Chapter 2
Introduction Part B. Ultra-efficient Solid-State Lighting: Likely Characteristics, Economic Benefits, Technological Approaches

Jeff Y. Tsao, Jonathan J. Wierer Jr., Lauren E.S. Rohwer, Michael E. Coltrin, Mary H. Crawford, Jerry A. Simmons, Po-Chieh Hung, Harry Saunders, Dmitry S. Sizov, Raj Bhat, and Chung-En Zah

Abstract Technologies for artificial lighting, as illustrated on the left side of Fig. 2.1, have made tremendous progress over the centuries: from fire, with an efficiency of about a tenth of a percent; to incandescent lamps, with an efficiency of about 4 %; to gas discharge lamps, with an efficiency of about 20 %; and soon to solid-state lighting (SSL), with efficiencies that in principle could approach 100 %.

At this point in time, there is virtually no question that SSL will eventually displace its predecessor technologies. A remaining question, however, is what the final efficiency of SSL will be. Will it be, as illustrated on the right side of Fig. 2.1, 50 %, which is what the community (Haitz and Tsao in Phys. Status Solidi A 208:17–29, 2011) has long targeted as its "efficient" lighting goal? Will it be 70 % or higher, which is what some (Phillips et al. in Laser Photon. Rev. 1:307–333, 2007) have called the "ultra-efficient" lighting goal? Or will it be even beyond an effective efficiency of 100 %, something that might be enabled by smart lighting (Kim and Schubert in Science 308:1274–1278, 2005), in which one doesn't just engineer the efficiency with which light is *produced*, but the efficiency with which light is *used*?

In this chapter, we give a perspective on the future of SSL, with a focus on ultra-high efficiencies. We ask, and sketch answers to, three questions. First, what are some of the likely characteristics of ultra-efficient SSL? Second, what are some of the economic benefits of ultra-efficient SSL? And, third, what are some of the challenges associated with the various technological approaches that could be explored for ultra-efficient SSL?

J.Y. Tsao (✉) · J.J. Wierer Jr. · L.E.S. Rohwer · M.E. Coltrin · M.H. Crawford · J.A. Simmons
Physical, Chemical and Nano Sciences Center, Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185-0601, USA
e-mail: jytsao@sandia.gov

P.-C. Hung
Konica Minolta Laboratory USA, Inc., 2855 Campus Dr. Suite 100, San Mateo, CA 94403, USA

H. Saunders
Decision Processes Incorporated, 2308 Saddleback Drive, Danville, CA 94506, USA

D.S. Sizov · R. Bhat · C.-E. Zah
Corning Incorporated, One Science Center Drive, Corning, NY 14831, USA

T.-Y. Seong et al. (eds.), *III-Nitride Based Light Emitting Diodes and Applications*, Topics in Applied Physics 126, DOI 10.1007/978-94-007-5863-6_2,

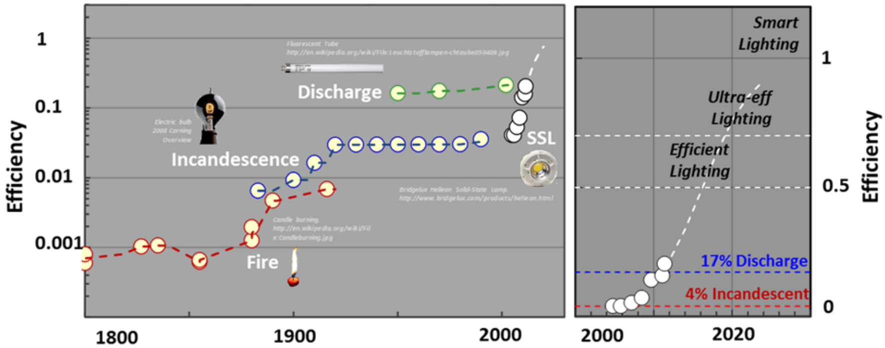

Fig. 2.1 200-year evolution of the efficiency of various lighting technologies. Adapted and updated from: Tsao [29, 30], Bergh [2], Haitz [10, 11], and Nordhaus [21]

2.1 Some Likely Characteristics of Ultra (>70 %) Efficient SSL

We first ask the question: what are some of the likely characteristics of ultra-efficient SSL? We believe there are at least two likely characteristics, both mutually compatible and complementary.

The first likely characteristic of ultra (>70 %) efficient SSL is that, unlike in the current dominant paradigm, it not make use of the wavelength downconversion that is acceptable for (>50 %) efficient SSL. Because about 80 % of white light power is green or red, and because the Stokes deficit on converting from blue to green and red is about 25 %, SSL in which wavelength downconversion is used to produce green and red is automatically at most $1 - 0.8 \times 0.25 = 80$ % efficient [30], and likely even less because of other loss factors. So the first likely characteristic of ultra-efficient SSL is that it make use of efficient electroluminescence, not wavelength downconversion, across the visible spectrum. Of course, as illustrated in Fig. 2.2, this will be challenging due to the well-known green-yellow gap in the electroluminescence efficiency of compound semiconductors [4]. However, it will be necessary for ultra-efficient SSL.

The second likely characteristic of ultra-efficient SSL is that, also unlike the current dominant paradigm in SSL technology, its white light spectrum not be broadband and continuous, but rather narrowband and "spiky." To see this, Fig. 2.2 shows the spectral power densities of the output optical power from various white light sources.

Incandescence The least efficient source is the incandescent lamp, with the continuous spectral power density of black-body radiation shown in red, extending extremely far out into the infrared where the human eye does not see at all. All the light produced in the infrared is wasted, and the spectral efficiency of the light is very poor.

