‘No Blue’ White LED

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New Lighting—New LEDs

Aspects on light-emitting diodes from social and material science perspectives

Editors

Mats Bladh & Mikael Syväjärvi

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Contents

Foreword

The papers published in this volume were presented at *Sveriges Energiting 2010* (The Swedish Energy Parliament 2010) in Älvsjö south of Stockholm in March 16-17.

Sveriges Energiting is Sweden's largest scene for discussion of energy and climate related activities. It gathered about 2300 participants and had a broad range of energy related issues covered, such as transport, future energy systems, industrial energy, energy and climate, energy efficiency and many more, including several on lighting. One session was initiated and organized by me: "New Lighting—New LEDs".

I hope this kind of cooperation between lighting researchers will continue in the future. One step in this direction is Nordic Light Emitting Diode Initiative (NORLED), initiated by Professor Mikael Syväjärvi, Linköping University. The aim of the NORLED project is to develop an innovative and industrially feasible white LED technology for general lighting. The project consortium is composed of partners from Sweden, Denmark, Germany and Norway.

Linköping, September 2010

Mats Bladh

Head Authors

Monica Säter, Ph.D. candidate, Head of Lighting Design Department at Jönköping University, Jönköping, Sweden. Monica Säter's research focuses on the interaction between human, light, colour and space. Her research looks at methods of designing lighting in order to evaluate known and unknown users' lighting requirements from psychological, physiological and visual perspectives. The aim of the research is to evaluate design methods and technical options in the field of lighting design based on the psychological, physiological and visual responses of users.

Mikael Syväjärvi, Dr., Docent, IFM, Department of Physics, Chemistry and Biology, Linköping University, Linköping, Sweden. Mikael Syväjärvi's research since 15 years focuses on growth of new materials for energy and environment, such as fluorescent silicon carbide, cubic silicon carbide, aluminium nitride, and graphene. He is one of the founders of Senmat – Semiconductor Energy and Environmental Materials Initiative, which applies a production oriented research methodology.

Haiyan Ou, Dr, Associate Professor, Department of Photonics Engineering, Technical University of Denmark (DTU), Lyngby, Denmark. Haiyan Ou has a background on semiconductor devices and microelectronics. For more than 10 years, her research has focused on fabrication of advanced Si based devices using the state-of-the-art facilities at DTU Danchip. She has broadened her research interests in later years to improve the energy efficiency of light emitting diodes by implementing nanostructures like photonic crystals, surface plasmonics etc.

Satoshi Kaiyama, Professor, Department of Materials Science and Engineering, Meijo University, Nagoya, Japan. Satoshi Kamiyama has 24 years of experience in semiconductor optoelectronic devices, and has authored 170 papers. He had been working on the theoretical analysis, MOCVD growth and device processing of the short-wavelength semiconductor lasers made of AlGaAs, AlGaInP, ZnMgSSe and AlGaN systems. His recent research is on the white LED consisting of nitride-based NUV LED and fliorescent SiC substrate.

Mats Bladh, Dr, Docent, Department of Thematic Studies—Technology and social change, Linköping University, Linköping, Sweden. Mats Bladh has a background in economic history, and has been working at the interdisciplinary social science department of Thematic Studies at Linköping University for 15 years. He has written books, papers and reports on housing construction, housing finance, the postal service, the electricity supply industry, and path dependence. His research in later years has focused on energy efficiency, households and use of domestic electrical appliances, especially lighting.

Introduction: A Paradigmatic Shift?

Mats Bladh & Mikael Syväjärvi

Linköping University, Sweden

The LED and other light sources

The light-emitting diode for lighting purposes in homes and offices is a new light source. It is new in relation to other light sources. Basically there are two other sources, incandescence and discharge. The birth of a functioning lamp based on incandescence is associated with Edison in 1879 and its application in two centralized systems in 1882 in New York and London. However, the organic material used as filament made the lamp blacken with use. The take-off in diffusion came when a filament made of tungsten or osmium was introduced during the first decade of the 20th century.

The most common lamp among the discharge family is the fluorescent. This has been used widely in offices and contributed to improvements in energy efficiency due to its high lumen per Watt ratio. Its blue and cold light has made its popularity as home lighting limited in certain lighting cultures, even though substantial improvements in colour rendering has been made. The fluorescent has become a competitor to the metal incandescent lamp for residential purposes in the form of compact fluorescent lights. With internal electronic ballast, ordinary sockets and sometimes a pear-shaped bulb, it has been intentionally designed to replace the incandescent for the sake of improving energy efficiency of the lamp stock in use.

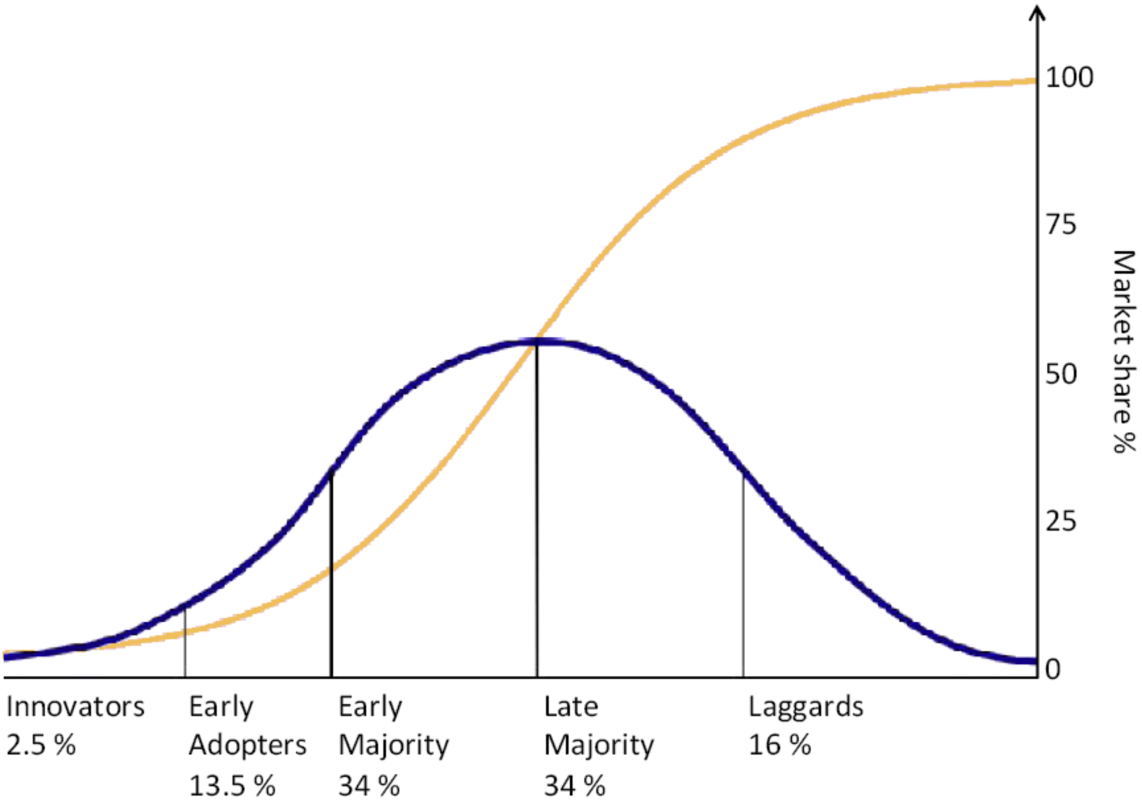
The LED is even more efficient, but its quality of light has been relatively deficient in ways that resemble that of the fluorescent. LED-lighting technology is developing quite fast, and possibly we will see a LED with light qualities close to that of the incandescent. Undoubtedly, LED represents a shift in “paradigm” as the diode is basically a different source for artificial light. LED has several advantages, of which energy efficiency is one and length of life is another, which means economizing both on energy and material resource use. But does this mean that an equally “paradigmatic shift” will occur in lighting use?

