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LEDs for lighting: Basic physics and prospects for energy savings

Les LEDs pour l'éclairage : physique de base et perspectives pour les économies d'énergie

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A B S T R A C T

In 2014, Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura received the Nobel Prize in Physics for "the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources". Indeed, in the recent years, Light-Emitting Diodes (LEDs) have progressively made their way to the home lighting market, as well as to other mass markets. This article aims at giving an insight on LEDs physics, on the key inventions that led to the 2014 Nobel Prize and on the prospects for energy savings that LEDs could allow.

R É S U M É

En 2014, Isamu Akasaki, Hiroshi Amano et Shuji Nakamura ont reçu le prix Nobel de physique pour « l'invention des diodes électroluminescentes bleues efficaces, qui a conduit à des sources de lumières blanches brillantes et énergétiquement économes ». En effet, au cours de ces dernières années, les diodes électroluminescentes (LEDs) ont progressivement pénétré le marché de l'éclairage domestique, ainsi que d'autres marchés de masse. Cet article vise à donner un point de vue sur la physique des LEDs, sur les inventions-clés qui ont conduit au prix Nobel 2014 et sur les perspectives d'économies d'énergie que les LED pourraient permettre.

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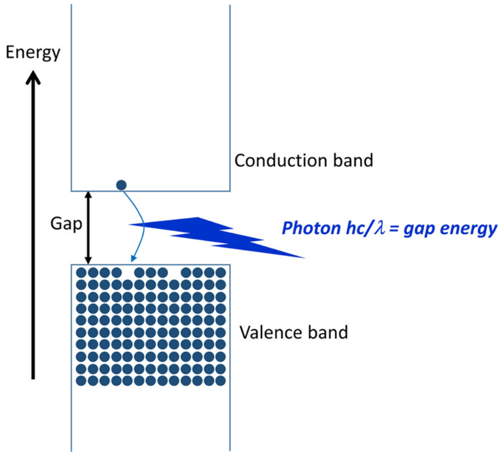

Fig. 1. Schematics of a semiconductor band structure. The vertical scale is an energy scale for electrons. For an intrinsic semiconductor, the valence band has all of its level occupied by electrons, while the conduction band is empty of electrons. In this case, electrical conductivity is not possible (an electron in the valence band is frozen as it has no other state to move to). The energy difference between the maximum of the valence band and the minimum of the conduction band is called the band gap of the semiconductor material. When there are electrons in the conduction band, electrical conductivity is made possible. It is also the case when some electrons are missing in the valence band (so called holes). Finally, when a conduction band electron and a valence band hole are at the same place in the semiconductor, they can recombine (i.e. the electron leaves the conduction band to fill the valence band hole) and emit a photon, with an energy (and hence a wavelength) corresponding to the band gap of the material.

1. Introduction

Light-Emitting Diodes (LEDs) have been part of daily life for many decades, starting with indicator lamps and infrared remote controls in the 1960s. Yet it is only in 2014 that the Nobel Prize in Physics was awarded for LEDs, and namely for blue LEDs that eventually allowed one to produce white light. The aim of this article is to discuss basic LED physics so as to show why LEDs are potentially excellent light emitters, in particular for lighting applications, to present a short history of the various inventions that led to modern LEDs and in particular to explain why the 2014 Nobel Prize in Physics was awarded to Akasaki, Amano, and Nakamura. Finally, I shall discuss whether current LEDs really lead to energy savings, and more prosaically whether at the individual consumer level it makes sense to buy LED bulbs for domestic lighting.

2. Semiconductor LEDs, how do they work?

In this section, I will present a rapid background on the history of electroluminescence, focusing on electroluminescence of inorganic semiconductors, with eventually a discussion of the physics of modern LEDs. Electroluminescence is in general the process through which light is emitted when a current is flown through a material. Note that it might be argued that incandescent bulbs (the “Edison” bulb) are electroluminescent, but in that case the current flow is heating the material and light emission is only due to the filament high temperature: it is therefore more correct to speak of electroluminescence when the current flow is directly responsible for the light emission mechanism. The first report of electroluminescence was made in 1907 by H.J. Round, working for the Marconi Company [1]. What he did was to bias a piece of silicon carbide (at that time named *carborundum*) and to observe light of various colors depending on where he would put the electrodes and on voltage. He did not at that time understand the phenomenon. Twenty years later, Oleg Losev, a young Russian working as a technician at the Nizhny Novgorod Radio Laboratory, made tremendous progresses in the experimental observation and understanding of silicon carbide light-emitting diodes [2]. In particular, he filed a patent in 1929 [3] including the following claim: “The proposed invention uses the known phenomenon of luminescence of a carborundum detector and consists of the use of such a detector in an optical relay for the purpose of fast telegraphic and telephone communication, transmission of images and other applications when a light luminescence contact point is used as the light source connected directly to a circuit of modulated current.” This is truly incredible: a 26-year-old technician without much of a formal education in physics patented in 1929 the high-rate transmission of data by electrically modulating a semiconductor light source! The visionary papers and patents of Losev remained, however, very little known for decades [4]. In the 1940s, a better mastery and understanding of semiconductors led to the first p–n junction [5], and subsequently to the first transistor [6]. The first LEDs based on well mastered p–i–n junctions could thus be elaborated and improved.

