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Comparison of simulated and measured light emission spectra from solid state incandescent light emitting devices

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ABSTRACT

In this paper, the light emission phenomena over solid-state incandescent light emitting devices have been modelled based on Planck's law of blackbody radiation. The emission spectra from the thermal excitation of nano-resistors with and without inclusion of an Indium Tin Oxide (ITO) or amorphous silicon (a-Si) thin film filter is simulated and compared with those measured from actual devices. The simulated emission spectra are further utilized to study the light characteristics for SSI-LED with ITO, a-Si and polycrystalline silicon (poly-Si) thin film filters.

INTRODUCTION

Conventional LEDs emit light by electron-hole or exciton-exciton recombination [1]. As a result, emission of narrow band light corresponding to the band gap energy of the semiconductor material is observed. Regardless of their high efficiency, such LEDs are made up of hetero-epitaxy layers grown on single crystal substrate that uses low deposition rate molecular beam epitaxy or highly toxic MOCVD process, which requires the minimization of lattice mismatch [2]. Moreover, the lifetime of this kind of device is highly dependent upon defects in the bulk films and at interfaces [3]. Contrary to

this, the warm white light emission phenomena from a single solid-state incandescent light emitting device (SSI-LED) was reported by Kuo's group [2,4-8]. This device is composed of a very large number of nano-resistors formed from the breakdown of a MOS capacitor with a few nm-thick high- k gate dielectric thin film on a p-type Si wafer, under the stress of a large negative gate voltage ($-V_g$) [4,5]. Light in the visible and infrared range is emitted during the passage of the current through the nano-resistors as a consequence of electromagnetic radiation generated by thermal excitation of the nano-resistors [7,8]. The light emission phenomena have been reported to last for more than 20,000 hours under the continuous operation condition in air without a passivation layer [9]. The emitted light can be narrowed down using thin film filters like hydrogenated amorphous silicon (a-Si:H), making such devices a potential useful light source for on-chip optical interconnect systems [10]. A-Si:H is a widely known material used in ICs, thin film transistors, solar cells, etc. [11-19]. It is known to absorb light with wavelength below 600 nm [20]. Optical interconnection is probably the ultimate solution to the signal delay in ultra-high-density ICs [3]. It has been reported that light source with narrow bandwidth is desirable for the on-chip optical interconnect in order to achieve a high contrast ratio between on and off states [21,22]. Zhang and Kuo showed that when the SSI-LED was coated with an a-Si film, the spectrum of the emitted light was shifted from the range of 450 nm-950 nm to the range of 530 nm-950 nm and the peak was moved from 700 nm to 810 nm [10]. Moreover, the emission spectrum can be transformed into a major narrow peak at 850 nm with a bandwidth of ~ 8 nm and a minor peak of 650 nm using a 9-layer (HL)²HH(LH)² Fabry-Perot filter where H and L are 52.0 nm thick a-Si:H film and 105.9 nm thick SiN_x film, respectively [10]. Additionally, Shukla and Kuo recently reported that the equivalent blackbody temperature of nano-resistors, formed in the high- k dielectric thin film, responsible for the light emission is around 4,000K [23].

In this paper, the authors model the light emission from the SSI-LED. The emission spectra from the thermal excitation of the nano-resistor at different temperatures with and without inclusion of an ITO or a-Si thin film filter are computed and compared with those measured from actual devices.

METHODOLOGY, RESULTS AND DISCUSSION

Spectral radiance $B(\lambda, T)$, which is the power emitted per unit area of the body, per unit solid angle of emission in the wavelength interval λ to $\lambda + \Delta\lambda$ ($\Delta\lambda$ denotes an increment of wavelength) at absolute temperature T , from the black-body radiation theory according to the Planck's law [24,25], is utilized to calculate theoretical emission spectrum using equation (1):

$$B(\lambda, T) = \frac{2hc^2}{\exp\left(\frac{hc}{kT\lambda}\right) - 1} \quad (1)$$

where h is Planck's constant, c is the speed of light and k is the Boltzmann constant. The calculated spectra are all normalized for comparison purposes. Note that in this study it is assumed that under the same gate voltage driven condition, the temperature of the nano-resistor does not vary with size. Figure 1 is the comparison of spectra calculated from equation 1 at 3,000K and 4,000K, separately, and the experimentally measured optical emission spectrum from a 300 μm diameter SSI-LED.

Figure 1. Black body emission spectrum at 3000 K and 4000 K respectively compared with SSI-LED emission spectrum when driven at -20V.