PC-LED The second least efficient source is the phosphor-converted white LED shown in black, which has very broad green and red phosphor emission extending

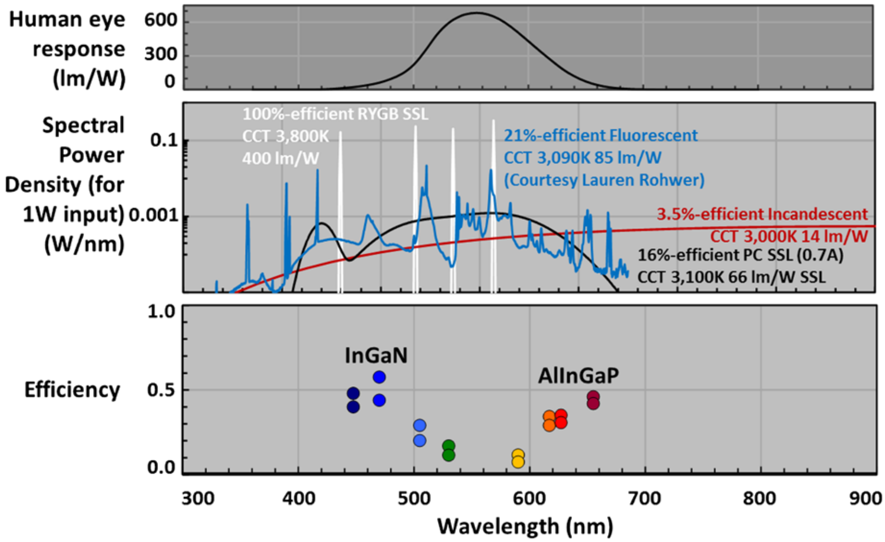

Fig. 2.2 *Top*: Photopic (daytime) human eye response. *Middle*: Spectral power densities of the output power of various sources for 1 W input electrical power to the source. For the fluorescent lamp, the red phosphor is Y_2O_3:Eu^{3+}, the blue phosphor is $BaMgAl_{10}O_{17}$:Eu^{2+} (BAM), while the green phosphor is either $LaPO_4$:Ce^{3+},Tb^{3+} or $CeMgAl_{11}O_{19}$:Tb^{3+}. *Bottom*: Power conversion efficiencies of state-of-the-art commercial monochromatic light-emitting diodes (LEDs) driven at 350–750 mA/mm^2 [26]

into the deep red which the human eye can see but not very efficiently. Just as with the incandescent lamp, though not as severely, that wasted power in the deep red means that the spectral efficiency of the white light is poor.

Discharge Compared to the two lamps just discussed, the discharge-based fluorescent lamp is a much more efficient source. It does not have much wasted light in the deep red, with a spike in its spectral power density near the ideal shallow-red wavelength of 615 nm. But its efficiency is still limited, for the following reasons: the gas discharge is itself only 65 % efficient; the Stokes loss from the UV mercury lines at 254 nm into the visible around 555 nm adds an additional 50 % inefficiency; and the quantum yield of the phosphor blend is only about 85 % efficient. So, despite its spiky and efficient spectral power density [23, 33], its ultimate maximum efficiency is only about 25 %.

100 %-Efficiency In fact, the best lamp of all would be one that produces the four spikes of light shown in white. There are just enough spikes, spaced widely enough apart, to fill the visible spectrum and render quite well the colors of objects typical in the environment around us [30]. Additionally, the spikes are concentrated within the visible spectrum, without spillover of light into wavelengths at which the human eye is insensitive, resulting in the highest spectral efficiency possible.

2.2 The Ultimate SSL Source Is Spiky

One might now ask: how is it that the spiky source illustrated in white in the middle panel of Fig. 2.2 could be a good white-light illuminant? First, how could such a spiky four-color spectrum really render the colors of objects in the environment around us well, and be a visually pleasing white light illumination source, even while it is missing so much spectra in between the spikes? And, second, does such a spiky four-color spectrum also maximize luminous efficacy of radiation? In this section, we discuss these two questions in turn.

2.2.1 Spiky Spectra Give Good CRI

Let us start with how it is that spiky spectra can give good color rendering quality.

In fact, spiky sources are not only predicted to be a visually pleasing white-light illuminant by color science [22], but have been shown to be so in a recent experiment [20]. In that experiment, an *extremely* spiky illumination source was created using four visible lasers: blue, green, yellow and red. The relative powers of the lasers were tuned to maximize color rendering quality and to match color temperature and overall lumen output of a number of reference sources, including the output of an incandescent lamp. Then, two side-by-side scenes were illuminated, one with the four-color laser illuminant and the other with the various reference sources.

One of the results is illustrated in Fig. 2.3. Although the similarity of the side-by-side photos does not automatically imply similarity in human visual experience (because the image sensor in the camera is not the human eye), the human visual experiences of the two scenes were in fact quite similar. As might be expected, when any one of the four colors is removed, the scene looks visually displeasing. But, when that color is put back in, the scene looks visually quite pleasing. In fact, the four-color laser illuminant was, in double-blind tests, on average preferred over the phosphor-converted neutral-white and cool-white LED lamps, and on average neither preferred nor dispreferred over phosphor-converted warm-white LED and incandescent lamps.

Why is this? The reason is that most objects in the world have relatively broad reflectance spectra. It is a rare object, like a diffraction grating, that has a narrow reflectance spectrum that would enable the human eye to distinguish between spiky and non-spiky illuminants.[1]

So the striking conclusion of theory and experiment is that spiky sources do indeed give excellent color rendering quality.

[1] Rare, but not non-existent. Any iridescent object which supports optical interference phenomena (e.g., opals, soap bubbles, some butterfly wings) would distinguish between spiky and non-spiky illuminants.

