Chapter 5

Conclusion

5.1 Summary

In the conclusion, the white-light and blue-green EL from an Ag/SiO₂:Si⁺/n-Si/Ag MOS diode with the defect-enhanced blue-green PL, made on a thermally annealed, multi-recipe Si-ion-implanted SiO₂: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 SiO₂. 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 SiO₂ 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 SiO₂: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 $2.5 \times 10^{16}$ to $4.8 \times 10^{17}$ 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’\(\delta\)-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’\(\delta\) 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’\(\delta\) 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\(_2\)O fluences, the process pressure and the substrate temperature used in the fabrication are 1:6, 60 mtorr and 400\(^\circ\)C, respectively. Since the dissociation energies of the molecular SiH\(_4\) and molecular N\(_2\)O are 75.6 kcal/mol and 101.5 kcal/mol, respectively, molecular N\(_2\)O dissociates less easily than molecular
SiH₄ resulting in the deposition excess Si atoms and increasing the density of nc-Si. The threshold voltages of the ITO/SiOₓ:nc-Si/p-Si/Al that was prepared at 300, 350 and 400°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 /°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 SiO₁.₂₅ film using a CO₂ laser rapid thermal annealing process at nearly ablation threshold 𝑃_{laser} = 5.8 kW/cm² is characterized. Due to the relatively high absorption coefficient of SiO₂ material at 10.6 μm, the required 𝑃_{laser} is much lower than those at other wavelengths. The thickness of SiO₁.₂₅ film was thinned from 280 to 240 nm during the dehydrogenating process at 𝑃_{laser} = 4 kW/cm² for 1.4 ms. The color of SiO₁.₂₅ film changes from light yellow to dark yellow is due to both the increasing absorption coefficient and refractive index of SiO₁.₂₅ film. HRTEM analysis reveals the average diameter and density of 5.3 nm and 1.56×10¹⁷ cm⁻³, respectively, for the precipitated Si nanocrystals in the annealed SiOₓ film. The Si nanocrystal dependent PL were observed at 806 nm or longer, whereas the CO₂ laser ablation at 𝑃_{laser} > 6 kW/cm² damages the SiO₁.₂₅ film and induces significant blue PL at 410 nm by oxygen-related structural defects. Such a phenomenon was never observed in furnace annealed SiOₓ film since the high-temperature and long-term furnace annealing usually causes a gradual recovery on the compressing strain of SiO₂ matrix nearby Si nanocrystals. The refractive index of SiO₁.₂₅ 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 CO₂ laser annealed SiO₁.₂₅ 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/CO₂ laser RTA SiOₓ/p-Si/Al MOSLED is preliminarily demonstrated. Dense nc-Si can be synthesized in the SiO₁.₂₅ film by using CO₂ laser RTA at \( P_{\text{laser}} \) of 6 kW/cm² for 1 ms. The comparison on PL spectra of CO₂ laser annealed and furnace-annealed PECVD-grown SiO₁.₂₅ samples reveals the contribution of oxygen related defects. Since the CO₂ 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 CO₂ laser annealed SiOₓ 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/CO₂ laser RTA SiOₓ/p-Si/Al MOSLED under a biased voltage of 85 V and current density of 2.3 mA/cm² is reported to date.

The premier observation on the enhanced F-N tunneling mechanism from the novel SiOₓ/nano-Si-pyramid/Si structure is demonstrated. Dense Si nano-pyramids can be synthesized at the SiOₓ/Si interface by reducing the ICP power during the PECVD growth of Si-rich SiOₓ 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 \( 1.6 \times 10^{11} \) cm², 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 $\mu$-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 $2.8 \times 10^{10}$ 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 $2.8 \times 10^{10}$ 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 $\mu$W/cm$^2$, 5 $\mu$A 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 $5 \times 10^{-5}$. One order-of-magnitude improved maximum EL power of 0.7 $\mu$W is obtained at biased current of 375 $\mu$A. 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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台灣光電科技研討會 2003 年優良論文獎共同作者
Title: Pumping intensity dependent red-shift micro-photoluminescence of silicon-ion-implanted quartz induced by anomalous carrier transfer between self-coupled Si nanocrystals