The S-shaped adoption curve

According to Everett Rogers’ famous theory, adoption of new technology often takes the form of an S-shaped curve over time. This is explained by adoption by different categories of adopters: A few per cent of possible adopters, such as all households or all owners of office buildings, are very keen of new things. Rogers call them “innovators”, but we may also call them nerds, as they seek novelties at (almost) whatever cost. These are the guys that line up when the new iPhone 4 is released. Now, new lighting technology may not be so attractive as information and communication technologies, but nevertheless, at a lower level, there may be a few individuals trying the new LED ahead of everyone else. After this avant-garde group comes, according to Rogers, “the early adopters”, comprising perhaps 10-15 per cent of all users. They often open up for the other adopter categories. Then come “the early majority”, “the late majority” and lastly “the laggards”. Figure 1 show the adopter categories and the cumulative effects on total adoption. This is, of course, a stylized way of describing actual adoption of innovations.

A more historical picture is given in Figure 2. As can be seen telephone and automobile diffusion was delayed during the economic crisis in the 1930s, but the radio was not hit by this. The TV spread quite fast, and can be taken as a hopeful proof for innovations today.

Figure 1. The S-shaped curve of adoption and adopter categories according to Rogers.



Based on Rogers, 2003, p. 273, 281.

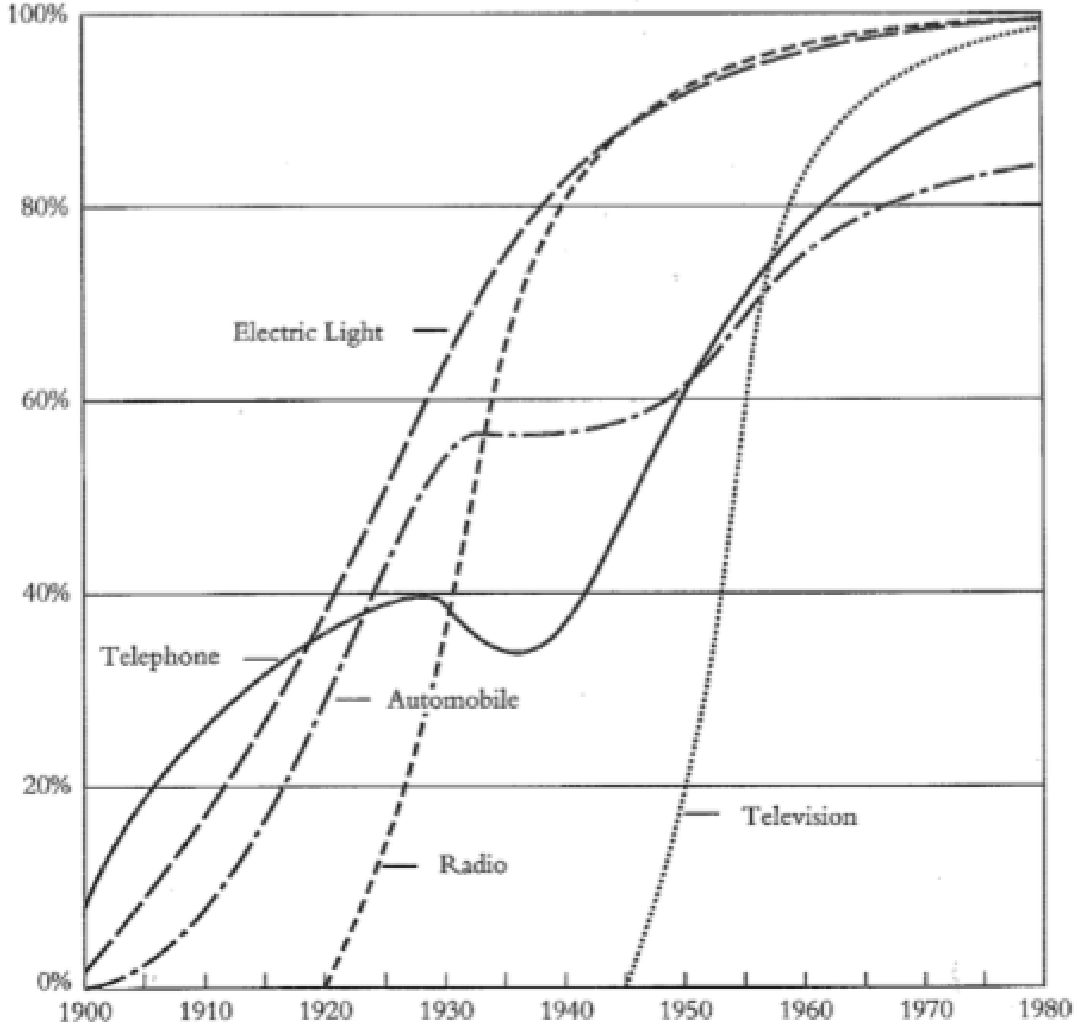
However, it took more than a decade for TV-sets to reach 80 per cent of the households, very fast but still about 12 years. It may be argued that the general innovation tempo is quicker now than in the 1950s, but on the other hand TV was much "newer" and more attractive than LED is for lighting.