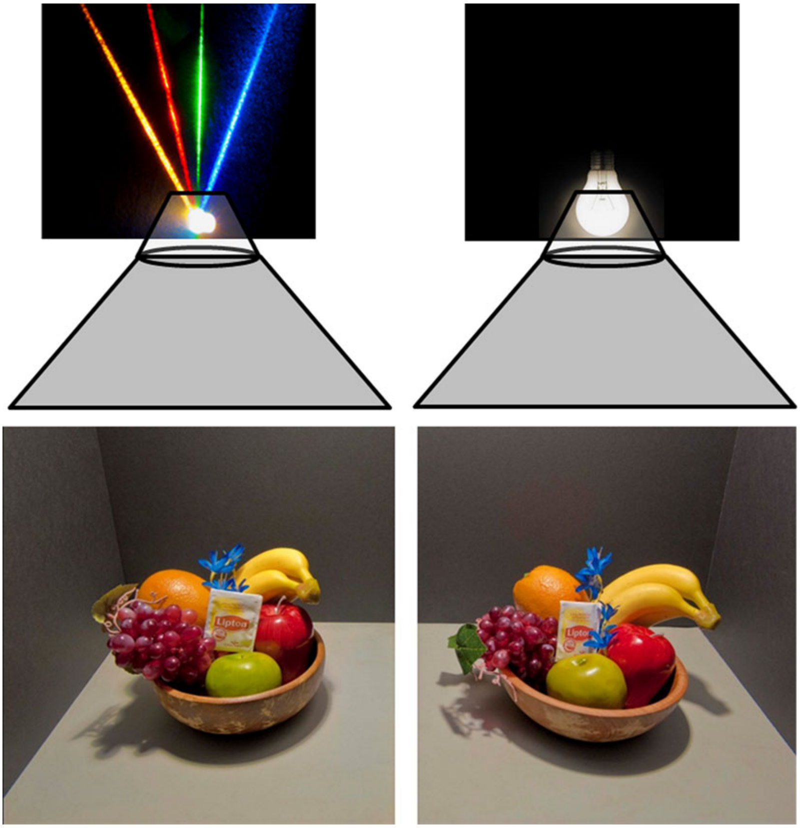

Fig. 2.3 Schematic of side-by-side test of the color-rendering quality of a four-color "spiky" laser illuminant and a number of reference sources (including the incandescent lamp depicted). To give a sense for the color-rendering quality of the laser illuminant, the photos of the *left* and *right* bowls of fruit were illuminated, respectively, by the four-color laser illuminant and by an incandescent lamp. Although the image sensor in the camera is not the human eye, so the similarity of the photos does not automatically imply similarity in human visual experience, in fact the human visual experience *was* quite similar

2.2.2 Spiky Spectra Give the Highest MWLERs

Let us now consider whether spiky spectra also give good luminous efficacies of radiation.

To answer this question, the right side of Fig. 2.4 shows recent simulations of spectral power densities, unconstrained by whether the spectra are continuous or spiky, which maximize white luminous efficacy of radiation (MWLER) given particular values of standard color rendering index[2] (CRI) and correlated color tem-

---

[2]In our treatment here, we mean the standard color rendering index R_a [3].

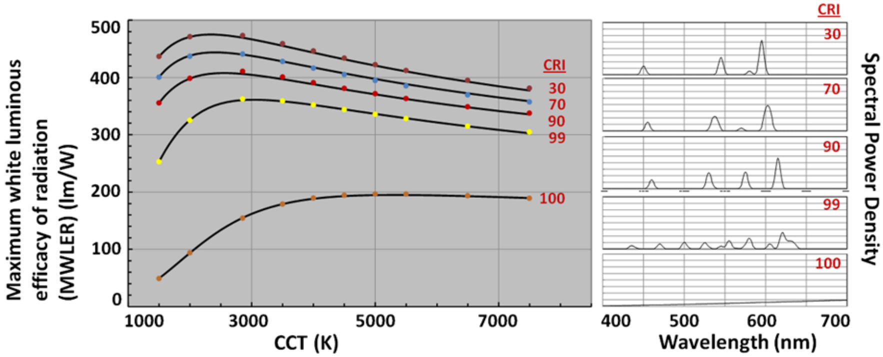

Fig. 2.4 *Left*: Maximum white luminous efficacy of radiation versus correlated color temperature (CCT) for various standard color rendering indices (CRIs). *Right*: Relative spectral power densities for various CRIs for a CCT of 2856 K. After Hung [13]

perature (CCT) [13]. In fact, the spectral power densities that maximize the white luminous efficacies of radiation are, except for the very highest CRI (of 100), all spiky. Of course, for a very high CRI, as in the panel with CRI of 99, there may be more spikes, but nevertheless the spectral power densities are all spiky. We can conclude that spikiness is in fact a general feature of spectral power densities that maximize luminous efficacy or radiation.

Now, *given* a spiky spectral power density, the maximum white luminous efficacy of radiation does of course depend on CCT and CRI. One can see from the family of curves illustrated in the left half of Fig. 2.4, that, for all CRI values, the MWLER peaks at a particular CCT and drops off at higher or lower color temperatures on either side. The physical reason for this is that, starting from a very high CCT, as CCT decreases, spectra shifts first from the blue to the green and then from the green to the red. Because luminous efficacy of radiation is highest in the green, the MWLER first increases then decreases.

One can also see from the family of curves illustrated in the left half of Fig. 2.4 that, as CRI increases, all luminous efficacies of radiation decrease. The physical reason for this is that the higher the CRI becomes, the more "spread out" the white light spectrum (even if it is spiky) becomes. The more spread out the white light spectrum becomes, the further the spectrum penetrates into the wings of the human eye response (hence further from the peak of the human eye response at 555 nm), and the lower the luminous efficacy of radiation.[3]

We can conclude that spiky spectra are preferred over non-spiky (continuous) spectra: they not only give good color rendering quality, but also maximize white luminous efficacy of radiation.

[3]Note that the higher the CRI, the higher the CCT at which the MWLER maximizes, as discussed in Hung [13].

2.3 Economic Benefits of Ultra-efficient SSL

Up to this point, we have discussed the characteristics of ultra-efficient SSL: it must not make use of wavelength downconversion, and its spectrum should be spiky. But what are the economic consequences of ultra-efficient SSL? The benefits (i.e., profits) of efficient lighting to the SSL industry will have already manifested themselves by the time SSL has achieved 50 % efficiency. At that point, SSL will have beaten both incandescent and gas discharge lamps and will have begun to replace them. Are there additional economy-wide benefits (beyond profit to the SSL industry) that would make it worthwhile to pursue ultra-high efficiencies of 70 % and beyond?

