Review

Imitating Broadband Diurnal Light Variations Using Solid State Light Sources

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ABSTRACT

Many studies have documented the success of light therapy in treating disorders of the human internal clock (circadian rhythm). Recent biological research has shown the importance of developing light sources that are tunable in the blue region of the spectrum for treatment to be safe and effective. A novel tunable broadband solid-state light source is presented here that mimics the diurnal variation in sunlight by modulating the intensity of blue light emission.

KEYWORDS: Solid State Lighting (SSL), Light Emitting Diodes (LED), Circadian Rhythm, MOCVD

1. Introduction

Solid State Lighting (SSL), using light emitting diodes (LEDs) as the illumination source, is becoming a practical future for general illumination as LEDs continue to improve in efficiency and luminous output. LEDs can be smaller, more efficient, more robust, longer lived, and more easily controlled than conventional lamps. Yet, for solid state lighting to provide a competitive advantage over conventional lighting it must enable new innovations rather than being a more cost effective replacement. The controllability provided by solid state lighting sources lends itself to the development of new sources for general illumination.

Another application well-suited for solid state lighting is light therapy. Recent biological research has investigated the relationship between the human internal clock (the circadian rhythm) and light. Circadian rhythms modulate a wide range of physiological, hormonal, behavioral, and cognitive functions. Therefore, disorders arising from a disruption of the circadian rhythm can result in many negative effects on physical and mental health. In addition, in some applications such as space flight there is a need to control a person's physiological functioning in that environment. Studies have shown that certain circadian rhythms can be entrained with traditional broadband light sources such as fluorescent tubes, however more work is required to understand the effects of new light sources such as LEDs. Additionally, light in the blue region of the

spectrum has been shown to be most effective in enacting changes in the circadian rhythm and thus the ability to tune this light holds the key to realizing the full benefits of light therapy¹⁾.

In light of this, a circadian light source has been developed that modulates its total intensity and correlated color temperature (CCT) by adjusting the intensity of the blue portion of its spectrum to mimic natural daylight on Earth during the course of a normal day. This device utilizes an integrated solid state light source that can mimic the diurnal variation in daylight. This source has been designed using a dual wavelength LED to preferentially pump a combination of phosphors. The overall spectral power distribution (SPD) of the source can be tuned with the proper control system.

2. Broadband Diurnal Light Source

Both three terminal and two terminal dual-emitting LEDs were investigated for this source. The two terminal device ultimately proved most viable and is presented here. The broadband diurnal light source employs the two terminal dual wavelength LED to preferentially pump a combination of phosphors creating a broadband spectrally tunable light source. Color mixing uniformity is enhanced by the design of the device where all light is effectively generated from one point. A phosphor free white LED has been reported, but the device relied on inefficient yellow- and red-emitting InGaN quantum wells and was not shown to be tunable, which was the goal here²⁾.

Figure 1 Schematic of two terminal dual LED structure

Two Terminal Tunable Dual Wavelength LED

Two wavelength spectrally tunable LEDs have been reported using two and three terminal device designs^{3,4)}. The three terminal device design requires the implementation of a III-Nitride tunnel junction which is difficult to achieve and adds complexity to the device. However, the three terminal design allows for complete control of the two emission bands. On the other hand, the two terminal design simplifies the structure but limits control of the two emission bands. Previously reported two terminal devices lack enough dynamic range to be used as a tunable light source and are limited to static emission. A modified two terminal design using barrier doping that increases the dynamic spectral range of the device is presented here.

Various samples were grown in a highly modified commercial MOCVD reactor with trimethylaluminum (TMAI), trimethylgallium (TMGa), triethylgallium (TEGa) and trimethylindium (TMIn) as the group III precursors, gaseous ammonia (NH₃) as the group V precursor, and diluted silane (SiH₄) and bis-cyclopentylmagnesium (Cp₂Mg) as the n and p dopant precursors, respectively. Electroluminescent measurements were performed using an Optronic Labs OL-770 spectroradiometer. The spectral power distribution at different drive currents was measured to determine the dynamic range of each device structure.