Within the EU there is now a phase-out of inefficient lighting (hitting primarily incandescent lamps) going on. This favours energy efficient lighting, but will LED win the battle against CFL and halogen? Some answers will be given in Säter's and Bladh's contributions in this volume.

Path dependence and dominant design

What diagrams over innovations do not show, and often cannot show, are all those failures that could have been successful but did not survive. It cannot be defended that the market has been an objective testing ground where the bad has lost out to the good. Paul David and Brian Arthur have shown that inferior technology may not only survive in niches but also conquer the dominant position. Their example is the qwerty keyboard still around today even on computer keyboards. Another example is cars. At the turn of the century 1900 there were three types of cars with equal opportunities to dominate car sales and manufacturing, the electric car, the steam car and the petrol car. It is not obvious why one would be "superior" to the other as each one of them had both advantages and drawbacks. A third example is rail gauge. As railways developed privately, and separately in different countries, we still have different rail gauges around today. In fact, there is a lot of standardization work going on behind the scene concerning electricity, radio, mobile phones etc.

Figure 2. Diffusion of five innovations among U.S. households 1900-1980.



Source: Fischer, 1992, p. 22.

Another theory concerning innovations is that of James Utterback. This theory is based on several case studies, among which the development of electric light was one. The theory can be condensed as comprising two phases of innovation, partly in parallel. The first is the emergence of a dominant design. This is the story of how Edison first invented a carbon filament incandescent lamp. Still there were many aspects of the shape and content of a lamp that had to be decided. Eventually a dominant design emerged around 1910 with e.g. a screw socket and metal filament. The next phase concerned process innovations, i.e. improvements in manufacturing made costs decrease radically. Utterback's point is that incremental improvements on the basic product innovation, and process innovations in manufacturing, became intertwined and co-dependent "… that neither can change without deeply influencing the other." This creates inertia or technological conservatism as dominant design and cost reductions give old technologies advantages in use and in price. Users are familiar with the dominant technology, and the dominant technology is cheaper due to the volume of production and learning curves.

Radical and conservative innovations

LED is "radical" in the sense that it changes the root or base for the electric light. Conservative innovations are improvements on the new base, such as the elimination of flicker from fluorescent tubes when high frequency electronic ballast was introduced. Even though LED is radical, it is not radical in relation to electric light: Both Edison's first light bulb and the newest LED-lamp uses electricity. In that sense Edison's invention was more radical as he invented not only a lamp (in fact, others had come up with electric lamps before him or, at least, the principle of it) but also an electric system including power generation and distribution—the central supply.

According to Wolfgang Schivelbusch the birth of the electric light was a reprise of the birth of gaslight some seventy years earlier. Instead of every lamp carrying its own fuel a central supply of gas had been developed in England, primarily London in the 1810s. The central supply of energy was a radical break with the past, as it made property owners and other users dependent on a system and the system's tenders. "The gas burner that replaced the oil lamp or the candle was no longer a lamp in the strict sense, but an extension of the gas-works." The success of the light bulb was not that it was a good electric light but because it imitated and superseded the gaslight system. The drawback for the gaslight was that it consumed a lot of oxygen, polluted the air and raised indoor temperature. Edison invented the electric light—the light bulb was only a component of the system, albeit a crucial one. If electric light had failed as innovation, or had been delayed, it is probable that ventilation of houses and purification of the gas had been improved upon, making it more difficult for the electric light to succeed.

In order for LED to be "radical" in relation to the electricity supply system, it must be made to work independently from it. It is possible to use LED in isolated systems using photovoltaics for example. However, for widespread use the LED must find a place within the existing central supply systems, and therefore compete with existing lighting technologies adapted to that. This means that imitation (of the design and of the quality of light) and cost reductions are essential for success.

Looking back on earlier forms of alternatives to the incandescent lamp we can see two results. One is positioning as niche technology, the other is imitation of dominant design. Different types within the group of electric lights have settled for different niches—in the Nordic lighting culture the fluorescent is widely used in offices but not in homes (however, in the Japanese lighting culture this can be radically different). For the fluorescent to be able to expand into the functions normally possessed by incandescent lamps, imitation has been necessary. The tube had to be done away with in favour of something that imitated the bulb, or could be placed in a bulb fitting. The result is the compact fluorescent lamp with a screw-socket, sometimes with a pear-shaped bulb. Such an imitation strategy for a lighting technology within the electric lighting system has a historical parallel in the way Edison imitated the gaslight system.

What about regulations and users?

Still, the innovation literature has its own deficiencies. It is reluctant to take notice of political regulation, for example concerning energy labelling of household appliances. Nor is users a part of the picture, especially not ordinary consumers. Users of gaslight and electric light become part of the system too, as they adjust their behaviour to existing technology. Users can also refuse to adjust or combine different light sources for different purposes. The user of gaslight would most probably not place a painting near the gas burner due to combustion residues, while a user of electric light can use small lamps attached to the frame. However, these lamps may in the long run turn the painting pale, an effect the LED has the possibility to eliminate.

The point is that the use of lighting develops in relation to the existing lighting technologies and thus become a part of that conservatism that the innovator has to overcome. Joseph Schumpeter actually saw this almost a hundred years ago: "It is, however, the producer who as a rule initiates economic change, and consumers are educated by him if necessary; they are, as it were, taught to want new things, or things that differ in some respect or other from those which they have been in the habit of using". However, Schumpeter's entrepreneurial determinism tends to eliminate all creativity and independent choice on the part of the user. Let us recall that Roger's "innovators" (or nerds) are consumers exceptionally interested in novelties, and they may do something unexpected with the new gadget.

And fashion?

Turning attention to the majority of adopters, it is implied in Roger's theory that they listen to early adopters. However, consumers listen also to advertisements and fashion. Lamps are not only components of an electricity system but also a component of the home. A way of influencing home design is through magazines and TV-shows. Interior decorating is paradoxical in several respects. It is often the result of many small decisions over the years, so that the dwelling is eventually filled with a chaotic stock of details. On the other hand it can be the result of meticulous style planning. The latter is most uncommon in reality but probably common as dream or wish. Now, home "make-over" magazines and TV-shows suggest planned interior decorating of kitchens and bedrooms, or even the full implementation of "extreme make-over" as a way to do away with path dependence in the dwelling milieu. What is implemented actually, is a sort of aesthetic system where every detail is adapted to all other components.

