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LEDs: The new revolution in lighting / Les LED : la nouvelle révolution de l'éclairage

Foreword

The award of the 2014 Nobel Prize for Physics to Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura "for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources" illustrates the worldwide societal impact of light-emitting diodes (LEDs). It also emphasizes the importance of lighting throughout the history of human societies, relying on ever-improved lighting technologies and acting as a lead user when new energy sources emerged, leading to fast-increasing light production with improvement of service and cost decrease.

Nitride-LED-based lighting, with a 100% theoretical power conversion efficiency limit and novel light quality capabilities, is in line with this historic evolution of lighting technologies enabling new implementations and higher lighting use along history.

Due to the many high-impact effects of the revolution brought by LED lighting compared to former lighting solutions, it is therefore timely to devote an issue of the *Comptes rendus Physique* to the exploration of the various aspects of the LED lighting revolution.

A first paper by Claude Weisbuch [1] explores the long history of lighting, a major human need throughout the ages, and the serial revolutions brought along by technological advances: the oil lamp, the candle, the gas and kerosene lamps, electrical light bulbs, fluorescent tubes, and finally LEDs. A remarkable feature of this history is that lighting has continuously been at the leading edge of many energy revolutions, the most recent ones being the successive appearance of gas, petrol, and electricity.

At the origin of the LED lighting revolution was the invention of the high-efficiency blue LEDs based on nitride semiconductor materials. The invention, development, and status of the blue LEDs is reviewed by Daniel Feezell and Shuji Nakamura [2]. They detail the long road from the first production of device-quality GaN to the present high-efficiency LEDs, which incorporate many advances such as heterostructures and quantum wells, alloy active materials, low-resistivity contacts, light-extracting structuration of LED chips, etc. They also discuss the remaining scientific and technological roadblocks to reach the physical limits of nitride devices. They end up with a discussion of a possible next technology: laser-based lighting.

The transition to high-efficiency solid-state lighting (SSL) made possible by LEDs will enable significant reduction in electricity consumption. The state of the art is reviewed by Paul Morgan Pattison, Monica Hansen, and Jeffrey Y. Tsao [3], and they analyze the various sources of losses in lighting systems and their mitigations. They also discuss applications of SSL beyond the simple gain in efficacy made possible by the properties of LED light.

The association of high-efficiency LEDs and small low-cost solar panels will have a large impact in both developed and developing economies – in the latter by bringing light to those many parts of the world where there is no electrical grid today. This is part of a worldwide trend towards individual or local pico-power off-grid systems that, associated with other super-efficient appliances, will bring major changes in the quality of life for more than a billion people. The design and impact of these systems is discussed by Peter Alstone and Arne Jacobson [4].

Visible light is produced by LEDs with highly-controllable color rendering. Therefore, a new era in light quality opens up, with a large variety of applications depending on the environment and their implementation – be it in museums, commercial displays, architecture, hospitals, plant factories, etc. At issue is the rendering of natural light by LED luminaires. Marc Fontoynont [5] discusses the present performance as well as the opportunity to generate natural light through LED luminaires.

While classic light sources have only a few choices of stable and reproducible colors, LEDs with their versatile spectra open the question of color rendering, and then first of color characterization. Aurélien David and Lorne A. Whitehead [6] describe the recent progress in color science and color rendering norms triggered by the appearance of LEDs.

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In the limited space of this dossier, we could not accommodate all the interesting aspects of lighting. By focusing on lighting applications of LEDs only, we left out the major field of displays, with the recent advances in organic LED (OLED) displays for phones and TVs [7], as well as the fast-developing field of micro LEDs [8].

The interaction between lighting, health, and well-being is strongly impacted by the spectral properties of LED lighting, with possible beneficial and adverse effects. Their exploration has begun, including proposing solutions to seasonal affective disorder (SAD) or mitigating the disruption of circadian cycles [9]. SAD is the depressed mood originating in the lack of light during the winter months in northern or southern regions of the globe. A remarkable case is that of treatment of personnel in polar base stations, for which blue-enriched white light counteracts the circadian misalignment during the polar winter [10]. On the other hand, disruption of circadian cycles has become a major health issue, with the development of blue light sources such as LED lamps and displays, which can affect human clocks, in particular in the evening and at night [9].