Going back to the basics, a semiconductor is a material whose conductivity can be modulated through introduction of impurities (called dopants). Inorganic semiconductors are crystals such as Si, GaAs, InP, GaN, with energy bands for electrons. The highest occupied energy band is called the valence band and is full of electrons for an undoped semiconductor, while the next band higher in energy is called the conduction band and is completely empty in an undoped semiconductor (Fig. 1). The energy difference between the minimum of the conduction band and the maximum of the valence band is called the band gap of the semiconductor. The light-emission process in a semiconductor is quite simple: when there is an electron

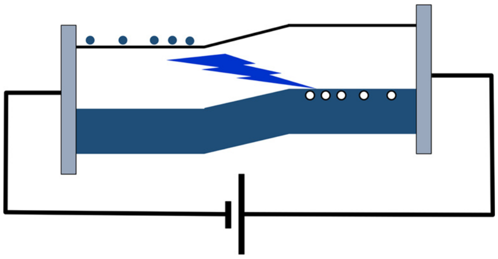

Fig. 2. Schematics of a p–i–n semiconductor junction. The semiconductor on the left is n-doped, i.e. has extra electrons that are in the conduction band, while the semiconductor on the right is p-doped, i.e. it has holes in the valence band. The non-doped region between the two doped regions sustains the electric field due to the junction. When a bias is applied as indicated, electrons can flow from the left to the right (meaning that holes are actually moving from the right to the left), so that electrons and holes can recombine and thus emit photons in the intrinsic region of the semiconductor. This is the principle of a semiconductor light emitting diode.

in the conduction band and an empty state in the valence band (i.e. a lack of electron, called a hole), the conduction-band electron can relax to fill the empty state in the valence band, the energy difference (i.e. the band gap) being released as an emitted photon (Fig. 1). In other words, the electron and the hole recombine to emit a photon. This process happens in most semiconductors, with some notable exceptions called indirect semiconductors such as silicon or germanium (for which the photon emission process is not directly allowed, so that it is extremely inefficient). To make a semiconductor LED, one thus needs to bring at the same place in the material electrons in the conduction band and holes in the valence band. This is where doping becomes important. While an intrinsic semiconductor is essentially an insulator (the electrons in the valence band cannot move at all as there are no free states to allow any electronic movement), semiconductors can be doped, in two ways. When impurities are introduced in the crystal with an extra electron per atom, these extra electrons end up in the conduction band. For instance, in a GaAs crystal, replacing some Ga atoms by Si atoms will lead to n-type doping, i.e. presence of electrons in the conduction band. Conversely, impurities lacking an electron can be added, leading to p-type doping, i.e. presence of holes in the valence band. An important point is that dopants are minority atoms in the crystal: one doping atom out of one million regular atoms can be enough to yield a large electrical conductivity. It is thus crucial to be able to master the doping level to tailor the electrical properties of semiconductors. It is precisely this mastery that started in the 1940s and 1950s and led to the microelectronics and optoelectronics revolutions. Coming back to LEDs, the basic structure to emit light from a semiconductor structure is thus to have in the same material a stacking of n-type (electrons in the conduction band) and p-type (holes, i.e. lack of electrons, in the valence band) material so that under electrical bias, electrons and holes (flowing in opposite directions as a hole moving leftward in the valence band is really all electrons in the valence band moving rightward) meet at the p–n junction and recombine to emit photons (Fig. 2). Once this was understood by the research community [7], what was needed to be done was clear: be able to produce high-quality crystals with well-mastered p-type and n-type doping. Thus the first GaAs infrared LED was demonstrated in 1962 [8], soon followed by the first visible LEDs by various groups. In particular, N. Holonyak, then a researcher at General Electric, promoted the GaAsP alloy that allowed him to demonstrate the first visible semiconductor diode laser [9]. It is important mentioning N. Holonyak, who among others has contributed to many progresses in the understanding and mastery of semiconductor light emitters. One very important point is that at a time when, due to lack of material quality, the first semiconductor LEDs were emitting extremely dim light, with efficiencies (electrical to optical power conversion ratio) of fractions of a percent, Nick Holonyak predicted that semiconductor LEDs would someday replace all light bulbs for general lighting applications in a 1963 issue of the Reader's Digest. On what basis did he make this forecast? What Holonyak realized is the following: as had been very well known, incandescent light bulbs emit roughly as black-body emitters, in other words they emit a spectral curve that is linked to the filament temperature: when the temperature becomes higher, the emission spectrum shifts to shorter wavelengths. For the most efficient incandescent bulbs, most of the emitted light is in the infrared, and thus does not serve the purpose of lighting, but rather of heating. The electrical power to visible optical power conversion is thus intrinsically limited, to something like 5%. For semiconductor LEDs, the physics is totally different: potentially 100% of the electrical power can be converted to optical power, with a well-controlled emission wavelength (remember: the band gap yields the energy and hence the wavelength of the emitted photon). One can thus imagine a device with LEDs emitting at various visible emission wavelengths, each with a very large (ideally unity) conversion efficiency, so that visible white light (or for that matter any chosen mixture of visible colors) can be emitted with no heat losses (Fig. 3). This in principle should work, the only issue being to reach the technological maturity to build such highly efficient LEDs at various chosen wavelengths. This quest kept semiconductor researchers busy for the next decades, and eventually led to the 2014 Nobel Prize.

