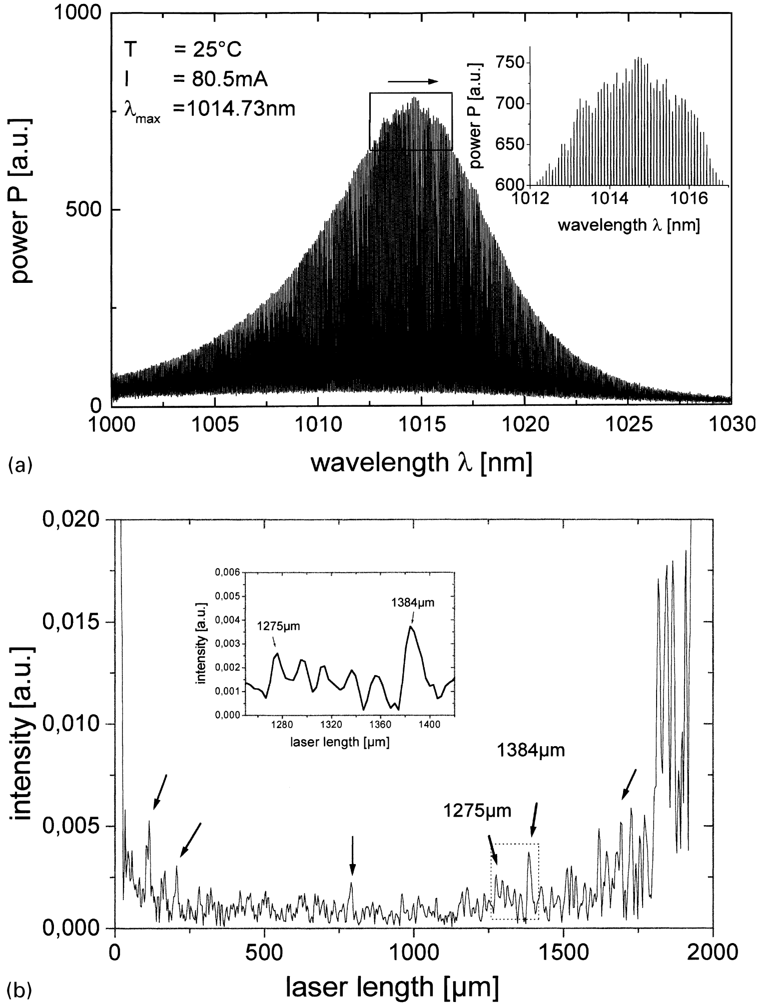

Fig. 1. Longitudinal mode spectrum (a) and corresponding fast Fourier transform (b).

InGaAs QW in regions showing changes in TEM contrast. The profiles taken with the As_k-line (here not shown) and the P_k-line are complementary.

4. Discussion

In the FFT longitudinal mode spectrum taken below the laser threshold peaks indicate irregularities in the laser structure. Cathodoluminescence investigations have shown, that these irregularities are located in the active region and are characterized by nonradiative recombination. In regions including these irregularities no shift of the wavelength emitted from the active layer was found. TEM/EDX investigations reveal that these irregularities show a composition different from the original structure. These regions are vertically limited by the GaAs/GaInP (GaInP/GaAs) interfaces. Their lateral dimensions are very small making their compositional analysis difficult. A few narrow neighbouring regions visible in TEM images correlate to one dark spot in the CL image, indicating that the GaAs/GaInP (GaInP/GaAs) interfaces

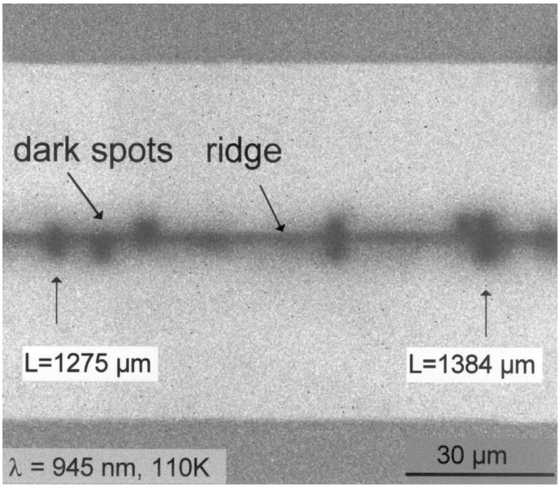

Fig. 2. CL-image taken with the wavelength of the active layer (950 nm) at 110 K showing dark spots in the ridge region.

