Novel Passivation Process for the Mirror Facets of Al-Free Active-Region High-Power Semiconductor Diode Lasers

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***Abstract*—A novel process for the passivation of mirror facets of Al-free active-region high-power semiconductor diode lasers is presented. Designed for technological simplicity and minimum damage generated within the facet region, it combines laser bar cleaving in air with a two-step process consisting of 1) removal of thermodynamically unstable species and 2) facet sealing with a passivation layer. Impurity removal is achieved by irradiation with beams of atomic hydrogen, while zinc selenide is used as the passivating medium. The effectiveness of the process is demonstrated by operation of 808-nm GaAsP-active ridge-waveguide diode lasers at record optical powers of 500 mW for several thousand hours limited only by bulk degradation.**

***Index Terms*—Atomic beams, life estimation, optical films, passivation, semiconductor lasers.**

I. INTRODUCTION

RELIABILITY is a key issue in fabricating high-power semiconductor diode lasers. Often, it limits device performance in areas, where the advantages of diode lasers as compactness, wide choice of wavelengths, or the possibility to couple the beam into optical fibers, are otherwise compelling. For single edge-emitters as multimode broad-area or single-mode ridge-waveguide (RW) lasers, the main factor limiting device reliability and maximum optical power is the stability of the mirror facets.

A number of facet passivation processes have been developed in the past with E2 [1] to name the probably most influential one. Based on cleaving the laser bars in ultrahigh vacuum (UHV), the process requires expensive and complicated equipment and, in its original version, is limited to laser wavelengths >800 nm. Recently, the process has been modified to yield operation of 800-nm RW lasers at 400 mW for at least 1000 h [2]. Thus further, mostly proprietary, processes have been created during the last decade. They concentrate on the elimination of facet degradation or catastrophic optical mirror damage (COMD) by decreasing optical absorption and/or reducing and stabilizing the interface state density in the facet region.

For this purpose, various technological means have been applied as, for instance, the increase of the interfacial bandgap by impurity-induced disordering of the quantum well(s), thus creating a so-called window-mirror structure [3], the removal of native oxide from the facets by irradiation with low-energetic (<50 eV) Ar ions or plasma [4] or, more recently, with low-energetic and reactive nitrogen ions [5].

Advantageous is that these techniques allow cleaving the laser bars in air. Irradiation of the facet region with energetic particles, however, is problematic generally since lattice defects in semiconductors can be generated at energies as low as 10 eV. We, thus, have recently introduced a novel facet passivation process [6] that combines bar cleaving in air with a purely chemical nonkinetic method of facet cleaning prior to facet sealing with a passivating layer. In this letter, the process is detailed and results are presented on the performance of thus treated high-power diode lasers.

II. FACET PASSIVATION

A. Concept

Process development has been guided by several principles as follows. First, technical simplicity was mandatory implying cleaving the bars in air and the use of standard semiconductor technology. Second, facet cleaning has to be accomplished by a purely chemical process without employing energetic particles potentially damaging the facet region. Cleaning has to concentrate on the removal of thermodynamically unstable species as arsenic, arsenic oxides, adsorbed water, etc. Their presence spurs gradual facet degradation, eventually leading to COMD. Third, the cleaned facets are coated *in situ* with a passivating layer preserving the clean state of the facets. The following implementation, as stated first in [7], has been investigated.

Purely chemical cleaning of III–V semiconductor surfaces is most easily accomplished by irradiation with atomic hydrogen. The technique is used routinely for epitaxial overgrowth of patterned GaAs or InP surfaces in molecular beam epitaxy. Atomic hydrogen can be generated in vacuum by cracking molecular hydrogen on hot filaments or by extracting it as neutral atomic beams from electron cyclotron resonance (ECR) plasma discharges. In any case, the kinetic energy of the atoms is below 1 eV, i.e., well below threshold for damage creation. Cleaning temperatures are below 400 °C making the process compatible with the employment of standard metallizations for contacting diode lasers. Al_2O_3, however, which is part of the native oxide of AlGaAs-based semiconductor regions, cannot be eliminated