In the 1960s and 1970s, the growth of high-quality semiconductors progressed at a large pace, allowing one to increase the performance of LEDs. First commercial applications were soon found, for instance as indicator lamps (for which small emitters working under low dc bias and emitting little light were required: perfect applications for early visible LEDs) or as infrared remotes (in that case, the spectrally narrow emission line at wavelengths invisible to the eye as well as the possibility to directly modulate the light output through electrical bias modulation fit perfectly the abilities of semiconductor LEDs). To be more precise, the better crystal quality (i.e. reduction in crystal imperfections such as point defects and dislocations) that was brought by modern crystal elaboration processes (high-quality epitaxy techniques such as liquid phase

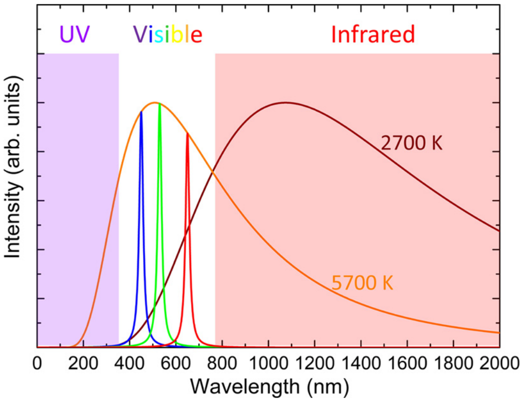

Fig. 3. These curves show the emission from the sun (black-body-like radiation at 5700 K) and from a light bulb (curve at 2700 K, which is about the maximum filament temperature for a conventional light bulb). One sees that sunlight peaks in the visible region (400–800 nm), while still emitting a sizeable fraction of light in invisible parts of the electromagnetic spectrum (ultraviolet below 400 nm and infrared above 800 nm). On the opposite, the incandescent light bulb has most of its intensity in the infrared region, thus emitting mostly heat and relatively little visible light. The three narrow red–green–blue emission lines show the kind of very efficient lighting solutions that LEDs could provide with high efficiency, while mimicking the sun's visible spectrum.

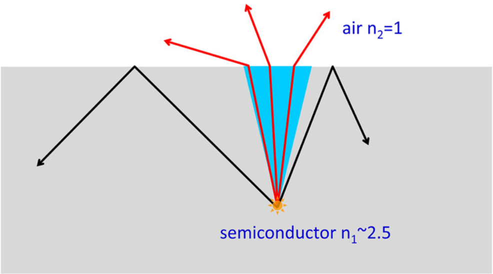

Fig. 4. Schematics of total internal reflection in a GaN sample: the light emitted from a point source inside the semiconductor is refracted at the semiconductor–air interface, due to the refractive index difference. Above a critical angle given by the Snell–Descartes law, light is totally reflected within the semiconductor. This is a critical issue to overcome if one is to design a semiconductor LED for which light is efficiently emitted outside the semiconductor chip.

epitaxy and later molecular beam epitaxy (MBE) and metal–organic vapor phase epitaxy (MOVPE)) allowed one to reduce the non-radiative recombinations (i.e. energy loss for electrons and holes through emission of heat and not photons), thus increasing the internal recombination efficiency. Technological progress in doping and contacting of semiconductors allowed one to reduce access Joule losses in the electrical injection process.