Each sample consisted of a 2 μm thick layer of silicon doped GaN with electron concentration of $3 \times 10^{18} \text{ cm}^{-3}$ on a sapphire substrate using a GaN buffer layer. This was followed by 6 quantum wells where the three bottom wells were designed to emit 460 nm light and the top three were designed to emit 400 nm light. Si doping was introduced into the barrier between the third and fourth quantum wells as shown in Figure 1.

Si doping of the barrier between the third and fourth quantum well was introduced to diminish hole transport across the barrier. Si doping of the barrier shifts the valence band of the barrier to a lower

energy thereby increasing the potential barrier experienced by the holes and decreasing the number of holes crossing the barrier. Sample A (see Table 1) had an undoped barrier between the third ($\lambda=460\text{nm}$) and fourth ($\lambda=400\text{nm}$) quantum wells, while samples B and C had Si doping of $1.5 \times 10^{18} \text{ cm}^{-3}$ and $3.0 \times 10^{18} \text{ cm}^{-3}$, respectively. Lastly, a p-type layer of magnesium doped GaN with a hole concentration of $5 \times 10^{17} \text{ cm}^{-3}$ was grown. Figure 2 shows the I-V curve for the device. The turn on voltage (V_t) of these dual LEDs is 3.3V, which is comparable to standard single emission LEDs.

Figure 2 Typical I-V curve of dual LED

$V_t=3.3\text{V}$

The dynamic range was assessed with the metric β which is defined as $\beta=I_l/I_s$, where I_l and I_s are the intensities of the long (460nm) and short (400nm) wavelength band peaks in the spectral power distribution due to electroluminescence. Sample B showed the greatest range of β of these samples with $0.08 < \beta < 2.5$ with current density $114.3 \text{ A/cm}^2 < J < 277.6 \text{ A/cm}^2$ as shown in Figure 3.

The bottom spectrum in Figure 3 is dominated by the 400nm emission resulting from recombination primarily in the 400nm MQW region. At this drive current β is 0.08 with very little contribution from the 460 nm emission. On the other hand, the top curve of Figure 3 has a β of 2.47 with the 460 nm emission dominating the spectral power distribution. These curves show the range of spectral power distributions possible with sample B. The dynamic range for a series of samples is compiled in Table 1.

Table 1 Dynamic range of three samples

Sample	Doping (cm^{-3})	Min β	Max β	$\beta = 1$
A	None	0.89	1.47	4 A/cm ²
B	1.5×10^{18}	0.08	2.5	220 A/cm ²
C	3×10^{18}	0.08	1.1	305 A/cm ²

Figure 3 Electroluminescent spectra of sample B without phosphor over range of β

Increased doping of the middle barrier produces a shift in the curve toward higher current densities indicating that higher current densities are required to achieve recombination in the long wavelength quantum well region. This can be explained by examining the band diagram as doping of the barrier is increased, Figure 4.

Increased Si doping shifts the valence band of the barrier to lower energies resulting in a decrease in hole transport across the barrier. At higher drive currents more holes are likely to cross the barrier and contribute to radiative recombination in the long wavelength MQW region. If no doping is present in the middle barrier β starts out high and is lowered with drive current indicating an electron trapping effect in the deeper quantum wells of the long wavelength MQW region. Therefore, β of a device is the result of competing rate equations. Electron trapping in the long wavelength region and hole trapping in the short wavelength region.

Increasing the middle barrier doping changes the balance between these rate equations and thus the number of holes in the long wavelength region and the number of electrons in the short wavelength region. Therefore the dynamic range of a two terminal dual LED can be controlled by doping the barrier in between the third and fourth quantum wells in the device shown.