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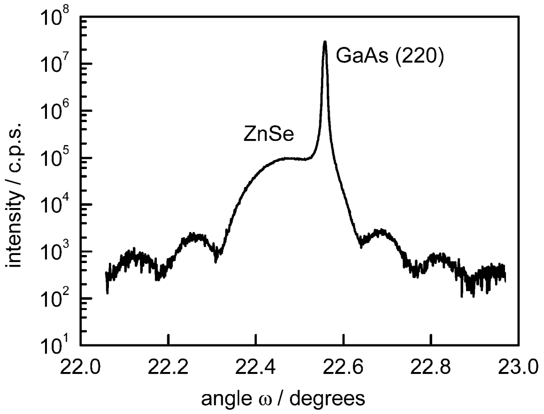

Fig. 1. High-resolution X-ray rocking curve of a GaAs (110) test piece attached to the laser bar fixture. The sample was cleaned with atomic hydrogen and coated *in situ* with a 40-nm-thick ZnSe layer. Thickness fringes beside the main GaAs and the ZnSe peak indicate good epitaxial growth of the ZnSe layer, which in turn proves the effectiveness of the cleaning procedure.

this way, thus limiting the new process to Al-free active region devices.

For passivating the cleaned facets, we have selected ZnSe. It can be deposited epitaxially on GaAs or related compounds, thus yielding a favorably low interface-state density at least on the oxide-free portions of the mirror facets. Deposition is easily performed at low (<300 °C) substrate temperatures from a single Knudsen cell type evaporator [8], [9]. In prior studies, this material has been used for passivating air-cleaved facets of 950-nm broad-area diode lasers [10] and UHV-cleaved facets of 980-nm RW [11] diode lasers.

B. Implementation

For demonstrating the feasibility of the technology, we used a custom-built UHV chamber equipped with an ECR plasma source for atomic hydrogen ($E_{\text{kin}} < 1$ eV) and a single Knudsen cell for evaporating ZnSe. In a first attempt, we proved the effectiveness of the cleaning procedure itself. Fig. 1 shows the high-resolution X-ray rocking curve of a GaAs (110) crystal, which has been heated, irradiated with atomic hydrogen and coated *in situ* with a 40-nm-thick ZnSe layer. Clearly, beside the main GaAs and the broader ZnSe peak (left), thickness fringes are observed indicating good epitaxial growth of the ZnSe layer on the cleaned GaAs (110) surface, which in turn proves the effectiveness of the cleaning procedure.

The passivation technology thus consists of the following steps. Laser bars cleaved in air are stacked in a fixture and introduced into the vacuum chamber. The stack is heated by thermal irradiation to the temperature required for atomic hydrogen cleaning. After treatment, the bars are cooled down to the temperature needed for ZnSe deposition, which is carried out on front and rear facets as well. Finally, the fixture is taken to a standard apparatus for optical coating for facet reflectivity adjustment.

III. LASER RELIABILITY

We have selected two charges of high-power diode lasers for proving the effectiveness of the passivation process presented herein, i.e., 980-nm single-mode RW lasers with compressively strained InGaAs quantum wells (QWs) and 808-nm RW lasers with tensile-strained GaAsP QWs. Laser structures of both types were grown by metal–organic vapor phase epitaxy on GaAs (001) substrates with the wafers processed to yield diodes with 3-μm stripe width.

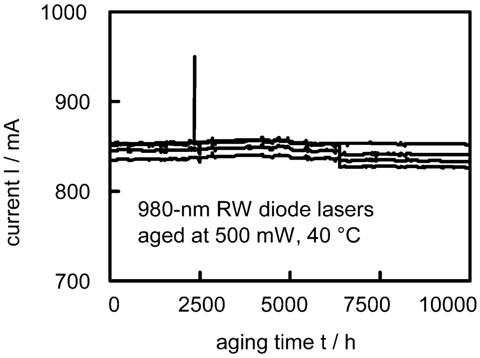

Fig. 2. Aging of 980-nm InGaAs QW RW lasers with facets passivated with the process described herein; five diodes have been aged in the COP regime at 500 mW and 40 °C without burn-in.

The wafer with 980-nm RW lasers was cleaved into bars with 3-mm cavity length. One set has been passivated according to the process described above and optically coated yielding front (R_f) and back (R_r) facet reflectivities of 1% and 94%, respectively. For comparison, a further set has been coated by a standard technique only.