One major issue was the contribution of photon extraction to the overall losses. This is due to total internal reflection in a high-index material. As is known from the Snell–Descartes law, beyond a critical incidence angle ($\sin^{-1}(n_1/n_2)$), photons undergo total internal reflection at the interface between two media of different refractive indices. While this is good for some applications of prisms, or for optical fiber communications (the light cannot intrinsically leave the core of the optical fiber due to total internal reflection), this is bad for semiconductor emitters that have a large refractive index (for instance 3.5 for GaAs) and need to emit their photons in air eventually (Fig. 4). If nothing is done to extract light from the semiconductor, emitted photons are mostly internally reflected and eventually reabsorbed by the semiconductor chip or the contact metal for instance, and never make it to the outer world to serve as useful lighting photons. This is a severe problem: one can easily calculate that, for a GaAs emitter, only 2% of the emitted photons go through at their first encounter with a GaAs/air interface. Many strategies were used to tackle this problem, including roughening the surfaces (which enhances the probability of extracting photons at an interface), thinning the semiconductor chips (for correctly chosen chip thicknesses below the wavelength of interest, interference effects increase the light extraction efficiency), all this while maintaining other performances of the LED device (electrical injection and radiative recombination efficiency) and being compatible with low-cost mass production. It turns out that in the 1990s and 2000s many progresses were made, with eventually extraction efficiencies reaching more than 80% [10].

So it seems that most technological issues concerning the efficiency of semiconductor LEDs could be solved, and the early dream of N. Holonyack could become true. The only problem was that while tremendous progresses were made on red and yellow LEDs based on AlGaAsP compounds, researchers very early understood that in order to produce white light, what was needed was a blue LED. Indeed, a blue LED could be mixed with other visible LEDs to produce white light. Another possibility could be to produce blue or ultraviolet (UV) LEDs to then excite phosphors emitting white light (similarly to fluorescent tubes for which a mercury-containing vapor emits UV light under electrical excitation to then excite phosphors – the whitish powder found on the inner surface of the tubes – which in turn emit white light). Despite many attempts in the 1960s and 1970s, the emission yield for blue LEDs remained extremely low compared to their red and yellow counterparts. And this is where the three recipients of the 2014 physics Nobel Prize stepped in.

3. The blue LED, brief story of a revolution

Among the candidates to make a blue or UV LED, GaN was early remarked. With a bandgap of 3.4 eV (corresponding to an emission wavelength of 365 nm, i.e. in the near UV), it could be the right choice to make short-wavelength LEDs. Notable early attempts by Maruska, Pankove and coworkers at RCA did allow for some progresses in the early 1970s [11], but they could never reach large efficiencies. Similarly, Isamu Akasaki, at the time working for Matsushita (mother house of Panasonics), managed to fabricate a GaN LED grown by MBE with a conversion efficiency of 0.12% [12], at that time a world record, but much too low to be useful. The problems with GaN were recognized early. One problem was that the grown crystal quality was too low, with many dislocations, point defects and defects at the interface with the growth substrate. Indeed, unlike GaAs or InP for which high-quality boules of the material could be elaborated and prepared as substrates for the epitaxy of LED structures, high-quality bulk GaN boules could not be grown (and, as a matter of fact, they still cannot be in 2017, despite progresses in the field of small size GaN substrates), so that GaN growth had to be done on other substrates (meaning crystals that do not have the same lattice parameter as GaN, thus yielding growth defects when attempting the epitaxy of GaN on such heterosubstrates). Most importantly, the p-doping of GaN could not be done, i.e. the candidates as impurities to dope GaN p-type did not work experimentally. The fact that the many growth defects tended to result in a large uncontrolled n-type doping surely did not help (remember that p-doping consists in removing electrons from the crystal through the dopants, if there are already many excess electrons in the conduction band due to uncontrolled n-type doping, p-type doping becomes even more difficult).