Another highly-discussed topic is that of the risk to the retina induced by the blue light contents of LED lamps [11,12]. This debate is complex, in part due to the difficulty of relating dangers identified on lab animals to hypothetical dangers for humans [13], and to the evolving norms used to assess risk [14,15].

Regarding the latter, Sliney [14] gives a history of the state of affairs: "When the initial IESNA (Illuminating Engineering Society of North America) and IEC standards were developed, essentially all LEDs had very low power ratings and no one seriously considered any potential hazards. LEDs were hardly mentioned in the initial lamp safety standards and when they were mentioned it was recognized that all LEDs were exempt. ICNIRP (International Commission on Non-Ionizing Radiation Protection) issued a statement in 2000 that there was no significant optical hazard from LEDs [ICNIRP 2000]. Most individual LEDs, similar to the typical low-wattage tungsten indicator lamps that they replaced, were actually very simple to test for spatially averaged radiance".

On modern norms, Martinsons writes: "IEC 62471 defines two different criteria to determine the viewing distance. Light sources used in general lighting should be assessed at the distance corresponding to an illuminance of 500 lx. Other types of light sources should be assessed at a fixed distance of 200 mm. For LED components, there is no ambiguity in the distance since LED components are not used per se in general lighting. In this case, IEC 62471 requires using the distance of 200 mm."

One sees a contradiction here: should we apply the norms of general lighting to LED lamps, or should we consider them as LED "components" – which obviously leads to very different conclusions?

In the most typical use of regular lighting conditions, we conclude by referring to guidance by the Swiss safety agency's information document [16], and to the US department of energy's safety sheet [17]. Their conclusion, consistent with those of many studies, are: 1) warm color-temperature lamps are safe; 2) high brightness lamps are to be used at a distance larger than 20 cm; 3) colored lamps, in particular blue-enhanced ones, are to be used with caution; 4) analysis of risks, both in laboratory conditions or in standard use conditions should be pursued.

Keeping in mind the need to properly use LED-based lamps, we are witnessing a new revolution in lighting, of similar proportion to that brought by electrical lighting. It should benefit many aspects of life.

Avant-propos

La remise du prix Nobel de physique 2014 à Isamu Akasaki, Hiroshi Amano et Shuji Nakamura « pour l'invention de diodes électroluminescentes bleues efficaces qui ont permis de produire des sources de lumière blanche brillantes et économes en énergie » illustre l'impact sociétal mondial de la lumière. Ce prix met également l'accent sur l'importance de l'éclairage dans l'histoire des sociétés humaines, qui va en s'appuyant sur des technologies toujours améliorées, en étant utilisateur principal des nouvelles sources d'énergie chaque fois qu'elles émergent et en apportant à chaque fois un meilleur service et une réduction des coûts.

L'éclairage par les LED basées sur les matériaux nitrure, avec une limite d'efficacité de conversion théorique de 100 % et de nouvelles capacités de qualité de lumière, s'inscrit dans cette évolution historique des technologies d'éclairage permettant de nouvelles applications et le développement de la consommation d'éclairage.

En raison du fort impact de la révolution apportée par l'éclairage LED par rapport aux anciennes solutions d'éclairage, il est apparu opportun de consacrer un numéro des *Comptes rendus Physique* à l'exploration des différents aspects de la révolution de l'éclairage par LED.

Un premier article, par Claude Weisbuch [1], explore la longue histoire de l'éclairage, un besoin humain majeur à travers les âges, et les révolutions en série apportées par les avancées technologiques : lampe à huile, bougie, lampes à gaz et kérosène, ampoules électriques, tubes fluorescents et enfin LED. Une caractéristique remarquable de cette histoire est que l'éclairage a toujours été à la pointe de nombreuses révolutions énergétiques, les plus récentes étant les apparitions successives du gaz, de l'essence et de l'électricité.

À l'origine de la révolution de l'éclairage par LED, on trouve l'invention des LED bleues à haut rendement à base de matériaux semi-conducteurs nitrurés. L'invention, le développement et l'état de l'art des LED bleues sont passés en revue par Daniel Feezell et Shuji Nakamura [2]. Ils détaillent la longue route entre la première production de GaN de qualité et les LED actuelles à haut rendement, qui intègrent de nombreux progrès tels que les hétérostructures et les puits quantiques, les matériaux actifs en alliage, les contacts à faible résistivité, la structuration des puces LED pour l'extraction de lumière, etc. Ils discutent également les obstacles scientifiques et technologiques restants pour atteindre les limites physiques des