Chapter 5
Conclusion

5.1 Summary

In the conclusion, the white-light and blue-green EL from an $Ag/SiO_2:Si^+/n\text{-}Si/Ag$ MOS diode with the defect-enhanced blue-green PL, made on a thermally annealed, multi-recipe Si-ion-implanted $SiO_2:Si^+$ film on a Si substrate with a nearly depth-independent Si-dose distribution profile, are studied. After annealing for 180 min, the main irradiative defects corresponding to PL at 415, 455 and 520 nm are completely activated. These defects are identified as WOB, the NOV-related defects and E'_δ-related defects, respectively. The annealing time is optimized to 3 h to activate completely the NOV defects and enhance the PL intensity. The ion-implantation introduces more dangling bond defects than other methods (such as PECVD and sputtering) for synthesizing the Si-rich SiO_2. During the Si implantation (or physical bombardment with high-energy ions), the oxygen vacancies and the oxygen interstitials (the precursors for the WOB defects) are created due to the relatively large quantities of oxygen that are displaced from their atomic positions in the SiO_2 matrix. In comparison with NOV defects, additional energy is required to form WOB defects from the oxygen interstitials. The NOV defects are therefore activated faster than the WOB defects for a given annealing condition, however, the increase in the number of both NOV and WOB radiative defects are of the same order of magnitude. This result again confirms the reaction rule for oxygen vacancies and interstitials in $SiO_2:Si^+$. A longer annealing eliminates a significant number of NOV defects, but the slow increase in the density of the E'_δ defects persists. The NOV defect concentration is found to rise from 2.5×10^{16} to 4.8×10^{17} cm^{-3} during 3-hr annealing; the data obtained from the C–V analysis agree quite well with those obtained by TRPL analysis, which also reveals a reduction in the luminescent lifetime from 26 to 3.6 ns. This result is consistent with the CWPL results, which reveal that 3-hr annealing increases the intensity by one order of magnitude. In contrast, the decreasing in the lifetime of the E'_δ-defect-dependent TRPL is moderate (from 47.5 to 23 ns). The reduction in the density of the WOB defects is more pronounced than that of NOV defects since two oxygen interstitials are required to generate a WOB defect. The complete activation of the E'_δ defects does not happen in experimental results, which reveals the nc-Si structures have not yet been well constructed. The EL power of the Ag/SiO_2:Si^+/n-Si/Ag MOS diode increases linearly with bias current after turn-on, and saturates near 0.97 A. The EL of the Ag/SiO_2:Si^+/n-Si/Ag MOS diode turns from blue to white-light emission when the bias current is close to the saturation condition, and eventually changes to a yellow-green emission as the bias current is increased to 3 A. The EL spectrum of the MOS diode under different reverse bias conditions indicates that the irradiative recombination is due to enhanced impact ionization of ground states of defects, such as WOB, NOV, and E'_δ defects, through the injection of holes accumulated in the inversion layer formed beneath the SiO_2:Si^+/n-Si interface.

In order to achieve the high excess Si atom density and reduce the defect density, the enhanced electroluminescence and external quantum efficiency of metal-SiO_x-Si MOSLEDs that are fabricated on nc-Si embedded SiO_x PECVD-grown at high substrate temperature and threshold plasma power are demonstrated. The formation of nc-Si, and the associated structural transition were investigated using EELS. The ratio of SiH_4 and N_2O fluences, the process pressure and the substrate temperature used in the fabrication are 1:6, 60 mtorr and 400^{o}C, respectively. Since the dissociation energies of the molecular SiH_4 and molecular N_2O are 75.6 kcal/mol and 101.5 kcal/mol, respectively, molecular N_2O dissociates less easily than molecular

SiH_4 resulting in the deposition excess Si atoms and increasing the density of nc-Si. The threshold voltages of the ITO/SiO_x:nc-Si/p-Si/Al that was prepared at 300, 350 and 400^{o}C are 49, 46 and 44 V, respectively. The maximum output power of 47 nW, associated with a P-I slope of 0.84 mW/A is determined. The internal quantum efficiency increases from 5.48×10^{-5} to 5×10^{-4} with a slope of 3.66×10^{-6} /^{o}C. The external quantum efficiency increases from 2.27×10^{-6} to 1.6×10^{-5}.