In 1981, Akasaki left Matsushita to join Nagoya University and start a new project on the epitaxy of GaN on sapphire by MOVPE. This was a new growth technique for GaN, and Akasaki wanted to give it a try. One must say that at that time, the research on GaN as a semiconductor for LEDs was quasi abandoned: the consensus was that many had tried and failed, and especially that p-type doping was hopeless. Akasaki hired in 1982 a young student, Hiroshi Amano (22 years old at the time), with the assignment to build a MOVPE reactor and optimize the growth of GaN on sapphire. MOVPE is a growth technique in which elementary atoms of the target crystals are sent as organic precursors on a heated substrate. Upon reaching the substrate, the organic molecules decompose, leaving the chosen atoms to form the crystals while C and H atoms leave the growth substrate. Typically, for the growth of GaN, nitrogen is brought by NH_3 while gallium is brought by $Ga(NH_3)_3$. The choice of sapphire as a substrate was motivated by the fact that sapphire has the same lattice symmetry as GaN (hexagonal), but with a huge lattice mismatch between the two crystals of about 14%. Due to this lattice mismatch, so far growth of GaN on sapphire led to the formation of macroscopic defects, bad surface quality and strong undesired residual n-doping. A first breakthrough by Akasaki and Amano was to achieve a good-quality layer of GaN on sapphire [13]. This was achieved by inserting an AlN layer grown at low temperature at the onset of growth on sapphire. Note that this was completely counterintuitive for epitaxial crystal growers at the time: the paradigm was (and still is in most situations) that a growth at high temperature would lead to a better crystal: indeed, at large temperature, atoms are more mobile on the surface of the crystal and are thus more likely to be incorporated at the “right spot” and thus form a high-quality crystal. In the new process developed by Amano and Akasaki, a thin (about 30 nm) AlN layer is grown at 500 °C on sapphire, which is a very low growth temperature for AlN. The grown AlN is then of very bad quality, polycrystalline, but upon heating to 1000 °C (the normal growth temperature for GaN), the grown AlN rearranges itself so as to form microcrystallites on which GaN can grow with a good enough quality. This allowed for the first time to grow high-quality GaN epitaxial layers with a good surface quality and a low residual n-doping. The issue of p-doping, however, remained unsolved. Akasaki and Amano were investigating this problem, with now the notable advantage of using GaN crystals which were not heavily n-doped from the start. They in particular knew which dopants were likely good candidates, for instance Zn or Mg from the VI column of the Mendeleev table, which would be atoms likely to capture an electron and thus leave a hole in the valence band, if substituted to Ga in the GaN crystal. But growing GaN doped with either Zn or Mg would not give p-type material. While investigating the phenomenon, Amano performed cathodoluminescence on doped samples, a technique in which an electron irradiation excites the luminescence of the studied sample, which can then be analyzed. Amano serendipitously observed that the more the GaN sample would be irradiated, the more its light emission would change. This suggested that electron irradiation unexpectedly was somehow changing the electronic properties of the crystal. He then probed again in electronic measurements the samples that had been irradiated by the cathodoluminescence electron beam and discovered that the irradiated samples indeed showed p-type conductivity, in particular for Mg-doped samples [14]. This naturally led to the demonstration of the first GaN LED functioning indeed as a p–n junction with well mastered n and p doping. This first demonstration was however hardly practical: first as the electron irradiation treatment was difficult to use in an industrial context for production of LEDs, and second as it was merely a GaN only LED, so that the emission color could not be adjusted.

At this point, Shiji Nakamura steps in the history of efficient blue LEDs. He is an engineer (without a PhD degree) working for the Nichia company since 1979. After years of working on GaAs devices, in 1989 he managed to convince his boss to work on GaN with the goal of developing efficient blue LEDs. As he tells the story, one of his main motivations was that at that time, GaN was a confidential topic and thus not too competitive (while ZnSe was the trendy material for

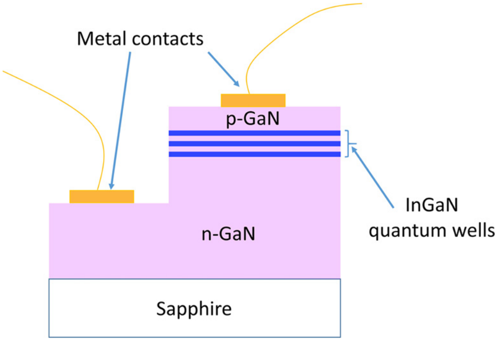

Fig. 5. Basic principle schematics of an InGaN/GaN LED. The semiconductor material is grown on a sapphire substrate. InGaN quantum wells are grown between the n-doped and p-doped parts of the junction. By choosing the composition of the InGaN ternary alloy as well as the thickness of the quantum wells (a few nanometers), one can design the emission wavelength of the LED. The semiconductor is then etched so that a metallic contact can be deposited on the n-doped part of the junction. Real-life efficient LEDs are based on this principle, but with much more complex design, notably to enhance the photon extraction efficiency.