Dual LED Plus Phosphor Combination

The range of β for the pump device sets the constraints for the phosphor mixture. The phosphor mixture was chosen to achieve a maximum range of correlated color temperatures from the final

Figure 4 Simulated energy band for various levels of doping in the middle barrier of the two terminal dual LED

Figure 5 Electroluminescent spectra for dual LED with phosphor emission at different β

integrated device with the range of β set by the pump device. Figure 5 shows the difference in spectral power distribution (SPD) for different β of the pump device. There is a significant change in the phosphor emission which translates to a shift in CIE coordinates of the SPD. The other significant difference is the emission from the 460 nm MQW (MQW₄₆₀) which acts to shift the CIE coordinates of the device as well. The orange and green phosphors are equally excited by MQW₄₆₀ and the 400 nm MQW (MQW₄₀₀). SrCa:Eu (red) and YAG:Ce were each excited strongly by MQW₄₆₀ and not by MQW₄₀₀. On the other hand the UV to white phosphor was excited strongly by MQW₄₀₀ and not by MQW₄₆₀. Thus, by changing the relative intensity of the pumps, different phosphors can be selectively excited and the total SPD can be controlled. When $\beta=0.08$ the pump SPD is dominated by emission from MQW₄₀₀ exciting the UV to White, orange, and green phosphors creating a SPD with CCT of 3228K. As β of the pump increases, contribution from the red and YAG:Ce add to the SPD, while emission from the UV to White

phosphor decreases. In addition, blue emission from MQW₄₆₀ contributes to the SPD as well. A CCT from 3228K to 5339K is achieved as β increases to ~ 2.5 . The increase of blue and red components creates a trend in CIE coordinates towards the bottom left corner as illustrated in Figure 6.

The change in SPD from lower to higher CCT is caused by the increase in long wavelength (red) and the increase in emission from MQW₄₆₀ and simultaneous decrease in the UV to White emission which has a peak in the yellow region. This is illustrated by a trend toward the bottom left hand corner corresponding to contributions from the long and short wavelengths. The change in SPD from the standalone pump source is mapped on the CIE diagram as well to show that the change in overall SPD is not entirely dependent on the pump SPD, but depends on the change in phosphor emission as well.

Intensity can be maintained over variations of drive current using a pulse width modulation scheme. The device is pulsed at a frequency higher than the sampling rate of the human eye giving the appearance of a continuous wave operation. If the duration of the pulse is changed but the total cycle period is unchanged the device will appear to dim or brighten. Calibrating the pulse width to compensate for the intensity change with drive current results in a spectrally dynamic dual wavelength LED in which a constant intensity can be maintained.

The development of the diurnal light source shows that a broadband spectrally dynamic solid state illumination source is possible. Such a device combines the controllability of RGB LED systems with the broadband characteristics associated with phosphor converted LED systems. The novel use of phosphors with varied excitation spectra enabled selective pumping by a dual wavelength LED to create a dynamic phosphor emission spectrum. Further optimization of the phosphor mixtures and more sophisticated phosphor mixing techniques could lead to a greater range of CCT with a smaller range of β . Further development of dual LEDs as pump devices will also lead to a diurnal light source with a wider CCT range. Three terminal devices have also been investigated that incorporate tunnel junctions and offer the potential for greater control over each individual emission peak with further development.

3. Effect of Light on the Circadian System

Recent studies have identified melanopsin as a new photopigment in the retina. In mammals melanopsin is only present in a small population (about 2%) of the retinal ganglion cells, that are directly photosensitive and have an absorption peak

around 470-480 nm. The axons of these cells form a neural pathway (i.e., retinohypothalamic tract) that is responsible for transmitting light information from the retina to the master circadian clock located in the suprachiasmatic nucleus of the hypothalamus. Therefore, it is believed that light in this range is the most effective in providing the light cues that are necessary for the synchronization of the circadian system. Besides its role in the entrainment of the circadian system, melanopsin has been also implicated in the regulation of pupillary light reflex and sleep. Very recently, it has been reported that loss of the melanopsin gene abolishes circadian control in some parameters of cone electroretinogram, thus causing significant attenuation of the diurnal

Figure 6 Change in SPD of diurnal light source plotted onto the CIE diagram

variation in cone vision. This new data suggests a melanopsin-dependent regulation of visual processing within the retina⁵.

