Light-Emitting Diode Technology for Solid-State Lighting

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Light-emitting diode (LED) technology has advanced tremendously since the first demonstration of a practical visible-spectrum LED almost fifty years ago (Holonyak and Bevacqua, 1962). The subsequent initial LEDs used in simple displays (e.g., calculators, watches) and indicator lamps (e.g., clock radios, compact disc players) have been replaced by more powerful, and more sophisticated, devices that produce not only red and green emission, but also blue and, most importantly, white. The latter were enabled by the development of the indium-gallium-nitride (InGaN) material system which commenced after key breakthroughs in materials technology in Japan in the lates 1980s (Amano et al., 1986; Amano et al. 1989). In the early 1990s efficient blue LEDs based on this material system were demonstrated (Nakamura et al., 1993; Nakamura et al., 1995), and in combination with a well-known yellow-emitting phosphor for scintillators and cathode-ray-tubes, $Y_3Al_5O_{12}:Ce^{3+}$ ("YAG"), these devices were able to demonstrate solid-state white light for the first time (Nakamura and Fasol, 1997). In the late 1990s, Watt-class high-power LEDs (Höfler et al., 1998) delivering meaningful levels of light output (from an illumination perspective) were made commercially available for the first time. Since then, InGaN-based LEDs have become more efficient and even more powerful, and the availability of suitable phosphors has increased, such that the variety, light output, and quality of LED-based white light has reached the point that it is beginning to unseat conventional lighting technologies in general illumination applications. Indeed, their high energy efficiency, coupled with strong environmental attributes (no lead, no mercury, long operating lifetime), ensure that LEDs will have a dominant role in the future of lighting.

LED BASICS

In principle LEDs are very similar to the simple silicon-based p-n junction diode. Layers of semiconductor material are deposited by an epitaxial method (usually metal-organic chemical vapor deposition, MOCVD) (Manasevit and Simpson, 1969) on a suitable substrate wafer. The layers are treated (i.e., doped) with extrinsic impurities to form negatively charged (n-type) and positively charged (p-type) regions. The charges induce a built-in electric field at the interface between these regions (the p-n junction). When a sufficient positive external voltage is applied to Ohmic contacts to the p- to the n-type regions, the built-in field is reduced, thereby initiating current flow. This current flow is sustained by the recombination of negative charge-carriers (electrons) with positive charge-carriers (holes) in the vicinity of the p-n junction. Each recombination event produces energy approximately equal to the electronic energy bandgap of the semiconductor material at the p-n junction. Since silicon is an *indirect* bandgap semiconductor (Bardeen et al., 1956), electron and hole recombination requires interaction with the crystal lattice meaning recombination current generates mostly heat. In other semiconductor materials, especially many III-V compound semiconductor materials such as GaAs, InP, and GaN, the transition for an excited electron to the valence band does not require momentum (i.e., lattice interaction) so the released energy is given in the form of light. Even in these *direct* bandgap materials, which are used for LEDs, such a radiative transition must always compete with crystal lattice imperfections and impurities which produce non-radiative transition pathways. Nevertheless, in very pure material such as GaAs and InP the radiative efficiency (internal quantum efficiency) can approach 100%. Also, the external applied voltage is approximately the same as that of the emitted photon. We can thus see that the LED has the potential for nearly 100% light generation efficiency, and provides a basis for what has been called the "ultimate lamp" (Holonyak, 2000). Typically, a layer(s) of specific composition is inserted at the p-n junction to allow control over the energy bandgap, and thus photon energy (or wavelength), of emission. Today, the InGaN-GaN system is employed for wavelengths from ~ 365 (ultra-violet, UV-A) to 550 (yellow-green) nm. For amber to red emission, the most efficient LEDs are based on the (Al,Ga)InP system.

Efficient generation of light does not alone make for an efficient diode. The light must escape the semiconductor crystal into air to be useful. Accomplishing this is less straightforward than one might expect, since the optical refractive indices of most III-V semiconductors is quite high (GaN: n ~ 2.4, InGaP: n ~ 3.5). The high refractive index means that light generated inside the semiconductor must impinge near normal-incidence at the semiconductor/ambient interface in order to escape. Light incident at higher angles is totally-internally-reflected back into the semiconductor, increasing the chance of absorption (e.g., at metal electrodes, etc.). Various means are employed to increase the probably of light exraction, such as chip shaping, texturing, and the employment of photonic crystal structures. In today's highest-performing LEDs, light extraction efficiency is ~80 % for InGaN and ~60% for AlGaInP (Krames et al., 2007).