research on blue semiconductor emitters) so that he would be able to at least publish some papers and present his work at conferences despite the fact that he was practically working alone on the topic at Nichia. His first contribution to the topic was the invention of two-flow MOVPE [15]. Contrarily to conventional MOVPE, in this process a neutral gas (H_2 and N_2) is sent towards the growth wafer so as to flatten the active gases (NH_3 and $Ga(CH_3)_3$ sent sideways) on the growth wafer. This lead to improvements on the homogeneity and quality of the grown GaN. Improving on the Amano/Akasaki findings, he then showed that high-quality GaN could be grown on sapphire using low-temperature-grown GaN (instead of AlN) [16]. Most remarkably, he then showed that the activation of Mg doping could be reached by a simple thermal annealing (instead of electronic irradiation, as demonstrated by Amano and Akasaki) [17], which was a major step for possible mass production of GaN-based devices. Most importantly, Nakamura and coworkers managed to understand the cause for the required activation of Mg dopants: during the MOVPE growth, Mg–H complex are formed, which inhibits the possibility for Mg to accept an electron and thus to create a hole in the valence band. By electronic irradiation or annealing, the hydrogen atoms are released from the crystal and thus allow Mg to act as an electron acceptor [18]. Things went then very fast for Nakamura; with the mastery of high-quality GaN epitaxial layers, he could then demonstrate the luminescence of high-quality InGaN layers grown on GaN (grown on sapphire), notably showing that the emission wavelength can be varied in the blue–violet range by changing the indium composition of the InGaN alloy [19]. Shortly after, he demonstrated the first bright InGaN/GaN LED emitting at 450 nm [20] which was in the same time commercialized by Nichia, and then the first violet laser diode [21], emitting at 417 nm, which then led to the Blu-ray technology.

After the key inventions by Amano and Akasaki, and then by Nakamura, blue InGaN/GaN LEDs continued progressing in efficiency while production costs were reduced (see Fig. 5 for a simple GaN LED schematics). White LEDs are then obtained by surrounding the blue LED with a phosphor that partially absorbs the blue and reemits at longer wavelength: the mixing of the remaining blue and the phosphor emission yields white light, the quality of which depends on the phosphors that are used.

The history of this Nobel Prize winning invention is particularly interesting for several reasons. One can first notice that these inventions were made by small teams, with limited resources, which is particularly noticeable for a technological invention. The inventors worked on a very confidential topic which was globally considered as a dead-end for the scientific community. The awarded results were published in applied physics journals such as *Applied Physics Letters* and the *Japanese Journal of Applied Physics*. While these are perfectly respectable publications, they do not have the prestige of *Physical Review Letters*, *Nature* or *Science*, in which most Nobel Prize discoveries are first published. It is also interesting to read about this history from the protagonists themselves and to note that Amano and Akasaki, on the one hand [22], and Nakamura, on the other hand [23], do not tell it in exactly the same way.

4. LEDs lighting and potential for energy savings

The Nobel committee awards its prize based on the benefit to mankind of the invention, in that case potential for energy savings for lighting. It is not my purpose to discuss extensively the history of lighting and how LED lighting (also called solid-state lighting) fits in. It can however be briefly recalled that the invention of the incandescent light bulb during the second half of the 19th century was a revolution in the sense that it allowed to have a reliable source of light, which was much more efficient and less hazardous than the oil lamp. The efficacy of a lighting device is expressed in units of lumen per watt. The lumen is the physical unit that measures the light power convoluted by the response of the human eye. The definition is that at the peak sensitivity of the eye (555 nm), 1 W of light corresponds to 683 lm. In other words, the maximum efficacy of a lighting device is 683 lm/W, for a device emitting strictly at 555 nm and with no losses. Evidently, a white light source will have a lower lighting efficiency as it will include wavelength for which the eye response is not optimum, and an ultraviolet or infrared light-emitting device will have a lighting efficiency of 0 lm/W. Note that the input

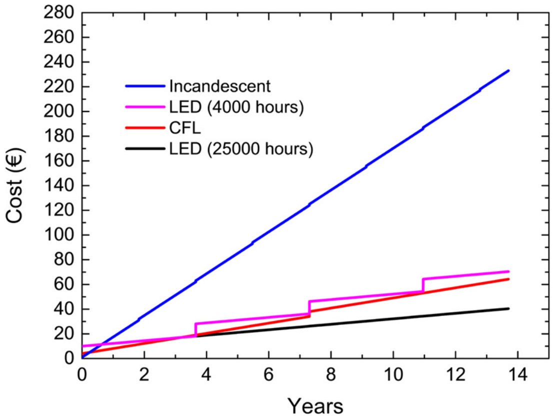

Fig. 6. Total cost over a few years for a domestic lighting system used 3 hours per day. Despite their low unitary cost, incandescent bulbs are much more costly than CFL or LED bulbs. The competition between LEDs and CFLs is dependent on their actual lifetimes, a LED with a long-enough lifetime being indisputably the most economical solution.

power can correspond to electrical power, or to chemical power, which allows us, for instance, to compare electrical devices and oil lamps. It is interesting to note that the lighting efficiency of an oil lamp is between 0.1 and 1 lm/W, while that of an incandescent light bulb is 15 lm/W [24]. This in itself shows how much of a revolution the incandescent light bulb has been in terms of energy savings for lighting. The other striking feature is that incandescent light bulb technology has been very constant for many decades. It has been so constant that it has become custom to express the lighting power of a bulb in watts, which in fact corresponds to the lighting power of an incandescent bulb consuming so many watts of electrical power. As people are not (yet) familiar with lumens, this led manufacturers to display strange equations on their so-called energy-saving bulbs, such as 11.5 W = 75 W, meaning: with 11.5 W of electrical power, you will get as much visible light as you would get with a traditional incandescent light bulb consuming 75 W.