This figure shows that the peak of the spectrum recorded from an SSI-LED device closely matches with the radiation spectrum emitted from nano-resistors heated to 4,000K. This is consistent with the earlier studies suggesting that the color-correlated temperature (CCT) of the SSI-LED lies typically between 2500K and 4500 K, which is a function of gate voltage, dielectric material, and processing parameters [26]. Additionally, electrothermal calculations under certain assumptions have been performed earlier to estimate temperatures in and around the conductive paths formed in the gate dielectric [23]. Hence, radiation spectrum of a blackbody at 4,000 K is exploited for the further study on the effect of the thin film filter on the emission spectra calculated theoretically from the Planck equation and light absorption data, are measured experimentally.

ITO thin film filter

Note that the SSI-LED spectrum in Figure 1 was recorded from the device with an ITO gate. Figure 2 shows the comparison of spectra of the black body emission at 4,000K filtered with an annealed ITO film and that measured from a SSI-LED made from ref. 5 process. The optical transmittance data of a 500 nm thick annealed ITO film was taken from ref. [27]. Although the ITO layer thickness in the SSI-LED was only 80 nm, the result on the ITO filtration effect does not change based on the assumption that the thickness only changes the light intensity not the spectral distribution.

Figure 2. Comparison between blackbody radiation spectrum filtered by an ITO thin film and an SSI-LED (with ITO gate) emission spectrum.

The filtered blackbody radiation spectrum shows a major peak near 750 nm in addition to a satellite peak near 550 nm. The major peak is observed to be close to the peak wavelength of SSI-LED emission spectrum. The slight deviation of major peak towards left of experimental spectrum might be due to the fact that ITO melts when the device is in operation as suggested by Zhang et al. [28] and corroborated by Shukla et. al. [23]. The determination of optical transmittance of molten ITO over the visible and IR wavelengths might help in achieving more precise comparisons.

A-Si:H THIN FILM FILTER

Similar calculations were made for a-Si:H thin film filters. The optical transmittance data was calculated using spectral dependence of optical absorption coefficient for a CVD a-Si thin film as reported by Hirose et. al. [29]. The data reported in ref. 29 corresponds to thin films with thickness in range of 0.5 - 1 μm . However, in our calculations, the transmittance of the a-Si film was estimated from that of a 100 nm thick film adjusted with the Beer-Lambert's law. Figure 3 shows the comparison between experimental spectrum recorded from an SSI-LED with a-Si thin film filter (red curve) of thickness 100 nm deposited using PECVD process as discussed in ref. 10, and theoretically calculated spectrum (blue curve) obtained from blackbody radiation at 4,000 K filtered with a-Si:H thin film of thickness 100 nm.

Figure 3 Comparison between theoretically calculated and experimentally measured emission spectrum (blue) for an SSI-LED with a-Si (red) and poly-Si (green) thin film filter.

For the a-Si:H filter, the light below the 450 nm wavelength disappears. This observation of absorption in short wavelength range is consistent with the earlier literature reports [20, 29-30]. The peak of the theoretical spectrum with a-Si thin film filter was found to be off towards the long wavelength range compared to the experimentally recorded spectrum. This deviation may be attributed to the fact that the a-Si thin film melts from the intense heat conducted from underneath nano-resistors [23]. It is highly likely that the a-Si film over the nano-resistors recrystallizes and forms poly-Si at such high temperatures. Therefore, we extended our study to see the effect of the poly-Si thin film filter on the blackbody radiation spectrum of the nano-resistors. The optical transmittance data for poly-Si thin film was calculated in a similar way as that of a-Si thin film based on the absorption coefficient data reported in ref. 29. The absorption coefficient data used corresponds to that of a poly-Si thin film prepared by the annealing of as-grown a-Si film in nitrogen gas for 1 hour in the temperature range of 700-1050°C [29]. The green curve in Figure 3 shows the comparison of emission spectra of 100nm-thick poly-Si filtered SSI-LEDs, calculated from the blackbody radiation equation assuming nano-resistors are heated to 4000 K, to that measured from the actual device.

The wavelength corresponding to peak of the computed spectrum for the poly-Si thin film filtered device is found to be in closer proximity to that of the actual device than that of a-Si thin film filtered device shown in Fig. 3. Although, this suggests that a-Si may have recrystallized under the device's light emission condition, it might be possible that it stays in the molten state during device operation, similar to the ITO filter case as discussed previously. More studies will be carried out when the optical transmittance of the molten silicon phase over visible wavelength range is available. In the higher wavelength range, the theoretical and experimental emission spectra for both a-Si and poly-Si filters are not observed to be in good agreement. Note that Si filters studied here are formed over the SSI-LED with the ITO gate electrode. Previous reports on compositional analysis of the high-k stack with the ITO gate electrode in SSI-LED show significant amount of Si in the ITO layer [7]. Therefore, it is probable that, in SSI-LEDs with a top silicon filter, silicon atoms can diffuse from the bulk Si wafer through nano-

resistors into the ITO layer which results in variation in emitted light characteristics. Although, there have been very few studies on optical properties of Si doped ITO filters, it is reported that films prepared by co-sputtering ITO and SiO_2 at higher power ratios (ITO/ SiO_2) have high extinction coefficients at longer wavelengths in the visible range when compared to that of films deposited at low power ratios [31]. This suggests that presence of Si in ITO may decrease the transmittance of for longer wavelengths in visible range which is consistent with the experimental emission spectra in Fig. 3.