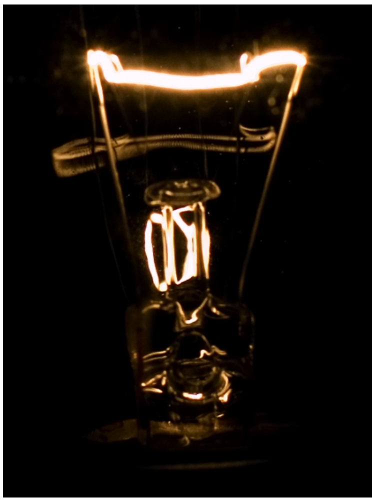
Seldom is energy efficiency a target in these makeovers and, furthermore, very few homes get changed in this radical way. Nevertheless, fashion influences us as consumers—the effects can appear as the installation of series of 6-8 retracted small halogen lamps in the kitchen. As they are turned all at once the installation is the equivalent of a 120-160 Watt lamp. Or the "uplight", a luminaire quite common in Swedish homes today. It combines a reading lamp with an adjustable arm and another directed at the ceiling for background light. The latter is a halogen lamp of 300 Watts, demonstrably a source of huge electricity consumption when it is turned on for many hours. Regulations in favour of energy efficient lighting cannot, and should not, interfere with private choices, but it can lower the average wattage of every lamp. Innovators can bring light quality and design to compete with existing technologies.

New materials and technological challenges

The new technologies do not appear easy. Before the incandescent and fluorescent lamps, the telephone, computer keyboard, cars and so on, there were many pre-inventors exploring the new technologies even before these were realized as technologies changing the society. For lighting it has been much focus on the right material and manufacturing technology. The basic function of the incandescent lamp is a material, shaped as a wire, which may handle the high temperatures so that light may be created by black body radiation. Physically, the wire releases its heat, which has been produced by a current and a high resistivity of the wire, by radiation. The light appears mainly in the infrared region, which produces large amounts of heat, and a smaller portion appears in the visible region. The energy efficiency is only about five percent, so in the new requirements in energy savings to produce a better environment, the light bulb has started to be phased out. Sir Humphry Davy demonstrated the first incandescent light in 1802, while Joseph Swan and Thomas Edison had to try many materials and socket technologies before there appeared a solution for a lighting product starting from last part of 19th century. Today's LEDs are based on gallium nitride. During the 70ies Isamu

Akasaki explored the growth technologies of this semiconductor material, and finally managed to make the research findings that led to the production starting from 1993 of blue LED with the work of Shuji Nakamura.

Figure 3. The incandescent lamp is based on a wire that can be heated to about 2500°C. The wire emits its energy as radiation, of which about 5% is in the visible region.



Actually, the very first time light was observed from an LED was in 1907 when Henry Round applied a current through carborundum, which is an early denotation of silicon carbide. He observed various colors, but the efficiency was very low due to the bad quality of the crystal that consisted of many crystalline grains. Since then the manufacturing technologies of silicon carbide have come in generations. Jan Anthony Lely introduced the first sublimation technology in 1955, from which larger single crystals could be prepared. Yuri Tairov and Valeri Tsvetkov presented the modified sublimation growth method in 1978, and by which today's silicon carbide wafers are produced. However, even though the first observation was made over hundred years ago, it was not until this century when it was realized that silicon carbide could be a very efficient material suitable for lighting.

Figure 4. Early material by the Acheson process, which was developed in the beginning of the 20th century, consisting of many grains and impurities.

The red and blue LED paradigm initiation

The development of LEDs started in the 1960ies with the material development of gallium arsenide, which has a direct band gap and allows a high probability of radiative emission. The first devices were simple pn-junctions with an interface between two areas having positively and negatively doped charges, respectively. Their energy could be released when these charges met at the interface. When the material was of high quality, the energy was released as radiation – light – while defective material transformed the energy into heat instead of light. Therefore there is a need to develop the manufacturing technologies so that high material quality can allow the paradigm shift of new technologies. The first gallium arsenide LEDs had a wavelength around 900 nanometres, which is close to the infrared region, but with further improvements the radiation appeared in the red region – red LEDs could be realized. The early performance was poor - the threshold current was high so that energy consumption was too high, there was a need to use pulsed current since efficiency dropped by the heat accumulated by a continuous current. Anyway, the success gave rise to intense development, and the efficiency increased when growth technologies could master several interfaces, which made the charged carriers to stay longer at the interface so that the probability of radiative recombination increased. The red LEDs became even more efficient with the downsizing of structures and use of stressed materials.

The initiation to the white LED was made by the findings in the blue LED development. It was only in 1969 when it was realized that gallium nitride had a direct band gap, and a couple of years later the first light emission was observed from small threadlike structures. During the 70ies it was not so easy to achieve high quality gallium nitride. The first insight that this material could be used and applied for LEDs was when Akasaki studied his grown crystals and found intense light from areas of high quality material. He developed his growth technology and made the two findings that led to the breakthrough – the buffer layer and p-type doping.

Figure 5. A replica of the reactor used by Akasaki to develop the growth technology for gallium nitride used for blue and white LEDs.

The white LED

The basic function of the white LED is simple: the light from a blue LED is passed through a phosphor which converts a part of the blue light to other colours in the visible spectrum, and the blue LED and phosphor combined produces white light. However, the conversion efficiency of the phosphor is not high enough and thus a blue tone may penetrate the white light. The second great challenge is in the blue LED, as it experiences an effect when aiming for general lighting by stronger light emission: the efficiency of the blue LED drops with increasing current. This effect is known as "droop". The physical mechanism behind this effect is not known yet, and researchers still discuss various possible mechanisms. There are some new technologies emerging which aims to solve problems which have occurred in the blue LED and it's phosphor. One approach is to utilize a UV-LED and convert this radiation to the visible by phosphors. Earlier the problem in UV LED has been a decrease of efficiency with shorter wavelength to reach deeper UV emission in nitrides, but during recent years there has been a continuous progress in UV LED efficiency. Other approaches are using solutions which are not based on phosphor, like ZnO nanocrystals which emits a broad spectrum which almost covers the visible range, and silicon carbide which cover the visible region by a two-layer approach and which can tune the color tone from blue to warm white. However, still the development produces a slow constant improvement of the LEDs and these are the LEDs we are introduced to in our lighting use.

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Materials and Growth Technologies for Efficient LEDs

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Abstract

The LED technology started to developed many years ago with red light emitting diodes. To achieve the blue LED, novel growth technologies and process steps were explored, and made it possible to demonstrate efficient blue LED performance from nitrides. The efficiency was further developed and blue LEDs were commercially introduced in the 1990's. The white LED became possible by the use of the blue LED and a phosphor that converts a part of the blue light to other colors in the visible range to combine into white light. However, even today there are limitations in the phosphor-based white LED technology, in particular for general lighting, and new solutions should be explored to speed the pace when white LEDs will be able to make substantial energy savings. In this paper we describe the fluorescent material and growth technology for a new type of white LED in general lighting with pure white light and several advantages for industrial development.