To understand the possible answers to this question, in Fig. 2.5 we sketch two possible scenarios for the energy economics of light. Using world gross domestic product (GDP) and world consumption of light and energy in 2011 as a baseline, we ask what the consequences of changes in the efficiency of lighting would be, *all other factors in the economy held constant*. We assume throughout that the impacts of a change in efficiency are twofold: first, less energy is consumed for a given amount of light consumed; and second, the effective cost of light (typically dominated by the energy used to produce the light) decreases.

2.3.1 Scenario 1: Light Is Not a Factor of Production

The first scenario is sketched in the left panels of Fig. 2.5. This is a scenario in which light is *not* a factor of production in the global economy. Thus, if the efficiency with which light is produced were to increase, world GDP wouldn't change, but would stay constant at its value in 2011 (about 60.5 trillion US dollars). This is also a scenario in which, if light were to become more efficient and hence cheaper, we would have no tendency to consume more (i.e., consumption of light is saturated).

Hence, in this scenario, the main benefit to increased efficiency is that the consumption of energy associated with the production of light decreases. Since the consumption of energy associated with the production of light is about 1/15 of all consumption of energy, as efficiency of lighting increases, consumption of energy could in principle decrease by nearly 1/15—from about 44.5 PWh/yr to about 42 PWh/yr.

But one can also see that the biggest decreases in energy consumption occur when efficiency is low. As efficiency increases there is a diminishing return or diminishing benefit to continuing to increase efficiency. For example, when efficiency has reached 0.9, increasing efficiency further from 0.9 to 1.0 only decreases energy consumption by 35 TWh/yr, which represents only about $4.3 B/yr.[4] This is not a small benefit, but it is *relatively* small, and it is not obvious that an efficiency of 1.0 would be worth the required R&D effort.

[4] Assuming a light-usage-weighted average world electricity price of $120/MWh [31].

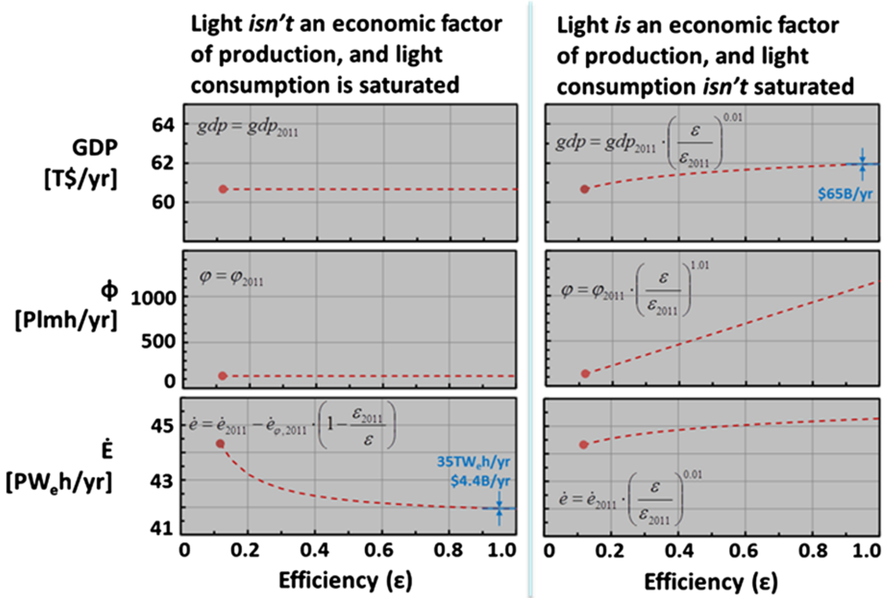

Fig. 2.5 Economic scenarios for world gross domestic product (GDP), world consumption of light (Φ) and world consumption of energy ($\dot{E}$). The scenario on the left is one in which light *is* considered to be a factor of production in the economy; the scenario on the right is one in which light is *not* considered to be a factor of production in the economy

2.3.2 Scenario 2: Light Is a Factor of Production

The second scenario is sketched in the right panels of Fig. 2.5. This is a scenario in which light *is* a factor of production in the global economy. So, if the efficiency with which light is produced were to increase, the cost of light would decrease, more light would be consumed, and world GDP *would* increase (above where it otherwise would be, again all other things in the world of 2011 held constant). This scenario has been analyzed in some detail using a simple Cobb-Douglas model which treats light as a factor of production in the global economy [32].

The result of that analysis is that there is no direct energy (or environmental) benefit to increased efficiency. Since the consumption of light increases as efficiency increases, energy consumption doesn't decrease. Indeed, because GDP increases as light consumption increases, there is even a slight increase in energy consumption. So, in this scenario, the main benefit to increased efficiency is an increase in global GDP. In fact, this benefit is huge. Although there is a diminishing return to the increase in GDP, if efficiency were even as high as 0.9, and were increased to 1.0, global GDP would increase by $65 B/yr. This economic benefit is huge, nearly 15× larger than in the first scenario, despite the diminishing returns.

Moreover, although in this scenario there is no direct energy (and environmental) benefit to increased efficiency, some of the huge increase in GDP could presum-