have been smeared out by interdiffusion over distances < 2 μm along the laser stripe. In most cases the QW in these regions is not destroyed. But EDX analysis shows, that phosphorus is present in the active region. These regions were observed only in laser structures after stress testing which indicates that they are created by processes induced under carrier injection. From EDX measurements we conclude that interdiffusion results in the development of a tensile strained Ga(As,P) layer over limited distances, most < 2 μm. The interdiffusion can be driven by the concentration gradient, different mobilities of the individual species and by a strain field (e.g. induced at the ridge edges). It is known, that interdiffusion limits the thermal stability of GaAs/GaInP (GaInP/GaAs) interfaces under annealing conditions [8,9]. Annealing experiments with GaAs/GaInP quantum wells at 650 and 700°C have shown, that the degree of intermixing is roughly twice as high for group III atoms than for group V atoms [8]. Due to the different diffusion velocity of group III and V atoms this interdiffusion can cause strain.

Assuming the diffusion length L in our samples to be equal to the GaAs spacer layer thickness and half the InGaAs QW thickness and taking the duration of laser operation as diffusion time t from $L = (Dt)^{1/2}$ the diffusion coefficient can be estimated to be roughly 10^{-18} cm^2/s. This is comparable to the value for P–As interdiffusion under annealing at 650°C given by Francis et al. [8]. The junction temperature during laser operation is much lower than this, only in case of COD can the facet temperature reach such values. Thus we suggest, that in analogy to the theory of recombination-enhanced defect reaction/motion (REDR/REDM) [1–3] the interdiffusion is triggered by the energy created by nonradiative recombination at point defects (e.g. vacancies) present in the layer. In-segregation, As–P exchange at the GaAs/GaInP

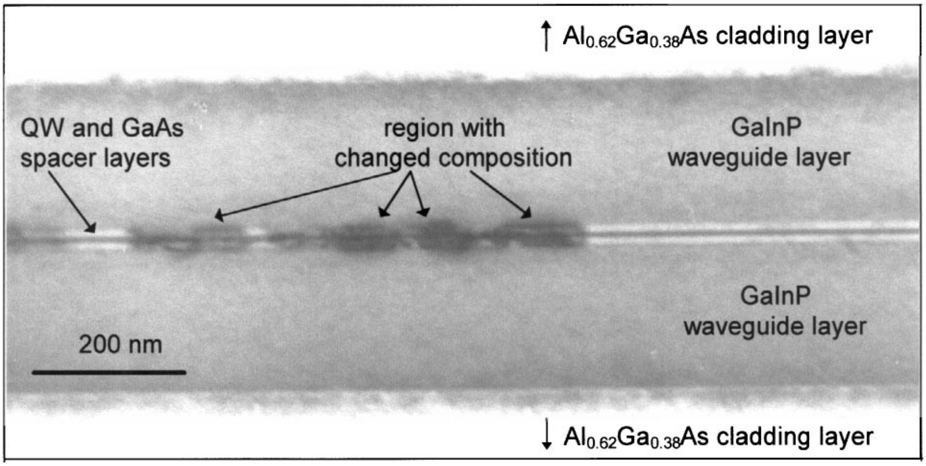

Fig. 3. Cross-section TEM image of an area showing dark contrast in CL using [2 0 0] diffraction vector.

