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# Visible Light Emission from Controlled α-Si/SiN Multi-layer Structures

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## 1. Introduction

One area of the key elemental efforts for constructing integrated Si-photonics systems is on achieving efficient light emission from Si-based materials. Much effort has been devoted to circumvent the silicon innate disadvantage as being an indirect bandgap material. Among those sought after, nanoscale silicon structures based on nanocrystal (nc)-Si dispersed in $SiO_2$ matrix have been widely studied. Various methods of synthesizing nc-Si were reported, including ion implantation, E-Beam evaporation, and annealing of silicon rich oxide (SRO) [1-4]. SiN-hosted nc-Si was also exploited and good result has been obtained [5].

***In this work, we report a new approach to fabricate Si-based light-emitter using controlled thin α-Si/SiN multi-thin layer stack and demonstrate stable electroluminescence. Such a structure can be easily prepared using standard CMOS compatible processes. The use of α-Si layers rather that nc-Si benefits from a much lower thermal budget required since the re-crystallization is not necessary, and also easier dimensional control as determined by deposition thickness. Due to bandgap offset between α-Si and SiN layers, carriers can be more confined in the thin α-Si layer where electron-hole pair recombination could take place radiactively.***

## 2. Experiment

Ten layers of alternating α-Si/SiN (for fixed thickness at ~10nm) were prepared by PECVD on 8”-n-type Si substrate. The silicon-nitride (SiN) layers were deposited by using $SiH_4$ and $NH_3$ as the reactant gases with $N_2$ dilution. The gas flow for $SiH_4$, $NH_3$ and $N_2$ were maintained at 110, 38 and 2500 sccm respectively during the deposition. The deposition temperature and pressure were maintained at 400°C and 4.2Torr respectively, with plasma power was 410W. α-Si layers were deposited using $SiH_4$ as the source gas with Ar dilution, with $SiH_4$/Ar flowed at 20/2500 sccm. The -Si thickness was targeted at 2, 3, and 5nm for three sets of samples. Deposition temperature/pressure were maintained at 400°C/~4.2Torr with RF power of 50W. Photoluminescence (PL) were obtained from fabricated samples annealed at temperature ranging from 600 to 1000°C, for durations of 10 to 90 minutes. Control sample with similar process flow but without α-Si layer deposition step were also fabricated concurrently as reference.

To fabricate the light-emitting diode (LED), substrate was pre-implanted with $As^-$ ion with 4e15 dose at 30keV, and activated at 1050°C for 5 sec as bottom N+-contact. For top electrodes, ~100nm poly-Si was deposited by LPCVD, and subsequently implanted with $BF_2^+$. with 4e15 dose at 20keV, The detail structure of the device is depicted in **inset of Fig.1**. For electroluminescence testing, all samples were annealed at 700°C for 10 min whereby the optimum PL result was obtained

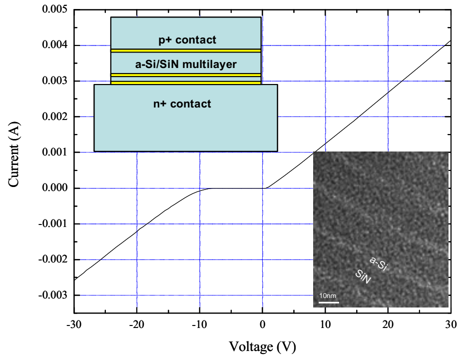


Fig.1 I-V characteristics of α-Si /SiN LED, area=0.025cm$^2$ . insertion top left: structure of LED, bottom right: TEM picture of a-Si/SiN multilayer stack

## 3. Results and Discussions

**Figure 1** shows a typical I-V curve of α-Si /SiN LED device under both forward and reverse bias conditions. **Figure 2** shows a TEM picture of 2nm-α-Si /10nm-SiN device, which has the thinnest α-Si layer among all samples. Phase separation of α-Si and 10nm SiN can be clearly observed, and the thickness of α-Si is ~2nm with good uniformity. The purpose of the multi-layer stack is to impose quantum confinement in the vertical axis along which the tunneling current flows. Extensive TEM and micro-Raman study were conducted and none showed any trace of nc-Si. Therefore we believe that the Si-thin films are amorphous in nature.

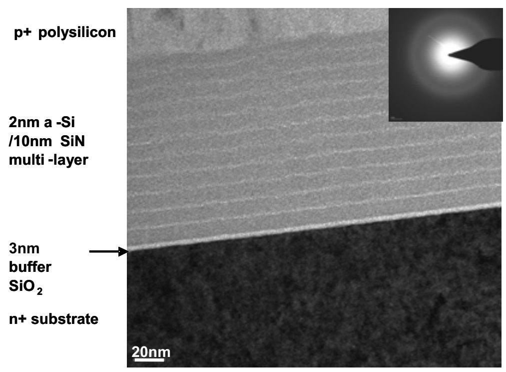


Fig.2 TEM image of sample 2nm-a-Si /10nm-SiN multilayer LED device. The insertion is the electron diffraction pattern of a-Si layer

**Figure 3** shows the evolution of the Raman-spectra for as-deposited samples to samples being annealed at 700°C for duration of up to 1.5 hrs. A reference signal of Si-substrate is included for comparison. For the remaining spectra, the strong peak observed at around 520 cm$^{-1}$ is due to the signal from the silicon substrate. All spectra are characterized by two broad bands around 150 $cm^{-1}$ and 480 $cm^{-1}$ corresponding to the transverse acoustic and transverse optic modes respectively. No observable shift to longer wavenumber can be detected as the sign of nanocrystal-formation [6]. **The inset in Fig. 3** shows the normallized, expanded view at the 520.5 $cm^{-1}$ crystalline Si peak. It can be seen that the half width half maximum are virtually identical for all curves. From these data, we conclude that the α-Si layers retained their amorphous state even after being subjected to long annealing process.