The structural and optical aspects of the localized synthesized Si nanocrystals in $SiO_{1.25}$ film using a CO_2 laser rapid thermal annealing process at nearly ablation threshold P_{laser} = 5.8 kW/cm^2 is characterized. Due to the relatively high absorption coefficient of SiO_2 material at 10.6 μm, the required P_{laser} is much lower than those at other wavelengths. The thickness of $SiO_{1.25}$ film was thinned from 280 to 240 nm during the dehydrogenating process at P_{laser} = 4 kW/cm^2 for 1.4 ms. The color of $SiO_{1.25}$ film changes from light yellow to dark yellow is due to both the increasing absorption coefficient and refractive index of $SiO_{1.25}$ film. HRTEM analysis reveals the average diameter and density of 5.3 nm and 1.56×10^{17} cm^{-3}, respectively, for the precipitated Si nanocrystals in the annealed SiO_x film. The Si nanocrystal dependent PL were observed at 806 nm or longer, whereas the CO_2 laser ablation at P_{laser} > 6 kW/cm^2 damages the $SiO_{1.25}$ film and induces significant blue PL at 410 nm by oxygen-related structural defects. Such a phenomenon was never observed in furnace annealed SiO_x film since the high-temperature and long-term furnace annealing usually causes a gradual recovery on the compressing strain of SiO_2 matrix nearby Si nanocrystals. The refractive index of $SiO_{1.25}$ changes from 1.57 to 1.87 with increasing P_{laser} as calculated from the reflection spectra with an enlarged interference fringe amplitude. In comparison with that of the quartz substrate or an as-grown sample, the red-shifted optical bandgap energy of a CO_2 laser annealed $SiO_{1.25}$ film from 5.21 to 2.43 eV has evidenced the effect of oxygen vacancy defects on the strong blue-green absorption. The enhanced near-infrared EL of an ITO/CO_2 laser RTA SiO_x/p-Si/Al MOSLED is preliminarily demonstrated. Dense nc-Si can be synthesized in the $SiO_{1.25}$ film by using CO_2 laser RTA at P_{laser} of 6 kW/cm^2 for 1 ms. The comparison on PL spectra of CO_2 laser annealed and furnace-annealed PECVD-grown $SiO_{1.25}$ samples reveals the contribution of oxygen related defects. Since the CO_2 laser annealing time is only 1 ms and much shorter than furnace-annealing time (3 hours), the annealing time is insufficient for precipitating larger-size nc-Si, whereas the oxygen-related defects are generated in the CO_2 laser annealed SiO_x film. These defects enhance the carrier transport through the MOSLED, reducing the tunneling threshold from 3.2 to 1.8 MV/cm as compared to the furnace-annealed sample. The elucidation on the role of the oxygen-related defects played on the improved carrier transport and enhanced light emission properties is addressed. A maximum EL power of nearly 50 nW from the ITO/CO_2 laser RTA SiO_x/p-Si/Al MOSLED under a biased voltage of 85 V and current density of 2.3 mA/cm^2 is reported to date.

The premier observation on the enhanced F-N tunneling mechanism from the novel SiO_x/nano-Si-pyramid/Si structure is demonstrated. Dense Si nano-pyramids can be synthesized at the SiO_x/Si interface by reducing the ICP power during the PECVD growth of Si-rich SiO_x on Si with high substrate temperature. The correlation between the surface density of interfacial Si nano-pyramids and the threshold F-N tunneling field has been illustrated. With these interfacial Si nano-pyramids at a surface density of 1.6×10^{11} cm^2, the F-N threshold can be reduced from 7 to 1.4 MV/cm. The elucidation on the role of the Si nano-pyramids played on the improved carrier transport and enhanced light emission properties are addressed. The existence of Si nano-pyramids greatly reduces the biased voltage from 200 to 65 V, which is required to obtain sufficient EL power from the

MOSLEDs. Consequently, a more stable near-infrared electroluminescence is emitted from the ITO/SiO_x/p-Si/Al MOSLED with interfacial Si nano-pyramids, providing a narrowing linewidth and a lengthened lifetime to >3 hours at room temperature operation. To date, an output EL power of nearly 150 nW under a biased voltage of 75 V and current density of 32 mA/cm^2 is reported.

Anomalous μ-PL characteristics of dense Si nano-pillars fabricating by dry-etching a SiO_2 covered Si substrate with Ni nano-dot mask is investigated. The optimum ICP-RIE recipes for Si nano-pillars with the highest density and aspect-ratio are under a chamber pressure of 0.66 Pa and a RF/Bias power ratio of 0.5. After ICP-RIE for 5 minutes, the obtained density, diameter, and height of the Si nano-pillars are up to 2.8×10^{10} cm^{-2}, 30 nm, and 320 nm, respectively. Both the visible and NIR PLs from the high-aspect-ratio Si nano-pillars were observed. The blue-green PL at around 430 nm is mainly attributed to oxygen-related defects formed on the surface of the Si nano-pillars. The defect-related NIR PL at 703 and 740 nm from Si substrate remain unchanged before and after formatting Si nano-pillars, while a blue-shifted PL phenomenon with its wavelength decreasing from 874 nm to 826 nm is clearly observed as the Si nano-pillar size shrinks from 7.2 to 6 nm. Such a rod-size dependent PL preliminarily confirms the occurrence of QCE on Si nano-pillars at diameter <7 nm. The nc-Si based MOSLED on Si nano-pillar array is demonstrated. Rapid self-aggregation of Ni nanodots on Si substrate covered with a thin SiO_2 buffered layer is employed as the etching mask for obtaining Si nano-pillar array. Dense Ni nanodots with size and density of 30 nm and 2.8×10^{10} cm^{-2}, respectively, can be formatted after rapid thermal annealing at 850 °C for 22 s. EL spectrum of Si nanocrystals grown on high-aspect-ratio Si nano-pillars is greatly enhanced. The optical intensity, turn-on current and power-current slope of the MOSLED are 140 μW/cm^2, 5 μA and 2±0.8 mW/A, respectively. The external quantum efficiency of up to 0.1% can be obtained under a power conversion ratio of 5×10^{-5}. One order-of-magnitude improved maximum EL power of 0.7 μW is obtained at biased current of 375 μA. Growth of Si-rich SiO_x layer on the Si nano-pillar array greatly enhances the roughness on top surface and bottom SiO_2/Si interface of the nc-Si MOSLED, which not only releases the total-internal reflection effect but also strengthens the Fowler-Nordheim tunneling effect. The reducing turn-on threshold and enhancing light-scattering performances of the nc-Si based MOSLED made on Si nano-pillar array essentially raises the possibility of its EL power toward

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國際期刊論文與研討會論文投稿及發表紀錄：

(A) 期刊論文

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