One has to note that an incandescent light bulb (made of a tungsten filament heated at about 3000 K) converts only about 5% of the electrical power into visible light, the remaining power being emitted as heat (this heat production is however not necessarily a loss, as it contributes to the overall household heating when required). One thus sees the potential progress possible by switching to a more efficient lighting technology. In industrial countries, lighting amounts to about 20% of total electrical consumption.

Fluorescent tubes, and their more recent avatars, i.e. compact fluorescent lamps (CFLs), are indeed more efficient than incandescent bulbs, with an efficacy of about 80 lm/W. While fluorescent tubes have been used for many years in industrial and professional contexts, they were not fully adopted by individual customers due to their time lag before turn-on, low color quality (both these issues have been solved along the years), but also due to the fact that their actual lifetime is usually lower than what is claimed. These bulbs contain mercury and thus are hazardous if broken and require proper recycling. Interestingly, incandescent bulbs have recently been banned in numerous countries to promote energy savings. For instance, in Europe, incandescent light bulbs were progressively banned between 2009 and 2012, at a time when the only alternative solution consisted of CFL bulbs. Eventually, consumers turned to halogen bulbs for domestic lighting (a sort of incandescent bulbs with slightly better energetic yield, which was oddly not banned). Despite many attempts at finding official information related to energy savings induced by this incandescent bulb ban in Europe, I could not find any, which at least questions the relevance of this ban.

In the last few years, LED light bulbs have become commercially available at reasonable prices and give out light that is comfortable to the eye and bright enough. Despite the larger price of the bulb itself compared to equivalent halogen lamps, LED bulbs for general domestic lighting are becoming popular.

One might wonder whether it is now economically relevant to switch to LED bulbs. Of course, this question is not general and can yield different answers for different situations. Let us take the following example: compare an incandescent light bulb, a compact fluorescent lamp and a LED bulb to give out 1500 lumen (i.e. the equivalent of a 100-W incandescent light bulb). From what I could find at my local retail store, I could pick a 4-€ CFL bulb, requiring 25 W of electrical power and with a claimed lifetime of 8000 h, or a 10-€ LED bulb, requiring 13.5 W of electrical power and with a claimed lifetime of 25000 h. I compare those two bulbs with a hypothetic 1-€ incandescent bulb requiring 100 W of electrical power and a lifetime of 2000 h (hypothetical as they are no more sold in Europe), and I assume a cost of electricity of 0.15 € per kW·h. As can be seen in Fig. 6, for a domestic household using the bulb three hours a day, it can be seen that the LED and CFL solutions are much cheaper than the incandescent bulb solution. As the average customer knows well, the actual lifetime of a device is not always as large as the manufacturer's claim. If the actual LED lifetime is 4000 h, the LED solution is still comparable to the CFL solution (and has the advantage of being mercury free). Note that the difference in cost between CFL and LED solutions is at most 2 € per year. For a commercial or industrial customer, using a bulb 12 h a day, Fig. 7 shows how advantageous the LED solution can be. In that case, the actual lifetime is crucial: if the real lifetime of the LED bulb is

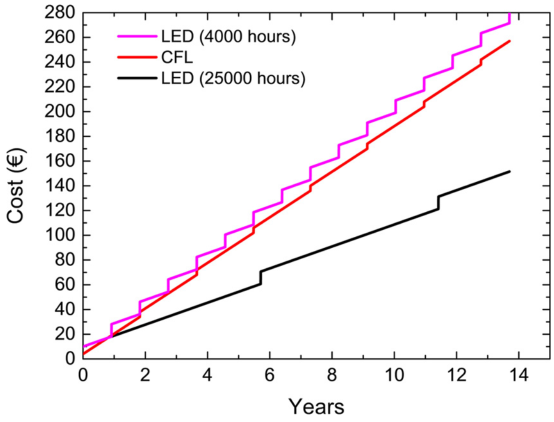

Fig. 7. Total cost over a few years for a commercial or industrial lighting system used 12 h per day. Incandescent bulbs are not represented on this graph as they are without discussion way too expensive (and they have not been used for such applications for many years). LEDs are the best solutions under the condition that their lifetimes is reasonably high. It thus appears clearly that the lifetime or replacement time of the bulbs is a key issue, at least as important as the consumption, in the competition between various so-called "energy saving" bulbs.

