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**Technical Report on Task Orders No. B239703 and B239705
Development of Technology of Al-free High-power Laser Diodes**

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Technical Report on Task Orders No. B239703 and B239705

(Development of technology of Al-free high-power laser diodes)

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Introduction

The modified liquid phase epitaxy (LPE) technique has been developed in our laboratory and successfully applied to fabrication of single quantum well, separate confinement heterostructure (SQW SCH) laser diodes in InGaAsP/GaAs system.

This quaternary system does not use easily oxidizable aluminum-containing components and provides a number of advantages. One of them is very low rate of dislocation spreading, which allows the usage of cheap substrates and prevents sudden mode failure of laser diodes. In addition, very low velocity of surface recombination in InGaAsP decreases nonradiative current leakage and drastically reduces mirror facet overheating, thus increasing catastrophic optical damage level. Another advantage of this system is simplified heterostructure growth and postgrowth processing of laser diodes. Al-free diodes have high chemical stability of cleaved surfaces, and therefore do not require immediate coating. Owing to this stability, single-mode buried lasers can be easily fabricated by regrowth of etched mesas.

InGaAsP/GaAs system is suitable for the wavelength range 740-890 nm. Our investigations show that, compared to conventional AlGaAs system, it has higher electrical-to-optical efficiency, significantly better degradation characteristics, lower mirror overheating and higher catastrophic optical damage limit.

The modified LPE technique

Quantum-well heterostructures in InGaAsP system can be grown by a simple version of short-period liquid-phase epitaxy (LPE), in which thin layers grow as the substrate is moved under the melt confined in a narrow growth slot. The relevant technological approach, started in 1983, was developed into working technology and summarized in [1,2].

The photoluminescent research and direct Auger study showed that the interface width in quantum-well structures grown by this technique is about several lattice constants, and quantum wells wider than 100Å can be considered rectangular [3,4].

Naturally, MOCVD and MBE are superior to liquid phase techniques in the reproducibility of samples with a given thickness of the active region and the degree of its spatial homogeneity. We believe, however, that the LPE method has an essential asset of providing a high stability in obtaining large values of the efficiency of spontaneous radiative recombination in the active region of SQW structures.

Band structure and design of InGaAsP/GaAs lasers

The band diagram is shown in figure 1. All structures are grown on *n*-type (100) GaAs substrate, and all the layers match GaAs in the lattice constant. The *n*- and *p*-cladding layers are $\text{In}_{0.49}\text{Ga}_{0.51}\text{P}$ doped with Te and Zn to $N=10^{18}$ and $P=10^{18} \text{ cm}^{-3}$, correspondingly. The waveguide and the active layer are made from intentionally undoped InGaAsP ($N \approx 5 \times 10^{16} \text{ cm}^{-3}$). The waveguide, of the total thickness 0.4–0.8 μm, is $\text{In}_{0.49}\text{Ga}_{0.57}\text{As}_{0.15}\text{P}_{0.83}$. The active layer is about 200Å thick, its composition depending on the required wavelength. The lattice mismatch at any interface does not exceed 0.1%.

Stripe-contact lasers (stripe width 100 μm) are formed by either SiO_2 or Schottky barrier isolation. The ohmic contacts to GaAs substrate and to *p*-region are made by vapor deposition of Au:Ge and Au:Zn alloys, respectively. At current densities above 1 kA/cm² the differential resistance of the diodes is about $1.5 \cdot 10^{-4} \text{ Ohm} \cdot \text{cm}^2$.

Efficiency of InGaAsP/GaAs lasers

The study of electrical-to-optical efficiency (EOE) of InGaAsP/GaAs lasers enabled us to distinguish four

Figure 1. Band diagram of InGaAsP/GaAs heterostructure.

Figure 2. Electrical-to-optical efficiency of InGaAsP lasers vs. wavelength; squares – typical values, triangles – maximal values.

wavelength regions. Figure 2 shows the result of this study; triangles represent maximum observed values of efficiency at each wavelength.

Since LPE cannot produce highly homogeneous layers, efficiency varies in different parts of the structure. Squares in figure 2 show typical EOE values for different wavelengths. At least 5 different structures were studied to obtain each typical point, and as many as 25 structures per point were measured in the region 780-840nm. All values were obtained on long-cavity lasers (longer than 1mm). Our postgrowth technology provides very low series resistance, so that lasers with cavity length over 1mm and 100 μ m-wide stripe contact have full resistance of 0.1-0.15 Ohm.

Relatively low efficiency in the range 740-780 nm is due to small bandgap difference between active region and waveguide in such structures, which results in strong carrier leakage into the waveguide layers and P-emitter. This leakage reduces EOE in short-wavelength lasers.