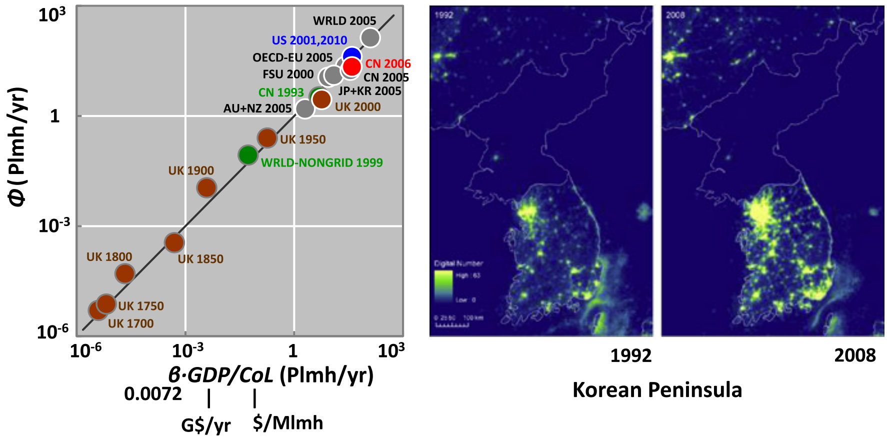

Fig. 2.6 *Left*: Consumption of light versus ratio between gross domestic product (GDP) and cost of light (CoL) for various countries at various times in history, after Tsao [31]. *Right*: Satellite images of the Korean peninsula taken in 1992 and 2008, showing the dramatic increase in consumption of light, correlated with the increase in national GDP during that same time period. After Henderson [12]

ably be harnessed to improve technologies *with* direct energy (and environmental) benefit, including those for renewable energy or for adaptation to the deleterious environmental effects of carbon-emitting energy technologies.

Thus, if this is indeed the scenario that best describes reality, there is a large direct economic benefit and hence large potential indirect energy and environmental benefits to continuing to improve efficiency.

2.3.3 A Qualified Nod to Scenario 2: More Light = More Productivity

Which of the above two scenarios best describes reality? We cannot know for sure, but if the past is any indication, then it is the second scenario.

The reason is illustrated in the plot on the left of Fig. 2.6. The vertical axis of this plot is consumption of light, in Plmh/year. The horizontal axis of the plot is a fixed constant, β, times the ratio between gross domestic product (GDP) and cost of light (CoL). If we use as our units for GDP billions of dollars per year, and for cost of light \$/Mlmh, we see that this ratio has the same units, Plmh/year, as the units of the vertical axis. And if we choose the fixed constant, β, to be 0.0072, we see that the empirical data fall very closely along a line of slope unity and zero offset [31].

The ability of this simple formula to predict consumption of light across several centuries and a wide range of countries and groups of countries has two implications. The first implication is that, as GDP has increased, consumption of light has increased. That is, the wealthier we are, the more light we consume.[5] One can see this graphically for the case of South Korea, where the consumption of light, as seen from outer space, has increased markedly from 1992 to 2008. The second implication is that, as cost of light has decreased, consumption of light has increased as well. That is, the cheaper light is, the more we have consumed.

In fact, these results are exactly what one would predict from the second scenario, the one in which light *is* a factor of production in the economy, so that the more efficiently light is produced, the more we consume and the more productive we are. Now, we do not know whether the future will be like the past, but if it is, then this analysis shows that it *is* worth the effort to continue to improve SSL efficiency, even to ultra-high efficiencies and beyond.

2.4 Two Competing Approaches: Low and High Power Densities

We have just discussed the potential economic benefit of achieving the highest possible efficiencies. In fact, there are two approaches, discussed below, that could be pursued to achieve this: one in which the emitters are run at low power densities and the emission is spontaneous; and one in which the emitters are run at high power densities and the emission is stimulated. Both have potential, but both also face challenges.

To illustrate these challenges, let us focus on just the blue light emitter. Eventually, as discussed above, it will be important to find green, yellow and shallow-red light emitters for ultra-efficient SSL. For our purpose here, however, let us assume the paradigm of white light based on blue light emitters and wavelength downconversion. Then, in Fig. 2.7, we show the implications of input power density into the blue light emitter on the efficiency and cost constraints of the blue light emitter, and also on the resulting heat-sink-limited area and white light flux producible from that area.

The key panel in Fig. 2.7 is the bottom one: the power-conversion efficiency of the InGaN-based blue light emitter versus the input power density into the emitter. On the one hand, spontaneous-emission-based blue LEDs (red line) cannot be driven at an input power density more than a few W/cm^2 before efficiency decreases—the so-called "efficiency droop" problem [4, 15, 28]. On the other hand, stimulated-emission-based blue lasers (blue line), because of the finite lasing thresholds, must be driven at an input power density more than about a few thousand W/cm^2 before they "turn on" and begin to achieve appreciable efficiency. There is a "valley of death" in input power density within which InGaN-based blue light emitters are not very efficient, and, thus, there is currently a tremendous amount of research aimed at circumventing this valley of death by improving the efficiency droop. If it cannot be circumvented, the valley of death motivates two very different approaches [29] to ultra-efficient SSL.

[5]Indeed, this correlation between GDP and light consumption is being explored as a means to "measure" GDP. See, e.g., Henderson [12].

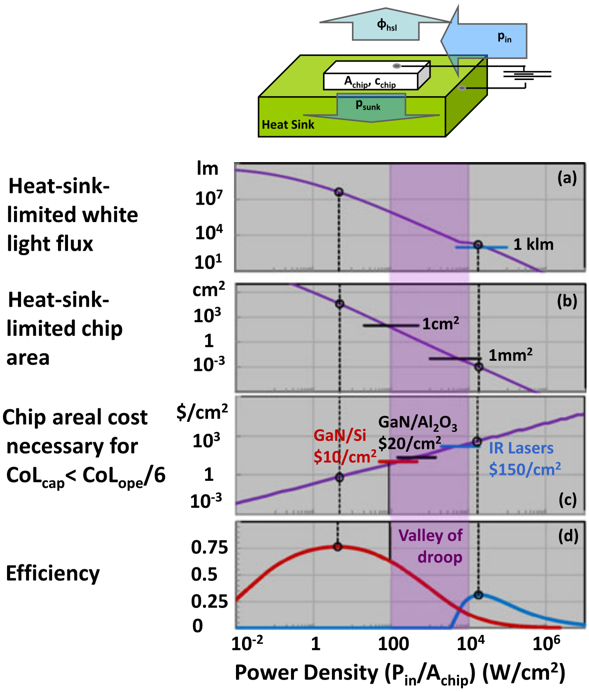

Fig. 2.7 Economics of low-power-density and high-power-density approaches to SSL

2.4.1 *Low Power Density Approach (LEDs)*

The first approach is to drive a blue LED at a low input power density, near peak efficiency. The red curve in Fig. 2.7(d) shows efficiency calculated using "ABC" coefficients [5] based on a state-of-the-art Philips Lumileds LED [26]. Peak efficiency is at a power density of roughly 5 W/cm^2, or at about a 15–20 mA drive current into a 1 mm^2 chip [35].