The white LED based on the blue light emitting diode

The development of light emitting diodes started in the 1960's with development of light emitting diodes and semiconductor lasers[1-4)]. The progress of LEDs has firstly provided light-emitting diodes based on gallium arsenide. The first devices were simple p-n junctions with a single interface and the direct bandgap of gallium arsenide made the first lasers to emit in the near infrared region near 900 nm, which was followed by red light emitting diodes[2)]. The semiconductor lasers had high threshold current densities and could only operate at pulsed conditions that made them to have small practical use but launched an intensified research that led to the continuous-wave semiconductors operating at room temperature using double heterostructures. The growth technology was liquid phase epitaxy and the technology made it possible to realize double heterostructures of gallium arsenide between Al_xGaAs_{1-x} layers which confined the GaAs by their larger bandgap. The confinement made it possible to accumulate in the gallium arsenide region and an increased probability to recombine across the bandgap[5,6)]. The semiconductor were further improved by use of molecular beam epitaxy and vapor phase epitaxy technologies, which made it possible to realize thin layers of less than 100Å and quantum confined effects could be studied to prepare an increased confinement of carriers, lower threshold current densities, more narrow line width of wavelength and possibility to tune the wavelength with the composition of the material. Later on the introduction of strain for example enhanced carrier recombination by a reduction of density of states at the valence band.

It was found in 1969 that gallium nitride exhibits a direct transition band structure with a bandgap of about 3.39 eV [7)]. A couple of years later optical emission was observed[8,9)]. The light was generated from needles of single crystal gallium nitride or from spots near the interface of the sapphire substrate that seemed to correlate with grain boundaries. There were major difficulties in the material with high residual donor concentration exceeding 10^{19} cm^{-3} that made fabrication of p-type material impossible. The crystal quality experience cracks in the surfaces and poor uniformity. The efficient luminescent properties were realized when discovering small microcrystallites which exhibited highly efficient light emission and which were prepared by forming n+ regions buried in insulating and n-type gallium nitride[10)].

The break-through of the blue LED came when the first p-n junction LED was demonstrated by the group of Isamu Akasaki. Later on Shuji Nakamura optimized the design and enabled Nichia to launch the first commercial LED in 1993. In the 1970's there were major problems with gallium nitride material, such as low crystal quality and very high and poorly controlled residual donor concentrations which made it possible to realize p-type conduction. In the 1970's Akasaki was struggling with these issues as a researcher at Matsushita Research Institute in Tokyo. When detecting that the high-quality microcrystals in the poor quality gallium nitride layers were emitting intense light, Akasaki realized that gallium nitride LED with a p-n junction had a great potential if the crystal quality could be controlled. This was possible by using the right growth process, and the choice fell on the MOVPE (metal organic vapor phase epitaxy) growth process even though the method was not commonly used. It has advantages since the reactions of growth species were positive in that atoms were not likely to leave the surface again once they had arrived. The more commonly used growth technologies of MBE (molecular beam epitaxy) and HVPE (hydride vapor phase epitaxy) had either very low growth rate at that time or too high growth rates to provide high crystal quality.

The research group built a home-made reactor at Meijo University, Figure 1a. Still, the material quality was poor. Only when the group realized a low temperature buffer layer technology, the high quality material was achieved. The buffer layer technology is a low temperature growth of a thin layer with physical properties similar to both the sapphire substrate used for growth template and the gallium nitride. As a result, near band gap emission was demonstrated, the residual donor concentration was decreased substantially and as well as showing an improved crystal quality[11)].

The next step was to achieve controlled p-type doping. The team discovered that the luminescence was increased by irradiating zinc doped gallium nitride with electrons, while still there was not p-type conduction. Akasakis group switched from using zinc as dopant to magnesium in another type of set-up (Figure 1b) applied irradiation on the magnesium-doped films and demonstrated p-type conductive gallium nitride films.

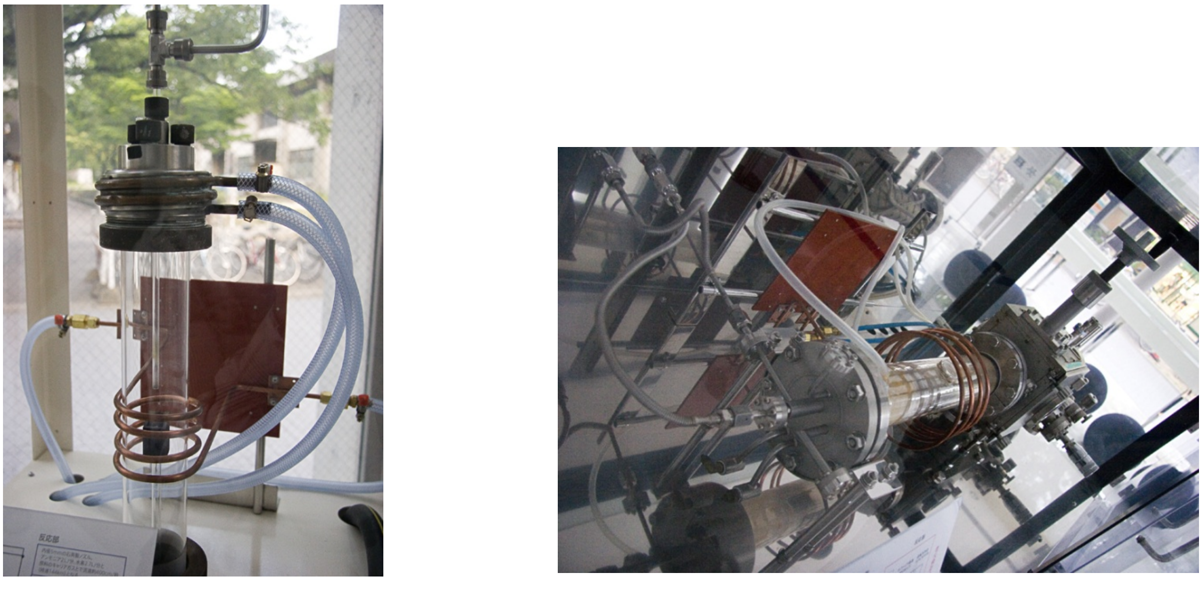


Figure 1. (a) A replica of MOVPE equipment to demonstrate buffer layer technology and high gallium nitride crystal quality; (b) One of the MOCVD equipments that were used to achieve magnesium doping.