Mounting experimental data indicates that melanopsin plays an important role also in mediating human circadian rhythms. Brainard et al.³ reported that in humans the action spectra for melatonin suppression has lambda max around 460 nm, thus suggesting that melanopsin is a key player in the photic regulation of melatonin levels and of the circadian rhythms and sleep. Additional studies have also shown that blue light in the range 440-480 nm is very effective in phase-shifting the human circadian clock, can increase alertness and may be used to treat seasonal affective disorders. Interestingly, it has also reported that this new photoreceptive system may actually modulate the entire visual system⁶.

Studies have shown that certain circadian rhythms can be entrained with exposure to light. A circadian light source that is able to modulate its CCT and total intensity to mimic daylight can help address a variety of disorders associated with an

unsynchronized or unbalanced circadian rhythm. These include advanced- and delayed-sleep phase syndromes, jet lag, shift work sleep disturbance, and age-related insomnia. Light therapy that mimics daylight has also been shown to be effective in treating SAD (seasonal affective disorder).

The suppression of serum melatonin levels following a brief light exposure during the night is a well established reliable method to assess the effect of different light source on the circadian system. In this study, the effectiveness of light of different wavelengths was tested to suppress serum melatonin levels during the night.

Rats (N=6 for each of the three groups) were exposed to a pulse of light (30 minutes) of different color (white, blue, or green) but of similar intensity ($1 \times 10^{-1} \mu\text{W}/\text{cm}^2$) in the middle of the night, then blood samples (80-100 μM) were collected from the tail artery in heparinized tubes. Controls (n=6) did not receive any light exposure. Melatonin was extracted from the serum (50 μM) using chloroform and then melatonin levels were measured by radioimmunoassay using a commercially available kit (ALPCO Diagnostics, Salem, NH). The sensitivity of the assay was 0.2 pg/ml. Intra-Assay variability was 9% and the inter-Assay was 13%^(7,8).

Figure 7 Suppression of serum melatonin levels following 30 minutes of light exposure

Blue light was effective as white light in suppressing serum melatonin levels (t -test, $P < 0.001$). Green light did not significantly suppress serum melatonin levels (t -test, $P > 0.1$).

This data demonstrate that exposure to 30 minutes of blue light in the middle of the night was as effective as exposure to white light in suppressing serum melatonin levels (t -test, $P < 0.001$, Figure 7). Conversely, 30 minutes of exposure to green light did not have any significant effect on the levels of serum melatonin (t -test, $P > 0.1$, Figure 7).

Melatonin is an important hormone that is implicated in the regulation of circadian rhythms and

sleep. The data indicates that blue LEDs are very effective on the brain centers that regulate circadian rhythms and sleep, which is consistent with the results of numerous other studies and the recent discovery of the melanopsin as a photopigment. However, it must be noted that blue light (420-460nm) within the intensity range of natural light can induce retinal damage in humans⁽⁹⁻¹¹⁾. Therefore when designing devices for light therapy it is very important to consider the whole SPD of the light produced in order to maximize both safety and effectiveness.

4. Conclusion

In conclusion, a novel broadband SSL source was demonstrated with tunable CCT from 3228K to 5339K. A new concept two terminal tunable dual-wavelength LED with selected barrier doping showed wide dynamic range up to 2.5. The test result of the effect of different light sources on the circadian system showed that exposure to 30 minutes of blue light (474 nm) in the middle of the night was as effective as exposure to white light in suppressing serum melatonin levels. This result is consistent with recent studies that suggest that photoreceptors containing melanopsin (which is most sensitive to blue light) have the most direct influence on circadian rhythm. Control of the blue region of the spectrum will thus prove to be important in the future development of solid state light sources for light therapy applications.

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