Study of Process Techniques of Vertical-Cavity Surface-Emitting Lasers

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Abstract

In this dissertation, we have studied the process technology and characteristics improvement of vertical-cavity surface-emitting lasers (VCSELs). VCSELs possess circular-output beam, low production-cost, single longitudinal-mode operation, and possible integration of two-dimensional array. Hence, VCSELs are potentially suitable for light sources in fiber communication systems, medium and short distance data transmission systems. Other applications include optical storage, optical sensing, and display systems *etc*. In the processes of fabricating VCSEL devices, there are several main techniques, including mesa etching, transverse confinement of electrical current or optical fields, ohmic contact metal deposition and dielectric film deposition. The most important fabricating process of VCSEL device is transverse confinement technique. A well design of transverse optical and electrical confinement will enhance the electrical-to-optical conversion efficiency or the wallplug efficiency of the devices. Basically, the transverse optical field can be confined inside the VCSELs using gain-guiding, index-guiding, or hybrid-guiding of gain-guiding and index-guiding mechanisms. This dissertation will focus on study of the processing techniques and devices performances of various transverse guiding methods of VCSEL devices. We tried to improve the characteristics of the VCSEL with traditional gain guiding structure, develop new type of index-guiding technique and combine the merits of

gain-guiding and index-guiding technique to obtain the high modulation speed VCSEL. The wafers used in this study are essentially GaAs-based 850 nm VCSEL wafers especially most on 850 nm GaAs VCSELs, because the mature epitaxial growth techniques and easy to purchase the VCSEL wafers. In addition, we also develop new guiding technique—photoelectrochemical oxidation for GaN-based materials.

Gain-guiding mechanism is a simple and planar process for fabricating VCSELs. However, due to the gain-guided nature of the proton-implanted VCSELs, the kinks usually occur in light output power versus current (L-I) curve, and the laser power output jitters and noise also tends to limit the modulated speed around 1.25 Gb/s. We proposed a new p-contact scheme using Ti and ITO transparent overcoating on the regular p-contact of the proton-implanted VCSEL and obtain substantial improvement in the kink characteristics and the modulation response of the proton-implanted VCSEL shows a more open clear eye and lower jitter of 35 ps operating at 2.125 Gb/s under 10 mA bias and 9 dB extinction ratio compared to the device without overcoated.

Because of gain-guiding mechanism nature of lacking ability of strong optical confinement, gain-guided VCSELs could not exhibit performance as good as index-guided VCSEL. We tried to find a new VCSEL structure with virtue of gain-guiding, simple planar process, and possessing index-guide. We utilize silicon implantation to replace proton implantation. The VCSELs with aperture of $13\times13\ \mu m^2$ exhibit kink-free current-light output performance with threshold currents about 2.2 mA, and the eye diagram operating at 2.125 Gb/s with 7 mA bias and 10 dB extinction ratio shows very clean eye with jitter less than 30 ps. The mode patterns of silicon-implanted VCSEL showed similar stable transverse mode patterns of oxide-confined VCSELs suggested that the silicon-implantation induce disordering of the implanted regions, so that silicon-implanted VCSELs have better index-guide than other ion-implanted VCSEL.

For high side mode suppression ratio (SMSR) single-mode VCSEL purposed for fiber communication, we suggested two hybrid-guided structures. One is oxygen implantation cooperated selective oxide-confined, another is using photonic crystal on proton-implanted VCSEL. In selective oxide-confined VCSEL with oxygen implantation, the oxygen implantation is for gain-guiding and the selective oxidation is for index-guiding. This approach showed single transverse mode emission within the full operational range with large emission aperture of 8 μm. It also exhibited good performance with a threshold current of 1.5 mA, and a maximum output power of 3.8 mW. Moreover, the single mode VCSELs also demonstrate superior high speed performance up to 10 Gb/s.

In proton-implanted VCSELs with photonic crystal structures, the 2-D photonic crystal is for gain-guiding and proton implantation is for index-guiding. This approach showed single-output transverse mode with high SMSR over 40 dB and ultra-low divergent angle about 7^{o}. Moreover, this device also had a ultra-low threshold current about 1.25 mA with proton-implanted aperture of 10 μm. We also applied this technique on the long-wavelength 1.3 μm InAs quantum-dots VCSELs and the VCSELs also show the single-output transverse mode in whole operation range.

All of the developed techniques studied in this dissertation showed promising applied on the long-wavelength (LW) VCSELs for the optical communication. But in short-wavelength of nitride-based blue and UV devices, wet selective-oxide technique not suitable for forming oxide-confined region in the GaN-based structure devices. For solving this problem, we developed photoelectrochemical (PEC) oxidation techniques and obtain stable growing oxide film on GaN material. We also applied the PEC oxidation on the *p*-GaN surface to enhance light output of GaN-based LEDs. We believe that the PEC oxidation could apply on fabricating GaN-based VCSEL. All in all, basic transverse confinement mechanisms are studied and several types of transverse confinement techniques applied on fabricating VCSELs are proposed. The characteristics of device operation and phenomenon of different confine mechanism were also investigated. We hope those all will turn into useful information in fabricating LW-VCSELs and blue/UV VCSELs in the future.