Contents

Abstract (in Chinese) I
Abstract (in English) III
Acknowledgement VII
Contents IX
List of figures XI

Chapter 1 Introduction **1**
1-1 A Brief History of Vertical-Cavity Surface-Emitting Laser (VCSEL) 1
1-2 Fabricating Processes of VCSEL Devices 4
1-2-1 Gain-guiding mechanism 6
1-2-2 Index-guiding mechanism 8
1-2-3 Hybrid-guiding mechanism 16
1-3 Overview of this Thesis 18
References 21

Chapter 2 Proton-implanted VCSEL with Transparent Contact **25**
2-1 Literature survey 25
2-2 Experiment 27
2-3 Results and Discussions 30
2-4 Summary 34
References 35

Chapter 3 Si^+-implanted VCSEL (Index-guided VCSEL) **37**
3-1 Literature survey 37
3-2 Device structure and fabrication 38
3-3 VCSEL performance 40
3-4 VCSEL reliability 44
3-5 Summary 44
References 46

Chapter 4 High Speed Oxygen-implanted VCSEL **49**
4-1 Literature survey 50
4-2 Device structure and fabrication 51
4-3 Results and Discussion 52
4-4 Summary 54
References 55

Chapter 5 Proton-implanted VCSELs with Photonic Crystal **59**
5-1 Literature survey and Background 59
5-2 Experiment 62
5-3 Results and Discussions 65
5-4 Summary 69
References 70

Chapter 6 Conclusion **71**
6-1 Conclusion 71
6-2 Future work 72
6-2-1 Long-wavelength VCSEL 72
6-2-2 Oxidation developed in GaN-based material 75
References 77

Vita 78

Publication List 79

List of figures

Chapter 1

Figure 1-1 Schematic structure of (a) edge emitting laser, (b) vertical-cavity surface-emitting laser. 3

Figure 1-2 Various choices of the active region materials for VCSEL 5

Figure 1-3 Schematic diagram of a gain-guiding VCSEL with circular electrode to confine injection carrier concentration into the active layer. 6

Figure 1-4 Schematic diagram of a gain-guided VCSEL ion implantation regions to confined injection carrier concentration into the active region. 8

Figure 1-5 Schematic diagram of aorposted VCSEL (index-guided structure); active layer (a) below and (b) within the airposted column. 9

Figure 1-6 Schematic diagram of aorposted VCSEL (index-guided structure) with intracavity design. 10

Figure 1-7 Schematic diagram of a buried heterostructure VCSEL (index-guided structure) with injection carrier concentration strongly confined uniformly inside the active region. 11

Figure 1-8 (a) Schematic diagram of an antiguided VCSEL; (b) the corresponding profile of effective refractive index n_{eff} and change of effective refractive index Δn_{eff} along the transverse direction of the laser cavity. 12

Fugure 1-9 Schematic diagram of an index-guided VCSEL with single oxide aperture. 14

Figure 1-10 Schematic diagram of a tapered waveguide buried heterostructure VCSEL (index-guided structure). 15

Figure 1-11 Schematic diagram of a hybrid-guided VCSEL using ion-implantation for gain-guiding and selective oxidation for index-guiding. 16

Figure 1-12 (a) The schematic structure of implant-apertured index-guided VCSEL (hybrid confinement), current confinement and photon confinement can be controlled independently. (b) The schematic of coupling relationship between transverse mode and gain spectrum. 17

Chapter 2

Figure 2-1 The schematic of the overcoated VCSEL device using Ti/ITO 28

Figure 2-2 The process procedures of proton-implanted VCSEL with transparent contact. 29

Figure 2-3 The *L–I–V* characteristics of a typical VCSEL with and without Ti/ITO transparent overcoating. 30

Figure 2-4 Eye diagrams of the typical VCSEL device (a) without and (b) with Ti/ITO transparent overcoating operating at 2.125 Gb/s with 10 mA bias and 9 dB extinction ratio. The horizontal scale is 40 ps/div. 32

Figure 2-5 The near-filed emission patterns of the typical VCSEL device (a) without and (b) with Ti/ITO transparent overcoating at different injecting currents. 33