The conventional nitride technology for white light emitting diodes is simply described by a nitride stack emitting blue light, and a part of this blue light is converted to other colors by a phosphor on top of the nitride layer, Figure 2. There are two main problematic issues of this technology. The first is that the intensity of the remaining blue light is stronger than the other colors from the phosphor due to the low efficiency of the phosphor, and the nitride LED has then a blue tone that is undesired by people using a white light LED on such nitride technology. The second issue is due to the uniformity and stability of the phosphor. When the phosphor is covering the nitride layer, the properties vary from location to location, and cause a slight difference between the light from LEDs made from different areas. As a result the LEDs have to be placed into different bins, which is a drawback in the production and use of the LEDs.

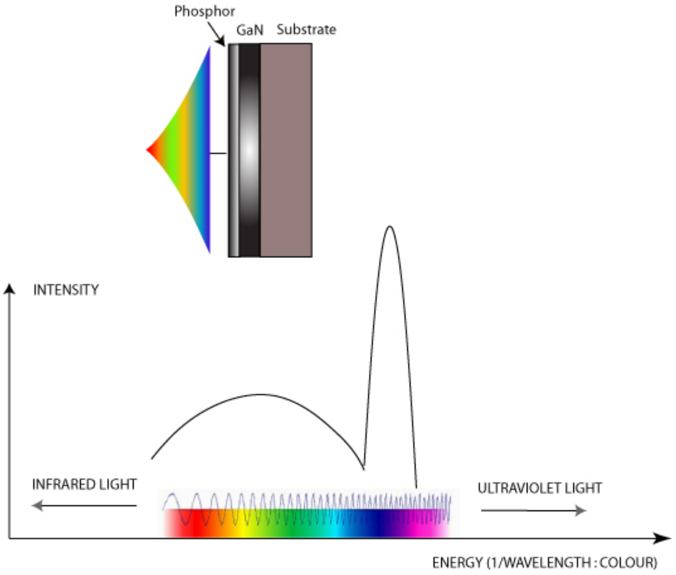


Figure 2. Schematic illustration of the phosphor based white LED using a blue LED and a phosphor that converts a part of the blue to other colors in the visible spectrum.

In a simplified scheme (Figure 3) the blue light emitting diode consists of an n-type region with a high concentration of electron, which may be obtained by doping with silicon. The second part of the diode consists of a region that is p-type and has an increased number of holes by use of magnesium doping. The driving force to create the light comes from the electron filling the holes in the active region between the n-type area and the p-type area. This is also the reason why the light is so direct and has small angular width in the spread of light, the active region is very narrow and the light comes from an edge of the diode. In this structure, the electrons close to the magnesium atoms have a tendency to have lower probability of radiative recombination, and often an electron layer is used to block electrons from the region with magnesium atoms.

The blue LED has encountered a profound challenge. When the current to drive the LED is increased to utilize the structure for high illumination purpose, it has been found out that the technology faces a phenomenon in which the efficiency is decreasing with increasing current. Different mechanism have been argued and dismissed, like that the heat that is generated causes the electron and holes to be less confined, or the clustering of indium. The heat theory was dismissed by demonstration of pulsed laser action still showed the droop effect, and the indium clusers which were observed were very likely appearing as an effect of the measurement technique, and not present in the layers before measurement. Still the phenomenon of droop is investigated. Tremendeous amounts of energy could be saved by replacing light bulbs by white light emitting diodes. Therefore the droop of the efficiency is a question that many research groups, as well as industrial actors, tries to solve.

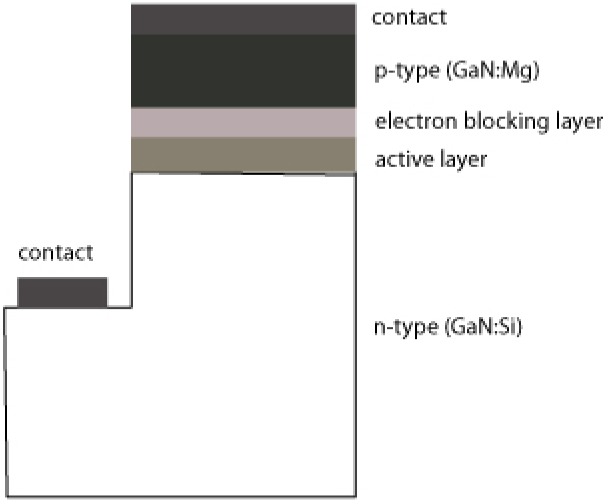
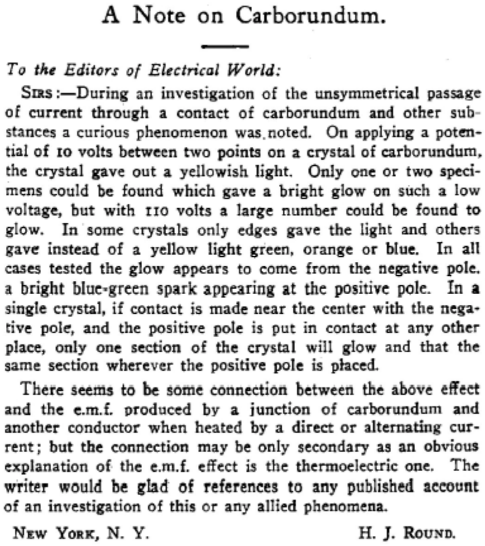


Figure 3. Simplified scheme of blue LED structure.

Flourescent silicon carbide

In 1907, Henry J. Round presented a note in *Electrical World* [12)] reporting a “bright glow” from diodes made on carborundum, which was the original denotation of silicon carbide, when exploring crystal detectors which were interesting to demodulate radio-frequency signal in crystal-detector radios, Figure 4. The light was produced by using two electrodes in contact with the material so that a rectifying diode was made when driving a current through the diode, and is the first observation of electroluminescence from a semiconductor.



A Note on Carborundum.

To the Editors of Electrical World:

Sirs:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

New York, N. Y. H. J. Round.

Figure 4. “A note on Carborundum” in Electrical World 1907 was the first observation of luminescence from a semiconductor.