In order to be deployed in the field, LEDs must provide an interface to end-users similar to other electronic components. Critical are provisions for accessing and contacting (e.g., reflow solderability) the electrodes and, especially for high power LEDs, removal of heat. The latter is usually accommodated by including a heatsink element (usually Cu) into the primary LED package. Indeed, today's high power LED packages (Figure 1) resemble very little their "5mm lamp" ancestors using small chips that dissipate less than 100 mW and produce very little heat. For example, today's LEDs used for automotive forward lighting are capable of dissipating up to 10 W of power (Dupuis and Krames, 2008).

PERFORMANCE

Sustained improvements to material quality, diode layer structure, and overall chip architecture have improved the performance of LEDs dramatically over the last decade or so. Figure 2 shows best-reported external quantum efficiencies (ratio of photons out per electrons injected) for power LEDs for both InGaN and AlGaInP. The best InGaN devices are in the blue-emitting region and have external quantum efficiencies of ~66%, meaning that 2 out of every 3 electrons injected into the electrical contacts emit a useful photon. Figure 2 also shows the photopic luminosity function, V(λ), which is a measure of the human eye response as determined by the Commission Internationale de l'Éclairage (CIE). It is an unfortunate truth that, as shown in the figure, the most efficient LED wavelengths are those at either side of the visible spectrum (i.e., towards the ultra-violet or infra-red). For AlGaInP, the reason for the reduced performance at shorter wavelengths is the fact that AlInP is an indirect bandgap semiconductor, and increased substitution of Ga by Al for shorter wavelength emission fundamentally reduces the probability of radiative (vs. non-radiative) transitions. For InGaN, the reason for decreased efficiency at longer wavelengths is attributed to the miscibility gap between GaN and InN (El-Masry et al., 1998), the increasing strain with higher InN mole fractions, and the fact that this wurtzite (asymmetric) crystal generates polarization-induced built-in electric fields at hetero-interfaces (Bernardini et al., 1997) which perturb the conduction and valence band profiles of layer structures and complicate the efficient recombination of electrons and holes. By working on a non-basal plane of GaN, polarization fields can be reduced, and the 550 nm data point of Figure 2 is in fact from a “semi-polar” (11-22) orientation InGaN-GaN LED (Sato et al., 2008) as opposed to the conventional “polar” (0001) orientation. While considerable improvement is possible (and expected) within the “green gap” region, the present performance of LEDs is nevertheless already very competitive against, and in many cases far superior to, conventional lighting technologies.

WHITE LEDS

While the combination of separate blue, green, and red LEDs can be tuned to make white light, by far the most common approached applied in industry is to down-convert blue, violet, or UV light into longer wavelength light by employing phosphors which are excited by the LED primary emission. The phosphors are typically applied around or on top of the LED chip by various methods. The most common approach is the use of YAG phosphor powder (typically mixed in an organic binder) overlying a blue LED chip emitting in the range of 440-460 nm. The blue LED chip excites the YAG, which produces yellow light. The YAG phosphor powder loading is tuned to allow a precise amount of the primary blue light to “leak” through. Done properly, the combination of this leaked blue light and the yellow phosphor emission yields a white light chromaticity in the 4000-7000K correlated-color-temperature (CCT) regime and with a fairly high conversion efficiency. To generate “warmer” white chromaticities (2700-4000K), red phosphors are typically added to the mix (Mueller-Mach et al., 2002).