Chapter 3

Figure 3-1 Schematic structure of a Si^+-implant VCSEL. The Si implanted aperture is 13×13 μm^2 and proton implanted aperture is 30×30 μm^2. 38

Figure 3-2 The schematic diagrams of fabricating processes. 39

Figure 3-3 (a) Power versus current curves at 20 ^oC to 90 ^oC. The Si^+-implanted VCSELs exhibit kink-free current-light output performance with threshold currents ~2.4 mA, and the slope efficiencies ~ 0.45 W/A. 40

Figure 3-3 (b) Voltage versus current curves at 20 ^oC to 90 ^oC. The series resistance of more than 90% Si^+-implanted VCSELs is within 40-45 Ohm indicating good re-growth interface. 41

Figure 3-4 Distributions plot for threshold current and slope efficiency of Si^+-implanted VCSEL. 42

Figure 3-5 The optical output power spectrum of a Si^+-implanted VCSEL driving at 3.5 mA (1.45 × I_{th}). Inset is the spectrally resolved intensity pattern. 43

Figure 3-6 Typical eye diagram of our VCSEL on TO-46 operating at 2.125 Gb/s (Fiber-Channel mask w. 20%-margin) with 7 mA bias and 9 dB extinction ratio at (a) 25 °C (b) 85 °C 44

Figure 3-7 The WHTOL (85 ^oC/85 humidity) performance of Si^+-implanted VCSEL chips. 45

Chapter 4

Figure 4-1 Schematic structure of single-mode VCSEL. The O^+-implanted aperture is 8 μm in diameter and the oxidation aperture is 10 μm in diameter. 58

Figure 4-2 Figure 4-2 Device process flowchart. (a) The O^+-implanted aperture was defined by photolithography with diameter of 8 μm. (b) The surface relief pattern with a diameter of 20 μm was etched by chemically assisted RIE (Reactive Ion Etching) 59

Figure 4-3 (a) L-I-V curves, spectral characteristics and the near-field pattern of the O^+-implanted VCSEL. The emission spectrum is obtained at 10 mA and the near-field pattern is obtained at 5 mA. They demonstrate that the O^+ implanted VCSEL has a fundamental mode only over the full operating range. (b) L-I-V curves of the comparable conventional VCSEL. 60

Figure 4-4 Characteristic eye diagram of (a) large-aperture single-mode VCSEL with diameter of 8μm; (b) conventional multi-mode VCSELs with diameter of 8μm, transmitted at 10Gb/s with a bias of 5mA and an extinct ratio of 6dB. 61

Chapter 5

Figure 5-1 Schematic of the 850 nm PC-VCSEL. Note that the first generation PC-VCSEL structure has no oxide current aperture. The oxide aperture is added to the second generation devices for current confinement. 60

Figure 5-2 The Schematic of lateral effective index variation provided by the photonic crystal 61

Figure 5-3 V_{eff} parameters for γ=0.06, which correspond to etching depths of 17 pairs, are calculated. 63

Figure 5-4 Schematic of PC-VCSEL. The hole depth of PC is 17 pairs out of 22 pairs of top DBR been etched off. The proton implantation position is 3 pairs of DBR layers above active region 64

Figure 5-5 CW L-I-V characteristics and near-field image (inset) of a PC-VCSEL. The ratio (α/Λ) is 0.5 and the lattice constant Λ is 5 μm. 65

Figure 5-6 Spectra of the proton-implanted (a) photonic crystal VCSEL with ratio (α/Λ) is 0.5 and the lattice constant Λ is 5 μm and (b) VCSEL without photonic crystal holes. 66

Figure 5-7 Sspectra of the proton-implanted VCSEL with photonic crystal ratio (α/Λ) is 0.5, seven-point defects and the lattice constant Λ 67

is 5 μm. The mesa of this device is 68 μm.

Figure 5-8 Divergent angles of the proton-implanted VCSEL (a) without and (b) with photonic crystal 68

Chapter 6

Figure 6-1 Schematic of photoelectrochemical oxidation setup. 74

Figure 6-2 L-I characteristics of conventional and PEC oxided GaN-based LEDs. 76