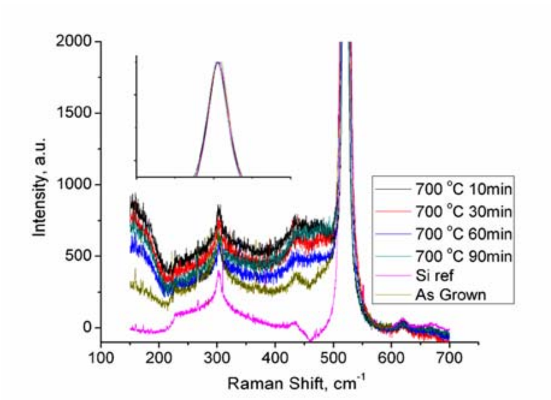


Fig.3 Raman spectra of samples from as grown a-Si(2nm)/SiN and for samples annealed at 700 °C for various time. A raman spectrum of crystalline Si wafer is included for reference. Insert shows the normalized, expanded view at 520.5 cm-1 crystalline silicon peak of the samples. The x-axis, denoting the Raman shifts, ranges 510 cm-1 to 530 cm-1. The y-axis which is the normalized intensity in arbitrary units is plotted from 0.3 to 1.

Both PL and EL can be observable with naked eyes in all samples with α-Si/SiN multi-stacks but not in the control sample with SiN-only films. It is worthwhile to mention that we also observed strong EL in the both the samples without post annealing and the samples with different annealing condition, however the samples after annealed shows better reliability and electrical characteristics, most probably due to the recovery of some defect-sites from previous process. **Fig. 4** shows the PL and EL spectrum of sample with 2nm α-Si layer. The salient peak of EL spectrum at 600nm (2.07eV) coincides with that of PL spectrum, meanwhile the peak at 500nm (2.48eV) approximately coincides with the shoulders around 480nm-500nm of PL spectrum. The double peak feature in the EL spectrum is most probably an optical artifact due to the multiple reflections between the active layer and top electrode. As such, we believe that the EL and PL originated from the same recombination sites. As the current injection increases, EL spectra do not change in shape while the integrated EL power increases almost linearly, as summarized in **Fig. 5**. This result, together with the lack of luminescence in the control sample, suggests that the luminescence most likely originates from within the thin α-Si layers. Therefore we suggest that the EL is from electron-hole pair recombination due to quantum confinement along the vertical axis.

## 4. Conclusions

We have successfully demonstrated, to the best of our knowledge, the first electroluminescence result from α-Si/SiN multi-layer stacks. The comparative analysis of PL and EL spectra suggests that the origin of electronluminescence is from electron-hole pair recombination in the thin α-Si layers. Therefore, this approach provides an alternating route towards achieving CMOS-compatible, low thermal budget silicon based light source.

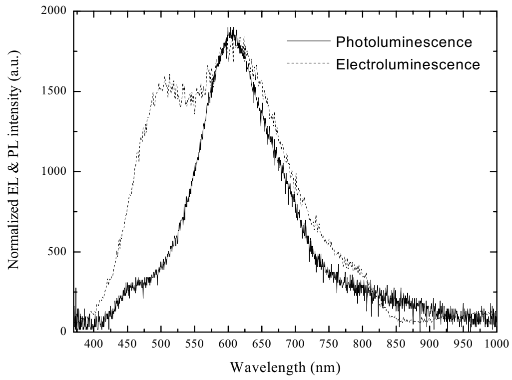


Fig.4 Normalized room-temperature PL vs EL for 2nm-a-Si /10nm-SiN. PL was measured using HeCD laser with excitation wavelength at 325 and power of 1.5mW

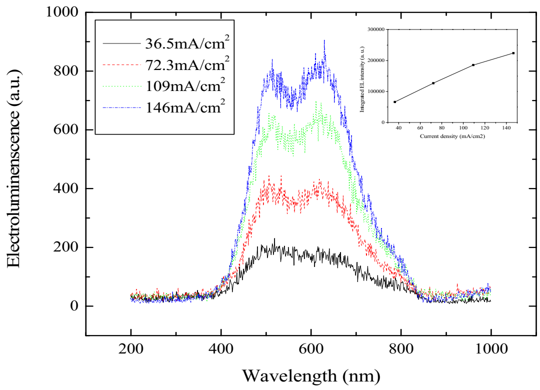


Fig.5 electroluminescence spectra of sample of a-Si (5nm)/SiN (10nm) multi-layer at reverse biased. Insertion: integrated emission power versus current density applied

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