The problem with this approach is that, if the chip isn't driven very hard, not much light is output from the chip per unit area. Large integrated chip areas would be required to produce an appreciable light output, so the chip cost per unit area must be low. To see how low, consider the two costs associated with light [30].

First there is the capital cost of light, which can be written as

$$CoL_{cap} = \frac{\alpha \cdot c_{chip} \cdot A_{chip}}{MWLER \cdot \varepsilon_B \cdot \varepsilon_{PP} \cdot P_{in} \cdot L}, \tag{2.1}$$

where α is the ratio between retail lamp price to the consumer and chip cost, c_{chip} is the areal cost of the chip (in \$/cm^2), A_{chip} is the area of the chip (in cm^2), $MWLER$ is the maximum white luminous efficacy of radiation (in lm/W), ε_B and ε_{PP} are the blue emitter and phosphor + package efficiencies, respectively, P_{in} is the electrical power input into the chip (in W), and L is the lifetime of the lamp (in Mh).

Second, there is the operating cost of light, which can be written as

$$CoL_{ope} = \frac{CoE}{MWLER \cdot \varepsilon_B \cdot \varepsilon_{PP}}, \tag{2.2}$$

where CoE is the cost of electricity (in \$/Mlmh).

For traditional (non-SSL) lighting, the capital cost of light is small relative to (and about $1/6$ of) the operating cost of light, and one can anticipate a similarly low ratio between the two costs for SSL in its steady-state future. If so, we would have $CoL_{cap} = CoL_{ope}/6$, and could then deduce that the areal cost of the chip must be roughly

$$c_{chip} = \frac{L \cdot CoE}{6 \cdot \alpha} \cdot (P_{in}/A_{chip}). \tag{2.3}$$

In other words, the higher the power density (P_{in}/A_{chip}) input into the chip, the higher the areal chip cost can be while still satisfying a low capital-to-operating cost ratio of $1/6$. Note that the absolute efficiencies of the blue emitter or of the phosphor $+$ package do not enter in, as these affect both the capital and operating costs in the same manner and cancel out.

If we now assume an input-power-density-dependent lifetime that decreases smoothly[6] from 0.03 Mh (at a typical LED input power density of 225 W/cm^2) to 0.01 Mh (at a typical laser input power density of 240 kW/cm^2), a retail cost of electricity of roughly 120 \$/MWh, and a retail-lamp-to-chip cost ratio[7] of roughly $\alpha \sim 10$, then we get the diagonal purple line plotted in Fig. 2.7(c). If one would like to drive the chip at 5 W/cm^2 power density, where efficiency is maximum for current state-of-the-art blue LEDs, one finds that chip cost per unit area must be lower than \$1/cm^2.[8]

There is thus a strong motivation for developing extremely inexpensive chip technologies, like GaN/Si or GaN nanowires. However, future scenarios [34] for GaN/Si chip technologies predict roughly 2$\times$ reductions from GaN/sapphire, not the 20$\times$ reductions that appear to be necessary. Thus, areal chip cost will be a key but difficult challenge for the low-power-density approach to ultra-efficient SSL.

A related challenge is to increase the power density at which ultra-high-efficiencies may be obtained, so that more expensive chips can be used.

[6] We use a simple logarithmic dependence of lifetime on input power density: $\log(L/0.03\ \text{Mh}) = 0.23 \cdot \log[(P_{in}/A_{chip})/(225\ \text{W/cm}^2)]$, where L is lifetime in Mh and P_{in}/A_{chip} is input power density in W/cm^2.

[7] This multiplier between the cost of a retail lamp to the cost of the chip within the lamp includes various sub-multipliers that connect the chip to the package, the package to the wholesale lamp, and finally the wholesale lamp to the retail lamp [7, 8]. Note that this multiplier is surprisingly similar to those for higher-power-density chips such as high-power IR lasers [16, 19] inserted into retail laser modules and for low-power-density chips such as solar cells inserted into residential retail panels [1, 6, 18]. Hence, we use the same multiplier across the range of input power densities considered here.

[8] To put this in perspective, current chip cost per unit area for state-of-the-art GaN/sapphire chips is much higher (about 20 \$/cm^2), while for single-crystal Si solar cells is much lower (about \$0.02/cm^2).

2.4.2 High Power-Density Approach

The second approach is to drive a blue laser at a high input power density where, due to stimulated emission, efficiency can again be higher. The blue curve in Fig. 2.7(d) shows a threshold-and-slope-efficiency calculation of efficiency based on a state-of-the-art Osram blue laser, showing that efficiency peaks at a power density of roughly 20 kW/cm^2, or at about a 70 A drive current into a 1 mm^2 chip [35].

In this approach, because the chip is being driven very hard, with a lot of light out per unit area, the chip cost per unit area can be high. In fact, if we apply the same economic constraints we applied before, that the cost to buy the lamp should be about 1/6 the lifetime cost to run the lamp, we find that, at the power density at peak efficiency for this blue laser, chip cost per unit area must be less than \$400/cm^2. In fact, high-efficiency [24] high-power IR laser chips, at \$150/cm^2 [16], are already much cheaper than this, with the possibility that they could become much cheaper still [16]. This provides an existence proof that such costs might someday also be achievable with laser chips in the visible.