In the early days of SiC research some studies have been conducted on pn-diodes and donor-to-acceptor pair recombination in single layers but the efficiencies have been low [13-17)]. A white light emitting diode structured using a combination of two doped fluorescent SiC layers has been proposed by Satoshi Kamiyama and co-workers at Meijo University[18)]. This new white LED does not have a phosphor. Instead the white light comes directly from the material in two broad spectra, covering the visible region, which results in a pure white light, Figure 5. In a simple description the light emitting diode principle is made of (i) a nitride stack which emits UV light into, (ii) a fluorescent silicon carbide which transfers the UV light into a white light, and the white light is emitted out from the LED structure with help of (iii) a moth-eye structure. The moth-eye structure is a non-flat patterned surface, which helps to bring the light out from the fluorescent silicon carbide, since a flat surface is well known to reduce the light extraction due to reflection at the surface from the silicon carbide to air. A great advantage in this LED structure is that the nitride stack that emits near ultraviolet light does not experience the droop effect.

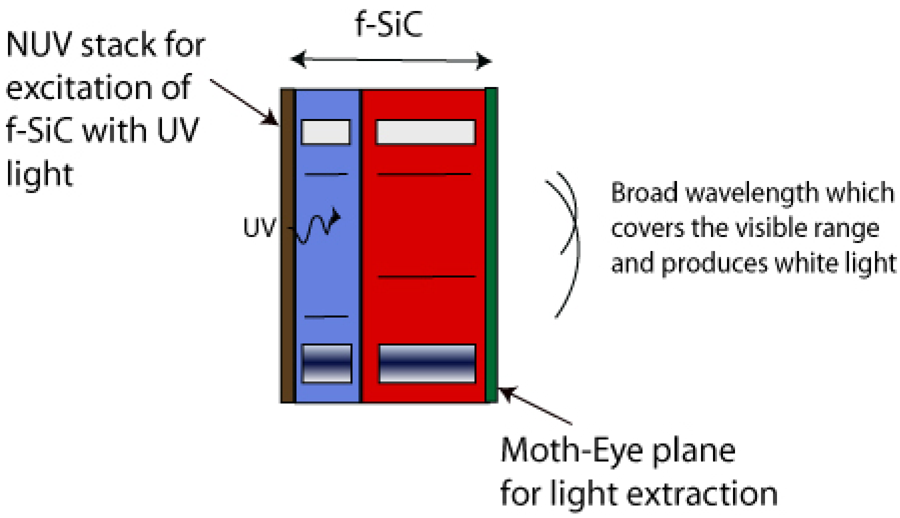


Figure 5. A schematic view of the silicon carbide based light emitting diode consisting of a near ultraviolet (NUV) nitride stack, the fluorescent silicon carbide (f-SiC) and the moth-eye surface.

The NUV light is absorbed within the volume of the f-SiC substrate, in which visible light is extracted through a moth-eye structure etched on the backside of the f-SiC substrate. The LED which is produced in this way has a high color-rendering index and is highly suitable for pure white LEDs. The f-SiC substrate is built up of two layers, both of which should be sufficiently thick to produce a strong light emission from volume of the fluorescent material. The first is a layer of fluorescent 6H-SiC doped with the optimum concentration of nitrogen and boron, which are acting as donor and acceptor, respectively. The second layer is a 6H-SiC layer doped with nitrogen at a concentration of and aluminum . It was realized for the first time that the material has a very high quantum efficiency 19) and is therefore an ideal material to produce a monolithic white LED chip. The N and Al doping yields a broad donor-to-acceptor band luminescence, which together with the broad donor-to-acceptor band luminescence in the N-B layer provides most wavelengths in the visible region with a light intensity (wavelength) distribution which does not have any dominating color, i.e. very pure white light. The nitrogen and boron doped SiC layer can emit warm white light with a peak wavelength of around 600 nm. The spectrum from nitrogen and aluminum doped SiC exhibits blue-green emission. By combining these two fluorescent layers and the two broad wavelength light outputs, a pure white light is obtained covering the whole visible spectrum. The luminescence between donors and acceptors is broad due to several energy levels close to the main level resulting in several transition possibilities, as typical in donor to acceptor pair luminescence. The recombination between donor and acceptor makes light output with energies over a continuous range, making a broad peak with an energy which is determined by the doping materials used (N - Al and N - B donor to acceptor pair luminescence have different positions with peaks in the visible region).