Figure 3 demonstrates the relative efficacies of white light generation at ~ 2900K by i) tungsten filament incandescence, ii) a tri-phosphor fluorescent lamp (FL), and iii) an LED employing blue-pumped phosphors. The incandescent tungsten (household filament bulb) radiates as a blackbody and at 2900K generates by far most of its radiation in the infra-red (i.e., heat). The overlap with the visible spectrum is very poor, and convolving the blackbody spectra irradiance with V(λ) gives a maximum luminous efficacy for this source of ~ 16 lm/W. In practice incandescent bulbs perform lower (~ 10-15 lm/W) than this theoretical limit. The tri-phosphor FL, on the other hand, employs line-emitting phosphors excited by the mercury (Hg) vapor discharge at 254 nm. The phosphors are specifically selected so that their emission peaks are in the eye-sensitive region, and indeed the maximum luminous efficacy for the FL spectrum in Figure 3 is quite high, 360 lm/W. However, the enormous Stokes' loss in photon energy from 254 nm to ~550-600 nm caps the maximum luminous efficacy (in lumens per electrical Watt) to ~ 150 lm/W. In practice, other loss mechanisms come in and typical performance for tube fluorescent lamps are in the 80-90 lm/W range. The LED in Figure 3 utilizes a blue emitter to pump a combined green and red phosphor mix to obtain the desired CCT of 2900K. The high intensity of blue light at the chip surface typically requires the use fast-decaying phosphors which provide broad emission. The result is an emission spectrum which has a close resemblance to the targeted blackbody curve in the visible-spectrum regime. (One might assume this provides a more *natural* appearing light, compared to the high-intensity peaks of the FL spectrum, but as of this writing the author is aware of no studies of the effects of smooth vs. spiked spectra on human perception.) The smoother spectrum brings a penalty in luminous efficacy, compared to the FL, and the maximum for the LED in this case is 310 lm/W. However, for a blue-pumped LED the Stokes loss is only ~ 20-25%, putting the maximum achievable efficacy at ~ 250 lumens per electrical Watt. Thus, the obtainable luminous efficacy for the LED is +60-70% higher than that for fluorescents, and more than 15 times that for incandescent lamps.

Figure 4 shows the performance evolution of "warm white" (2700-4100K) high-power LEDs along with an indication of projected performance provided in a recent report commissioned by the U.S. Department of Energy (Solid-state lighting research and development, 2009). Future LED performance is projected to be ~ 160 lm/W by 2018, which is still far away from the maximum attainable performance as described above. Nevertheless, even at the targeted performance level, LEDs would outperform all known technologies for generating white light, including high-intensity-discharge (HID) lamps.

CONCLUSIONS

As LED technology approaches its 50th year anniversary it appears well positioned to penetrate the general lighting market and change the world as we know it. LED-based light sources promise to provide reduced energy consumption, longer operating lifetime (and thus reduced waste), and no generation of materials known hazardous to the environment such as lead and mercury. In addition, the low-voltage drive and fast switching speed allowed by LEDs means lighting for the future could look very different than what we know today, and may include dynamic control features for automatic mood setting or tuning of light intensity and color to improve workforce productivity or simply to elevate people's moods. These additional features, combined with the energy savings and other "green" aspects, ensure that LED-based solid-state lighting has a very bright future.

REFERENCES

Amano, H., N. Sawaki, I. Akasaki, and Y. Toyoda. 1986. Metalorganic vapor phase epitaxial growth of a high quality GaN film using an AlN buffer layer. Applied Physic Letters 48: 353–355.

Amano, H., M. Kito, K. Hiramatsu, and I. Akasaki. 1989. P-type conduction in Mg-doped GaN treated with low-energy electron beam irradiation (LEEBI)," Japanese Journal of Applied Physics 28: L2112–L2114.

Bardeen, J., F. J. Blatt, and L. H. Hall. 1956. Indirect transitions from the valence to the conduction bands. Proceedings of the 1954 Photoconductivity Conference. R. G. Breckenridge, B. R. Russel, and E. E. Hahn, Eds. (Atlantic City, NJ): 146–154, Paper IIC.

Bernardini, F., V. Fiorentini, and D. Vanderbilt. 1997. Spontaneous polarization and piezoelectric constants of III-V nitrides. Physical Review B 56: R10024–R10027.

Carey, J. A., W. D. Collins, B. P. Loh, and G. D. Sasser. 2001. Surface mountable LED package. U.S. Patent No. 6,274,924.

Dupuis, R. D., and M. R. Krames. 2008. History, development, and applications of high-brightness visible light-emitting diodes. IEEE Journal of Lightwave Technology 26 (9): 1154-1171.

El-Masry, N. A., E. L. Piner, S. X. Liu, and S. M. Bedair. 1998. Phase separation in InGaN grown by metalorganic chemical vapor deposition. Applied Physics Letters 72: 40–42.