What is less obvious is whether one can get a reasonable amount of light out of a high-input-power-density light emitter. A limit to the amount of light will be imposed by heat sinking. To determine roughly what that limit might be, we use the usual scaling relationship [9, 17, 29] for the thermal resistance of a conduction-cooled (and hence relatively inexpensive) chip:

$$R_T = \frac{1}{2\kappa_T \cdot \sqrt{4A_{chip}/\pi}}, \tag{2.4}$$

where κ_T is the thermal conductivity of the heat sink, and A_{chip} is the area of the chip.[9] If the power sunk by the heat sink is $P_{sunk} = P_{in} - P_{out} = P_{in} \cdot (1 - \varepsilon_B \varepsilon_{PP})$, then the thermal resistance that enables the temperature increase of the chip due to this sunk power to be less than a maximum allowable ΔT_{max} is:

$$R_T = \frac{\Delta T_{max}}{P_{in} \cdot (1 - \varepsilon_B \varepsilon_{PP})}. \tag{2.5}$$

Equating the two expressions for the thermal resistance allows us to solve for the "heat-sink-limited" maximal area[10] of the chip for a given input power density:

$$A_{hsl} = \left[\frac{2\kappa_T \cdot \sqrt{4/\pi} \cdot \Delta T_{max}}{(1 - \varepsilon_B \varepsilon_{PP}) \cdot (P_{in}/A_{chip})} \right]^2. \tag{2.6}$$

[9] Note that this is an underestimate of the thermal resistance for a laser chip, as such chips may be non-square with a large aspect ratio.

[10] In other words, for a given input power density, efficiency and heat-sink properties, there is a maximum chip size that enables the temperature rise of the chip to remain manageable. This maximum chip size depends strongly on (inversely as the square of) input power density because the chip size that gives a particular thermal resistance depends strongly on (inversely as the square of) that thermal resistance.

The "heat-sink-limited" maximal light output of the chip, also for a given input power density, is proportional to this heat-sink-limited maximal area, and can thus be written as:

$$\begin{aligned}\Phi_{hsl} &= MWLER \cdot \varepsilon_B \varepsilon_{PP} \cdot \left(\frac{P_{in}}{A_{chip}}\right) \cdot A_{hsl} \\ &= \frac{MWLER \cdot \varepsilon_B \varepsilon_{PP}}{(P_{in}/A_{chip})} \left[\frac{2\kappa_T \cdot \sqrt{4/\pi} \cdot \Delta T_{max}}{(1-\varepsilon_B \varepsilon_{PP})}\right]^2. \end{aligned} \tag{2.7}$$

Both of these heat-sink-limited quantities, chip area and chip white light output are plotted in Figs. 2.7(b) and 2.7(a) for a *MWLER* of 400 lm/W, blue light emitter efficiencies given by those in Fig. 2.7(d), a phosphor + package efficiency of $\varepsilon_{PP} \sim 0.7$, a maximum allowable temperature rise of $\Delta T_{max} \sim 100$ K, and a thermal conductivity of $\kappa_T \sim 2\ \mathrm{W\,cm^{-1}\,K^{-1}}$ (between those of copper and silicon).[11]

One can see that, at the input power density of 20 kW/cm^2, at which the efficiency of a state-of-the-art blue laser maximizes, the chip must be less than a tenth of a mm^2 in area, but the heat-sink-limited light flux out of such a chip would still be over 1,000 lm (the rough equivalent of the light flux from a 75 W incandescent lamp). In other words, single high-power-density heat-sink-limited chips should have no difficulty generating useful amounts of light.

Instead, for this approach, the main issue will be getting to ultra-high efficiencies. Although peak efficiencies for a laser aren't limited by either the *A* or *C* coefficients in the *ABC* model for efficiency, they are limited by other losses such as injection efficiency, optical absorption and series resistance. So an important challenge will be to understand the origin of those losses, and to design ways of reducing them.

2.5 Summary

First, solid-state lighting is the latest in a series of technologies of ever-increasing efficiencies for producing white light.

Second, getting to the highest possible efficiencies will ultimately require both efficient electroluminescence across the visible as well as spiky spectra. Indeed, the ultimate spiky source, a 4-color laser illuminant, has been shown to provide very good color rendering quality and to maximize white luminous efficacy of radiation, and hence can be thought of as the "gold standard" for white lighting.

Third, getting to the highest possible efficiencies has potentially huge economic benefit, and is likely worth pursuing.

Fourth, and finally, the two different routes for ultra-efficient SSL that could be pursued, low and high power density chips, are both promising but face different

[11] Note that this thermal conductivity implies, through Eq. (2.4), a thermal resistance of 2.5 K/W for 1 mm^2 chip size, in the range of (but slightly lower) than that, 5.5 K/W, for a Philips Lumileds Luxeon K2 package [25].

challenges. The challenge for the low-power-density approach is not so much to improve efficiency, as this is already very high, but to reduce cost while maintaining such high efficiency (or to increase the power density at which such high efficiency can be obtained). The challenge for the high-power-density approach is not so much to reduce cost (as there is an existence proof that this can be low enough), but to increase efficiency.

Acknowledgements We thank Emma Johnson, Justin Sanchez, Emily Stirrup and Jack Wampler for careful reviews of this chapter and of other manuscripts on which this chapter is based, and thank Edward Stephens for helpful consultations. Work at Sandia National Laboratories was supported by Sandia's Solid-State Lighting Science Energy Frontier Research Center, funded by the U.S. Department of Energy, Office of Basic Energy Sciences. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