Maximum values of efficiency for this system were obtained in the most interesting range 780-840nm; the 65% point was measured on a laser with high- and antireflective coatings, lasing at 810 nm with optical power 3W, and the maximum optical power from this laser was 5.3W. Typical efficiency in this wavelength region is 30%.

The first investigations of InGaAsP/GaAs lasers in 840-860 nm wavelength region showed typical efficiencies of 25-30%, maximum value at 860 nm is 40%. This demonstrates the possibility of obtaining high efficiency in this wavelength region.

Structures with lasing wavelength longer than 860 nm have strained active region. First studies of such lasers gave EOE values of 20-25%. We believe, however, that this can be improved by optimizing layer compositions, thicknesses and growth conditions.

T_0 values of InGaAsP/GaAs lasers

Characteristic temperature T_0 was determined for the ambient temperatures in the range 0..60°C, in CW operation. Figure 3 is the wavelength dependence of typical T_0 values of SQW InGaAsP/GaAs lasers (cavity length ≥ 1 mm). These values were obtained on the same lasers that were used for efficiency measurements, and each point represents an average of at least 10 samples. As with efficiency, low T_0 values at short wavelengths are due to strong carrier leakage from the quantum well which is the result of small bandgap difference between active region and waveguide.

Temperature of the active region and mirror facets of InGaAsP/GaAs SCH SQW lasers

Optical methods have been developed in our laboratory for determination of local temperature rise in the bulk of the active region and at the mirrors of InGaAsP/GaAs ($\lambda=0.8$ μm) laser diodes [5].

For the first time it was shown that in long-cavity diodes with low series resistance and high values of η_d , the temperature rise in the bulk of the active region steeply slows down after the threshold and can be less than 10 degrees per watt of electrical power [5].

The photoluminescence study of mirror temperature of AlGaAs/GaAs and InGaAsP/GaAs SCH SQW lasers revealed one of the main advantages of the latter: in properly designed InGaAsP/GaAs SCH SQW laser diodes with a 100 μm stripe, the overheating of the mirrors can be less than 5 degrees at optical power of 1 W, while in AlGaAs/GaAs lasers it is about 200 degrees [6,7].

It is due to the insignificant temperature rise at the mirror facets and in the bulk of the active region of InGaAsP/GaAs diodes that CW optical power over 5 W was obtained, with electrical-to-optical efficiency 65% for powers up to 3 W [5].

Figure 3. Typical T_0 values of InGaAsP/GaAs lasers vs. wavelength.

In buried mesa InGaAsP/GaAs lasers optical density of 30 MW/cm² on the mirror facets was obtained without immediate damage, which is an evidence of very high optical strength of InGaAsP surface [8].

Study of degradation processes in InGaAsP/GaAs SCH SQW

A comparison between degradation behavior of AlGaAs/GaAs and InGaAsP/GaAs SCH SQW laser diodes revealed the second important advantage of the latter structure. During the testing of several hundreds of InGaAsP/GaAs laser diodes no sudden mode failure was observed that could be attributed to the catastrophic growth of dark line defects [5,9]. On the other hand, this type of failure occurred in a considerable part of AlGaAs/GaAs SCH SQW laser diodes tested.

High-power optical pumping experiments confirmed this difference. In AlGaAs/GaAs SCH SQW structures dark spot defects or mechanically produced defects (scratches) catastrophically grew under optical pumping due to dark line defect formation [10]. As for InGaAsP/GaAs structures, such degradation mechanisms were not observed even for essentially higher pumping levels [11]. The direct lifetime testing of InGaAsP/GaAs SCH SQW diodes with a 100 μ m stripe showed that at optical power of 1 W the power decrease can be less than 10% after 1.5×10^3 hours of testing [5].

Summary

Our investigations of InGaAsP/GaAs system have shown that it is in many ways superior to the conventional AlGaAs/GaAs system. Laser diodes fabricated from InGaAsP/GaAs exhibit low facet overheating, high efficiency, good degradation characteristics and high catastrophic optical damage (COD) limit. Our postgrowth technology provides stripe-contact lasers having very low series resistance and, therefore, high electrical-to-optical efficiency.

Conclusion

The described advantages of the InGaAsP/GaAs system make it a promising candidate against conventional AlGaAs/GaAs for high-power laser diode arrays operating in the range 740-890 nm. Such arrays are likely to be superior to AlGaAs ones in many characteristics.

Next step in development of Al-free lasers may consist in using InGaAsP/GaAs system for lasers with strained active region. Such lasers are expected to have lower threshold current densities and wider wavelength range.

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