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<table>
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<tr>
<th>SCIEI NO.</th>
<th>Author/Title/Journal</th>
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</thead>
<tbody>
<tr>
<td>2007</td>
<td>Gong-Ru Lin, Chun-Jung Lin, and Chung-Tao Lin, “Deposition temperature dependent electrical characteristics of low-plasma-power CVD-grown metal-oxide-semiconductor diode with buried Si nanocrystals”, Revised by <em>Nanotechnology</em>.</td>
</tr>
</tbody>
</table>


2005


2004


3. Chun-Jung Lin, Kuo-Cheng Yu, Hao-Chung Kuo, Miao-Jia Ou-yang, and Gong-Ru Lin, “Correlation between surface charge accumulation and excitation intensity dependent red-shifted


2003


2001


2006


2005


13 Chia-Yang Chen, Chun-Jung Lin, Hao-Chung Kuo, Gong-Ru Lin, Yu-Lun Chueh, Li-Jen Chou, Chih-Wei Chang and Eric Wei-Guang Diau, “Effects of N2O Fluence on the PECVD-grown Si-rich SiOx with Buried Si Nanocrystals”, *2005 MRS spring Meeting*, poster paper A19.11, San Francisco, CA USA, March 28-April 1, 2005


2004


2003


2002


2000


國內學術會議


2005

16. Chun-Jung Lin, Chi-Kuan Lin, and Gong-Ru Lin, “Synthesis of Si Nano-Pyramids at SiOx/Si Interface for
Enhancing Electroluminescence of Si-Rich SiOx Based MOS Diode”, Conference of Optics and Photonics Taiwan 2005, oral paper C-SA-IV2-3, Tainan, Taiwan, Dec. 9-10, 2005.


2004


<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Title</th>
<th>Conference</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>Chun-Jung Lin, Kuo-Cheng Yu, Hao-Chung Kuo, and Gong-Ru Lin</td>
<td>“The defect-related blue-green photo- and electro-luminescence of thermally annealed Si⁺ implanted SiO₂”</td>
<td>Conference of Optics and Photonics Taiwan'03</td>
<td>paper</td>
</tr>
<tr>
<td>2003</td>
<td>Gong-Ru Lin, Chun-Jung Lin, and Kuo-Chen Yu</td>
<td>“Determination of defect category and concentration in thermally annealed Si⁺ implanted SiO₂ using time-resolved photoluminescence and capacitance-voltage analysis”</td>
<td>Conference of Optics and Photonics Taiwan'03</td>
<td>paper</td>
</tr>
<tr>
<td>2003</td>
<td>Kuo-Cheng Yu, Chun-Jung Lin, M.-J. Ou-yang, Hao-Chung Kuo, and Gong-Ru Lin</td>
<td>“Pumping intensity dependent red-shift micro-photoluminescence of silicon-ion-implanted quartz induced by anomalous carrier transfer between self-coupled Si nanocrystals”</td>
<td>Conference of Optics and Photonics Taiwan'03</td>
<td>paper</td>
</tr>
<tr>
<td>2002</td>
<td>Gong-Ru Lin and Chun-Jung Lin</td>
<td>“The Defect Enhanced Photoconductive Response in Silicon-Implanted Borosilicate Glass”</td>
<td>Conference of Optics and Photonics Taiwan'02</td>
<td>paper</td>
</tr>
<tr>
<td>1999</td>
<td>Woo-Hu Tsai, Jin-Shin Lin, Hui-Tso Chou and Chun-Jung Lin</td>
<td>&quot;All-Fiber Polarization Mode Selector using Liquid Crystal,&quot;</td>
<td>Optics and Photonics Taiwan'99</td>
<td>pp.505-509</td>
</tr>
</tbody>
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