4000 h, the LED and CFL solutions seem to be equivalent, but the plot in Fig. 7 does not take into account the maintenance cost (i.e. the manpower to check for dead bulbs and to replace the bulbs).

Overall, the LED solution is evidently economically relevant, despite the larger price of the individual bulb. As one can see, from the previous analysis, the lifetime issue is key. It turns out that the lifetime of the semiconductor LED chip itself is very large, actually so large that it is difficult to have a direct customer feedback on this issue (more than 50,000 h, i.e. 6 years of continuous operation). But the LED lightbulb is not made only of the semiconductor chip: it contains electrical drivers that convert the AC 220 V (or 110 V) into continuous low voltage (around 3 V), which is suitable for the LED. Often the failure comes from these built-in drivers (or also from breaking of the metallic contacts to the LED chip). The lifetime of a LED bulb will thus usually be linked to the care (and cost) that the manufacturer has put in the packaging and in the electronic drivers.

There are still issues with the use of LEDs. As just discussed, LEDs work under continuous low-voltage current. In this respect, it might make sense to equip all buildings with a DC low-voltage (say 12 V) circuit that could drive LEDs without needing an AC–DC converter. But that would require major changes in the way domestic electrical circuits are conceived. LEDs are constantly evolving and getting better (i.e. with better lighting performances, but also with increased functionalities), yet, their lifetime is an important marketing asset. There is here a paradox: the LEDs we buy today will be outdated by new products long before they fail, meaning that their actual lifetime will be much shorter than it should just because they will be eventually be replaced by better LEDs (which overall will improve the customer experience, but at a larger cost due to premature bulb replacement). In particular, the difference in timescales for the building industry and the timescale of progress for LEDs is a major issue: how do you build a building supposed to last for at least thirty years with a lighting solution that makes significant technological progresses each year? Following further this line of reasoning, there is another obvious economical paradox: modern LED factories are very expensive to fabricate but are still profitable due to the very large production they are capable of. If the target of the LED industry were to replace all lighting bulbs by LED bulbs that each last 50,000 h (i.e. 45 years for a domestic use of 3 h a day!), the LED manufacturers would soon be out of business. Their business plan is thus probably that visible LEDs will be needed for an increasing number of applications (which they already are, for instance for backlighting of flat screens, for the automotive industry...) and will be often replaced despite their long lifetime. Indeed, with the advent of LED lighting, with its low maintenance and cheap operation, new applications are thought of, for instance lighting continuously highways at night for safety reasons (which by the way goes against the ecological concern to reduce the overall illumination at night to avoid perturbation of wild life). Another new application concerns LED illuminated industrial horticulture. One might at first think that it is an ecological aberration to grow plants under artificial lighting, but one has also to think about the fact that growing directly in large cities, or growing directly in countries with poor sun illumination (and ideally a large local supply of renewable energy) avoids transport cost (and the related pollution) of fresh vegetables and fruits. Overall, LED lighting is indeed a revolution as these new sources are economical, very bright and reliable, and still constantly progressing. Whether LED lighting will actually lead to an overall reduction in energy consumption for general lighting is not clear: each bulb might have lower running costs, but there might well be many more of them. New applications of LEDs and new use of lighting will certainly appear, although it is no clear yet in what way.

A final note: while I showed that LED bulbs allow for small but sizeable economies for domestic use, larger economies for commercial or industrial users, and overall questionable global economies due to a probable increased use of lighting concomitant with running cost reductions, one has to be aware of the fact that this applies to industrial countries. In particular, about 1.3 billion people on earth are still nowadays off-grid, meaning that they do not have access to the electrical distribution network. Many of them thus still rely on kerosene lamps for lighting. It is estimated that 3% of petroleum production is used for lighting. Kerosene lamps amount totally for 3% of total lighting, yet are responsible for 20% of CO_2 emissions due to lighting. This is not only an ecological problem, but also an economical one: when oil prices rise, lighting becomes unaffordable for these populations. It is finally a social problem as it is well known that children education remains limited in populations with a scarce access to domestic lighting. LEDs are particularly well suited to deal with this issue: they work on DC low voltage, as do solar panels and batteries, and they consume little energy. An application of LEDs that really brings progress is thus to equip off-grid populations with LED light bulbs connected to solar panels and batteries: these cheap equipment requiring little maintenance and thus with negligible running costs allow one to secure lighting for populations who badly need it (see for instance the non-profit organization Light Up the World for more information on the topic, www.lutw.org).

In conclusion, LEDs are now mature for lighting applications, are more economical than competing solutions and are still improving. Whether this will lead to an actual decrease in energy consumption is highly dubious, my personal forecast being that it will lead to overall more lighting, possibly more comfort in everyday life, and certainly new applications and thus new consumer's needs, but eventually little impact on energy consumption in industrial countries.

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