References

1. G. Barbose, N. Darghouth, R. Wiser, Tracking the Sun III: the installed cost of photovoltaics in the U.S. from 1998–2009. Lawrence Berkeley National Laboratory Report (December 2010)
2. A. Bergh, M.G. Craford, A. Duggal, R. Haitz, The promise and challenge of solid-state lighting. Phys. Today **54**, 42–47 (2001)
3. Commission Internationale de l'Eclairage, Method of measuring and specifying colour rendering properties of light sources. Technical Report 13.3-1995 (1995)
4. M.H. Crawford, LEDs for solid-state lighting: performance challenges and recent advances. IEEE J. Sel. Top. Quantum Electron. **15**, 1028–1040 (2009)
5. A. David, M.J. Grundmann, Droop in InGaN light-emitting diodes: a differential carrier lifetime analysis. Appl. Phys. Lett. **96**, 103504 (2010)
6. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, 2008 Solar Technologies Market Report (January 2010)
7. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, Solid-state lighting research and development manufacturing roadmap (July 2011)
8. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, Solid-state lighting research and development multi-year program plan (April 2012)
9. M. Grabherr, M. Miller, R. Jager, R. Michalzik, U. Martin, H.J. Unold, K.J. Ebeling, High-power VCSEL's: single devices and densely packed 2-D-arrays. IEEE J. Sel. Top. Quantum Electron. **5**, 495–502 (1999)
10. R. Haitz, J.Y. Tsao, Solid-state lighting: 'the case' 10 years after and future prospects. Phys. Status Solidi A **208**, 17–29 (2011)
11. R. Haitz, J.Y. Tsao, Solid-state lighting: why it will succeed, and why it won't be overtaken. Opt. Photonik **6**, 26–30 (2011)
12. J.V. Henderson, A. Storeygard, D.N. Weil, Measuring economic growth from outer space. Am. Econ. Rev. **102**, 994–1028 (2012)
13. P.C. Hung, J.Y. Tsao, Maximum white luminous efficacy of radiation versus color temperature and color rendering index: exact results and a useful semi-empirical expression. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6365765 (2013)
14. J.K. Kim, E.F. Schubert, Solid-state light sources getting smart. Science **308**, 1274–1278 (2005)
15. M.R. Krames, O.B. Shchekin, R. Mueller-Mach, G.O. Mueller, L. Zhou, G. Harbers, M.G. Craford, Status and future of high-power light-emitting diodes for solid-state lighting. J. Disp. Technol. **3**, 160 (2007)

16. A.L. Ladran, E.R. Ault, R.J. Beach, J.H. Campbell, A.C. Erlandson, A.J. Felker, B.L. Freitas, W.R. Meier, S. Telford, C.A. Ebbers, J.A. Caird, C.P.J. Barty, Inertial fusion energy's role in developing the market for high power laser diodes. Lawrence Livermore National Laboratory Report UCRL-CONF-237006 (2007)
17. W. Nakwaski, M. Osinski, Thermal resistance of top-surface emitting vertical-cavity semiconductor lasers and monolithic two-dimensional arrays. Electron. Lett. **28**, 572–574 (1992)
18. J. Lushetsky, The prospect for $1/Watt electricity from solar. DOE presentation at the $1/W Workshop (August 10, 2010)
19. R. Martinsen, Industrial markets beckon for high-power diode lasers. Optics and Laser Europe Magazine, 26–27 (2007)
20. A. Neumann, J.J. Wierer Jr., W. Davis, Y. Ohno, S.R.J. Brueck, J.Y. Tsao, Four-color laser white illuminant demonstrating high color rendering quality. Opt. Express **19**, 982–990 (2011)
21. W.D. Nordhaus, Do real-output and real-wage measures capture reality? The history of lighting suggests not, in *The Economics of New Goods*, ed. by T.F. Breshnahan, R.J. Gordon (The University of Chicago Press, Chicago, 1997), pp. 29–70
22. Y. Ohno, Spectral design considerations for color rendering of white LED light sources. Opt. Eng. **44**, 111302 (2005)
23. J.J. Opstelten, D. Radielovic, J.M.P.J. Verstegen, Optimum spectra for light sources. Philips Tech. Rev. **35**, 361–370 (1975)
24. M. Peters, V. Rossin, M. Everett, E. Zucker, High power, high efficiency laser diodes at JDSU, in *High-Power Diode Laser Technology and Applications V*, ed. by M.S. Zediker. Proc. of SPIE, vol. 64560G (2007)
25. Philips Lumileds, Luxeon K2 with TFFC Technical Datasheet DS60 (April 2009)
26. Philips Lumileds, Luxeon Rebel and Luxeon Rebel ES Color Portfolio Datasheet DS68 (December 2011)
27. J.M. Phillips, M.E. Coltrin, M.H. Crawford, A.J. Fischer, M.R. Krames, R. Mueller-Mach, G.O. Mueller, Y. Ohno, L.E.S. Rohwer, J.A. Simmons, J.Y. Tsao, Research challenges to ultra-efficient inorganic solid-state lighting. Laser Photon. Rev. **1**, 307–333 (2007)
28. J. Piprek, Efficiency droop in nitride-based light-emitting diodes. Phys. Status Solidi A **207**, 2217–2225 (2010)
29. J.Y. Tsao, Solid-state lighting: lamps, chips, and materials for tomorrow. IEEE Circuits Devices **20**, 28–37 (2004)
30. J.Y. Tsao, M.E. Coltrin, M.H. Crawford, J.A. Simmons, Solid-state lighting: an integrated human factors, technology and economic perspective. Proc. IEEE **98**(7), 1162–1179 (2010)
31. J.Y. Tsao, P. Waide, The world's appetite for light: a simple empirical expression spanning three centuries and six continents. Leukos **6**, 259–281 (2010)
32. J.Y. Tsao, H.D. Saunders, J.R. Creighton, M.E. Coltrin, J.A. Simmons, Solid-state lighting: an energy economics perspective. J. Phys. D **43**, 354001 (2010)
33. J.M.P.J. Verstegen, D. Radielovic, L.E. Vrenken, A new generation of "deluxe" fluorescent lamps, combining an efficacy of 80 lumens/W or more with a color rendering index of approximately 85. J. Electrochem. Soc. **121**, 1627–1631 (1974)
34. E. Virey, Silicon substrates contend for LED opportunity. iLED Issue **3**, 16–19 (2012)
35. J.J. Wierer et al., Comparison between blue laser and light-emitting diodes for future solid-state lighting. Manuscript in preparation (2013)

http://www.springer.com/978-94-007-5862-9

III-Nitride Based Light Emitting Diodes and Applications
Seong, T.-Y.; Han, J.; Amano, H.; Morkoç, H. (Eds.)
2013, XIII, 390 p., Hardcover
ISBN: 978-94-007-5862-9