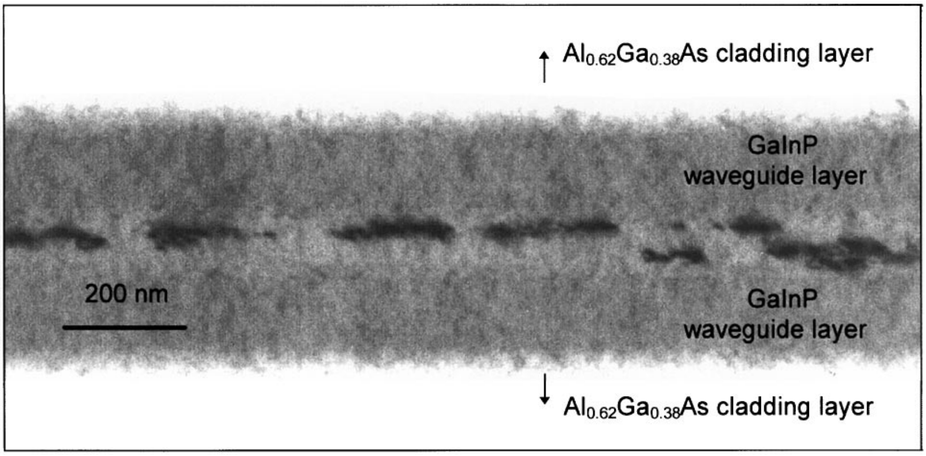

Fig. 4. Cross-section TEM image of an area also showing dark contrast in CL but using [2 2 0] diffraction vector.

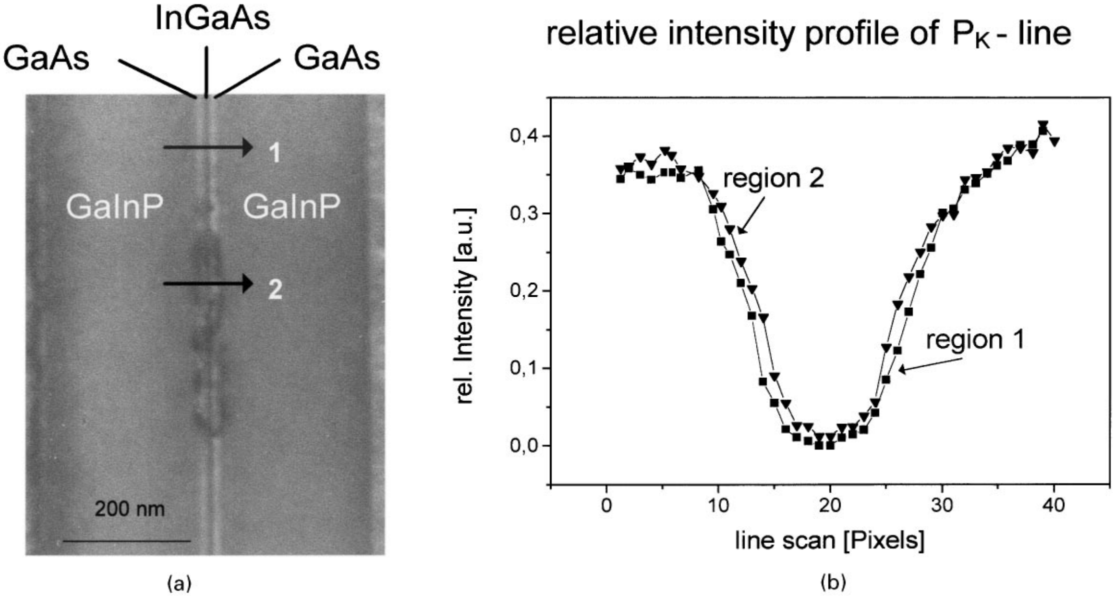

Fig. 5. EDX line scans (b) taken with P_k-line across the active region. The positions of line scans are indicated by arrows in (a) ((1) line scan across intact active region, (2) line scan across active region showing changes in TEM contrast).

and GaInP/GaAs interfaces and residual P/As incorporation in the GaAs(GaInP) layer can cause point defects and related defect complexes. To clarify the character of these defects further investigations concerning the chemistry of the interfaces are necessary.

5. Conclusions

The degradation of laser diodes emitting at 1017 nm is accompanied by a compositional instability in the region of the active layer including the interfaces GaAs/GaInP and GaInP/GaAs. This compositional instability is induced by As/P interdiffusion. The energy for this process originates from the nonradiative recombination at point defects.

Acknowledgements

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