Fig. 2 shows the driving current of five passivated diodes aged without burn-in in the constant-optical-power (COP) regime at 500 mW and 40 °C over a time of 10 000 h. The discontinuity at 6400 h is due to interruption for measurements. One diode failed after 2350 h. Optical inspection revealed no facet damage, which has been confirmed by imaging the electroluminescence of the facets below lasing threshold, displaying no dark regions. The overall degradation rate, i.e., the relative current change divided by the aging time, is below the detection limit in all cases. In contrast, five diodes coated by ion beam sputtering only, failed within 1500 h when aged at only 300 mW and 40 °C. This documents impressively the effectiveness of the new passivation process. We believe the reliability of the passivated 980-nm RW diode lasers to be at least comparable to those used in pumps for Er-doped fiber amplifiers.

The 808-nm RW laser bars with 2-mm cavity length have been passivated and optically coated to give R_f and R_r of 3% and 94%, respectively. Fig. 3 displays the driving current of five diodes aged in the COP regime at 25 °C at powers increasing from 300 to 500 mW by 100 mW. At 300 and 400 mW, no degradation was detectable except for one diode, which failed after 2060 h with, however, no facet damage. At 500 mW, the diodes showed initially, i.e., up to 2000 h, likewise no degradation. Later on, the degradation rate rose to a low 2–4 $\times 10^{-6}$ h^{-1} with the diodes failing finally after ca. 3000 h at this high power level. Optical inspection revealed weak front facet damage in all cases being, however, not typical for COMD. From similar experiments with broad-area (100-μm stripe width) lasers stemming from the same wafer, allowing the application of nondestructive longitudinal mode analysis [12], we conclude that defects develop primarily inside

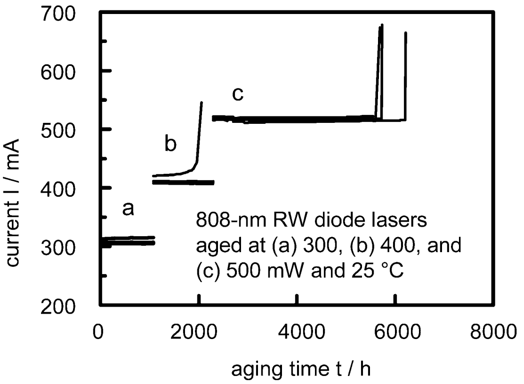

Fig. 3. Reliability of 808-nm GaAsP QW RW lasers with passivated facets. Five diodes have been aged step-wise in the COP regime at 300, 400, and 500 mW (25 °C) with no burn-in.

the cavity, grow, and eventually lead to device failure, if they approach the facet region. Thus, device lifetime here is limited rather by generation of bulk defects but not facet stability.

Similar devices from our laboratory optically coated with ion beam sputtering worked reliably up to output powers of 100 mW, i.e., with degradation rates of 1–2 × 10^{-5} h^{-1} up to at least 4000 h. Increasing the power level to 200 mW led to abrupt decrease of lifetime to less than 300 h. Hence, also the aging behavior of passivated 808-nm RW lasers proves the effectiveness of the novel passivation process. To the best of our knowledge, no comparable lifetimes have been reported for 808-nm RW lasers emitting at powers at 500 mW. The lower resistance to failure at a similar stress level as in 980-nm diodes is attributed to the lower defect resistance of the tensile-strained GaAsP QWs compared to InGaAs-based QWs, which are capable of blocking the spread of dislocations or similar defects. This issue now comes to the agenda as device lifetime is no longer limited by facet stability.

IV. SUMMARY

A novel process for facet passivation of high-power diode lasers has been presented. Allowing cleaving the laser bars in air, it is based on a nonkinetic purely chemical method of eliminating unstable components from the facets before passivating them with a stable layer. Composed of steps taken from standard semiconductor technology, it can be easily scaled up for high throughput or integrated into equipment for optical coating making it a cost-effective alternative to passivation procedures based on bar cleaving in UHV. Aging tests on 808- and 980-nm diode lasers demonstrate performance at least comparable to these, being however, much more complex technologies.

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