Höfler, G. E., C. Carter-Coman, M. R. Krames, N. F. Gardner, F. A. Kish, T. S. Tan, B. Loh, J. Posselt, D. Collins, and G. Sasser. 1998. Highflux, high-efficiency transparent-substrate AlGaInP/GaP light-emitting diodes. Electronics Letters 34: 1781–1782.

Holonyak, N., Jr. and S. F. Bevaqua. 1962. Coherent (visible) light emission from GaAs P junctions. Applied Physic Letters 1: 82-83.

Holonyak, N., Jr. 2000. Is the light emitting diode (LED) an ultimate lamp? American Journal of Physics 68: 864–866.

Krames, M. R., M. Ochiai-Holcomb, G. E. Höfler, C. Carter-Coman, E. I. Chen, I.-H. Tan, P. Grillot, N. F. Gardner, H. C. Chui, J.-W. Huang, S. A. Stockman, F. A. Kish, M. G. Craford, T. S. Tan, C. P. Kocot, M. Hueschen, J. Posselt, B. Loh, G. Sasser, and D. Collins. 1999. High-power truncated-inverted-pyramid $(Al_xGa_{1-x})_{0.5}In_{0.5}P/GaP$ light-emitting diodes exhibiting >50% external quantum efficiency. Applied Physics Letters 75 (16): 2365-2367.

Krames, M. R., D. A. Steigerwald, F. A. Kish, P. Rajkomar, J. J. Wierer, and T. S. Tan. 2003. III-nitride light-emitting device with increased light generating capability. U.S. Patent No. 6,521,914.

Krames, M. R., O. B. Shchekin, R. Mueller-Mach, G. O. Mueller, L. Zhou, G. Harbers, and M. G. Craford. 2007. Status and future of high-power light-emitting diodes for solid-state lighting. IEEE Journal of Display Technology 3: 160–175.

Krames, M. R. 2009. Status and prognosis for solid-state lighting technology. CLEO Conference (Baltimore, MD): presentation CM001.

Manasevit, H. M., and W. I. Simpson. 1969. The use of metalorganics in the preparation of semiconductor materials: I. epitaxial gallium-v compounds. Journal of the Electrochemical Society 116 (12): 1725–1732.

Michiue, A., T. Miyoshia, T. Yanamotoa, T. Kozakia, S-I. Nagahamaa, Y. Narukawab, M. Sanob, T. Yamadac and T. Mukai. 2009. Recent development of nitride LEDs and LDs. Proceedings of the SPIE 7216: 561.

Mueller-Mach, R., G. O. Mueller, M. R. Krames, and T. Trottier. 2002. High-power phosphor-converted light-emitting diodes based on III-nitrides. IEEE Journal of Selected Topics in Quantum Electronics 8: 339–345.

Nakamura, S., M. Senoh, and T. Mukai. 1993. High-power InGaN/GaN double-heterostructure violet light emitting diodes. Applied Physics Letters 62: 2390–2392.

Nakamura, S., M. Senoh, N. Iwasa, and S.-I. Nagahama. 1995. High-power InGaN single-quantum-well-structure blue and violet light-emitting diodes. Applied Physics Letters 67: 1868–1870.

Nakamura, S., and G. Fasol. 1997. The Blue Laser Diode. Springer (Berlin, Germany): 216–219.

Sato, H., R. B. Chung, H. Hirasawa, N. Fellows, H. Masui, F. Wu, M. Saito, K. Fujito, J. S. Speck, S. P. DenBaars, and S. Nakamura. 2008. Optical properties of yellow light-emitting diodes grown on semipolar (11-22) bulk GaN substrates. Applied Physics Letters 92, 221110.

Solid-state lighting research and development: Multi-year program plan FY'09-FY'15. March 2009. Prepared for the U.S. Department of Energy by Navigant Consulting, Inc., Radcliffe Advisors, Inc., and SSLS, Inc.

Vampola, K. J., N. N. Fellows, H. Masui, S. E. Brinkley, M. Furukawa, R. B. Chung, H. Sato, J. Sonoda, H. Hirasawa, M. Iza, S. P. DenBaars, and S. Nakamura. 2009. Highly efficient broad-area blue and white light-emitting diodes on bulk GaN substrates. Physica Status Solidi A 206 (2): 200-202.