Figure 4 Comparison of theoretically calculated emission spectrum for SSI-LED with a-Si:H (red), poly-Si (green) and ITO (pink) thin film filters respectively.

Figure 4 shows the comparison of theoretically calculated emission spectrum for SSI-LED with a-Si:H, poly-Si and ITO thin film filters of thickness 100 nm respectively. The shorter wavelength range, below 500 nm, has appreciable transmittivity through poly-Si and ITO thin film filters as compared to a-Si:H thin film with almost negligible transmission. The peak wavelengths corresponding to poly-Si and ITO filtered spectrum are nearly same and lie close to 750 nm. However, the peak wavelength for a-Si filtered spectrum lies between 800-850 nm. In the long wavelength range, the transmittivities of a-Si:H and poly-Si are almost the same as well as quite significant as compared to that of decreasing transmittivity of ITO thin film filter.

Calculated emission spectra for SSI-LEDs with different thin film filters can be utilized to find light characters such as color correlated temperatures (CCT's) and CIE chromaticity coordinates. The CCT can be calculated using peak wavelength (Wein's Displacement Law) of the theoretical emission spectrum for each type of thin film filter in Fig. 4. Additionally, the CIE 1931 color space, created by the International Commission on Illumination in 1931 [31], can describe all visible colors to the human eye. The CIE (x, y) chromaticity diagram shown in Figure 5(a) is widely used and is obtained from the spectral power distribution of the light source and the CIE color-matching functions [32]. Table I shows the calculated peak wavelengths, corresponding CCT's and CIE (x,y) chromaticity coordinates for emission spectra from the same nano-resistor without a filter and with different filters. The color corresponding to each filtered spectrum is obtained

from locating the CCT value on the Planckian locus. Fig. 5(b) is the light dot perceived from a nano-resistor heated at 4,000K with no filter whereas Fig. 5 (c) and (d) show light dots corresponding to the same nano-resistor filtered with a-Si and poly-Si (or ITO) thin films, separately. As shown in Fig. 4, lights emitted from the poly-Si and ITO filtered dots almost overlap in the visible wavelength range.

Table I. Calculated peak wavelengths, corresponding CCTs and CIE (x,y) chromaticity coordinates of lights emitted from a nano-resistor without a filter and with a filter made of a-Si, poly-Si and ITO, respectively

	λ_{peak} (nm)	CCT (Kelvins)	CIE (x,y)
No filter	724.4	4000 K	(0.380,0.376)
a-Si	825	3512 K	(0.404,0.390)
poly-Si	750	3864 K	(0.386, 0.380)
ITO	750	3864 K	(0.386, 0.380)

Figure 5 (a) CIE 1931 chart, and light dots corresponding to nano-resistors with (b) no filter, (c) ITO or poly-Si filter, and (d) a-Si filter.

CONCLUSIONS

The light filtration effect of ITO and a-Si:H thin films on the broad-band light emitted from the ZrHfO high-k dielectric based SSI-LED has been theoretically investigated and compared with the experimental observations. This study suggests that the ITO thin film filter above nano-resistors formed in the dielectric film may melt due to intense Joule heating during the passage of a large current. Similar conclusions are made for the SSI-LED with a-Si thin film filter where the experimental spectrum more closely fits with computed spectrum corresponding to SSI-LED with poly-Si thin film filter. The deviation in experimental emission spectrum from simulated spectrum, for SSI-LEDs with a-Si and poly-Si thin film filters, for longer wavelengths in visible range is attributed to variation in optical properties of ITO caused by diffusion of silicon atoms at elevated temperatures. The a-Si film may recrystallize to form poly-Si during operating conditions. Further, simulated light emission spectra for SSI-LEDs with different thin film filters are characterized using corresponding CCT's and CIE (x,y) chromaticity diagram. Emitted light characteristics of device with poly-Si and ITO filters are found to be similar in nature. In summary, the broadband light emitted from the SSI-LED can be narrowed down with the addition of a thin film filters. The peak of the new spectrum is found to be dependent upon the optical properties of the material of the filter.

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