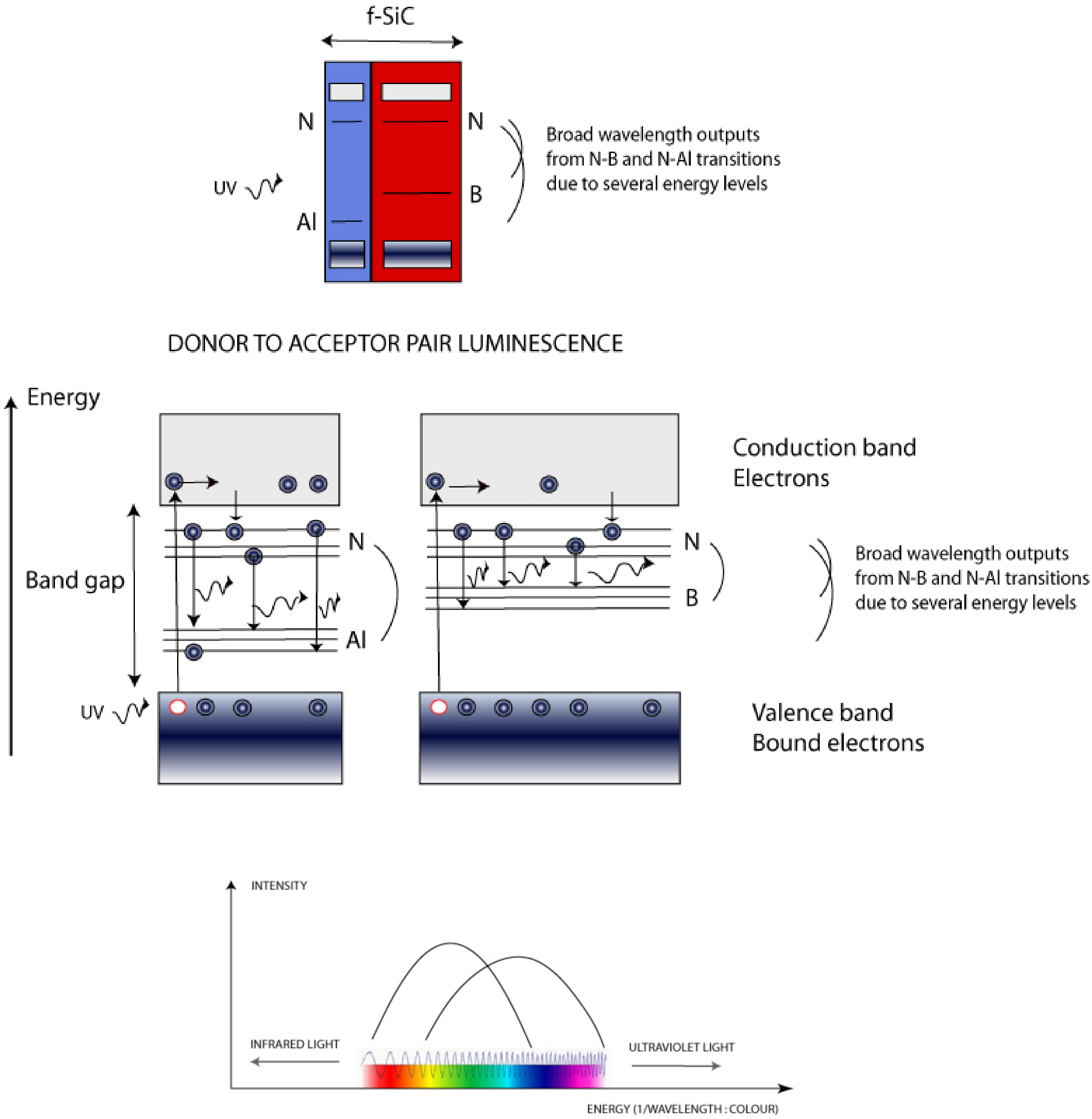


Figure 6. A schematic view of the light output from fluorescent silicon carbide and the optical transition.

Material quality and growth technology

As a central part in the white LED based on silicon carbide is the structural quality in the fluorescent silicon carbide material. The quality of this is crucial to provide efficient light. It has been possible to grow silicon carbide since hundreds years, first by the Acheson process in which a mixture of silica, carbon, salt and sawdust were heated in air using an electrical furnace. The yield of single crystal material was low but this material was used for cutting and grinding purposes due to the hardness of silicon carbide. In 1955 Lely presented an important step in growth technology evolution and single crystal material became available$^{20)}$. However, the size of these crystals was limited. In 1978 Tairov and Tsvetkov proposed the modified Lely method, in which a starting seed is used, and by this crystal enlargement became possible$^{21)}$. This process is based on physical vapor transport (PVT) and has since 1989 been used to commercially produce silicon carbide wafers for transistor applications and as substrate for white light emitting diodes based on nitrides.

In the SiC based LED a very high crystal quality is required. The PVT process used growth temperatures around 2300°C, and the chemical vapor deposition is limited into epitaxial growth at 1500-1600°C. At high growth temperatures it is difficult to maintain low dislocation levels, and dislocations cause non-radiative recombination instead of the desired radiative recombination of electrons. In the last years of 1990's Rositza Yakimova and Mikael Syväjärvi studied the concept of sublimation epitaxy, which uses a lower growth temperature than PVT (500°C less) while maintaining a high growth rate with high quality of the grown material[22,23)]. This has since 2007 been further developed into the Fast Sublimation Growth Process (FSGP)[24)] which is the perfect growth technology for making the fluorescent silicon carbide in the Kamiyama LED since it combines and manages the challenges in having high growth rate, low defect density material, thick layers and uniform doping possibilities at the same time, Figure 7.

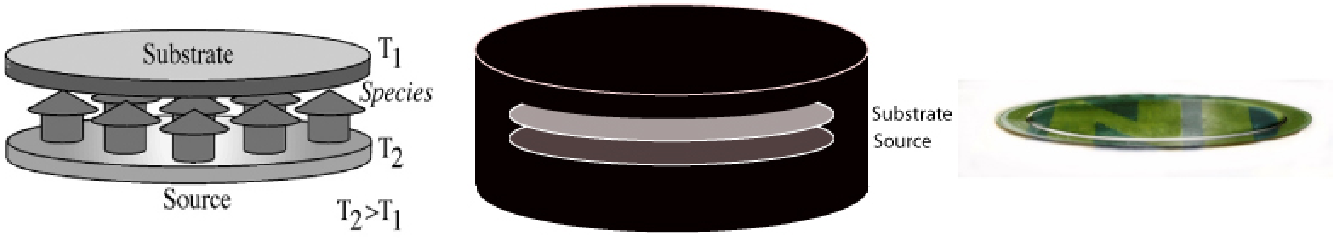


Figure 7. The configuration for the Fast Sublimation Growth Process.

The technology of SiC crystal growth via sublimation is a complex process in which a number of parameters have to be controlled. The following sub-processes are of main importance: (i) sublimation of the source material, (ii) mass transport of the vapour species to the growing crystal, (iii) nucleation at the seed/crystal surface, and (iv) feeding of the growing crystal. The crystal growth is driven by the shift along a temperature gradient of the equilibrium between the solid SiC and its vapour. The vapour is produced via incongruent decomposition of SiC source material and reactions with the environment.

Because of the large difference between the silicon and carbon vapor pressures, the Si/C ratio, which determines the stoichiometry of the grown material, is difficult to maintain stable during growth of large crystals. This may affect the polytype stability and cause micropipe formation. Mass transport is predominantly governed by diffusion, which limits the growth rate and may affect crystal perfection. Single crystal SiC nucleates through deposition of the supersaturated vapour species on a SiC seed crystal. Uniformity of the supersaturation is another critical characteristic that is responsible for crystal quality. The surface kinetics and the seed surface conditions also influence the nucleation process and consequently formation of defects.

The driving force for growth is provided by applying a temperature difference which yields a higher temperature at the SiC source compared with the seed. The source can be a piece of SiC or most commonly as powder in boule growth in the conventional Modified Lely method following the concept given by Tairov and Tsvetkov[21)]. The crucible has to resist the high temperatures applied and in case of SiC sublimation growth, crucibles made of graphite or TaC are used even though the latter is an expensive solution. Above a certain temperature, the source starts to sublime. The silicon and carbon bearing species are transported to the growing surface in the solid-vapor equilibrium along the temperature gradient. For growth of long boules a long source to seed distance (typically 5-30 mm) is required and interaction of the silicon and carbon species with the graphite walls will occur. The growth is performed in a low-pressure inert gas ambient (typically 5-40 mbar). This requires high growth temperatures to ensure high growth rates.

The epitaxial growth process has several advantages over the conventional modified Lely method. The distance between the source and the substrate is short, typically 1 millimeter, which has the positive effect that the vapor species do not react with the graphite walls. Instead of a silicon carbide powder as source material, the source is a monolithic silicon carbide plate. When the distance is short, any irregularities of the surface will reflect in the grown material, and hence defects will appear. The solid source is easier to control, while a silicon carbide powder will sublime in a non-uniform way. When the temperature is decreased, the pressure can be decreased to maintain a high growth rate. The lower growth temperature will result in higher quality of the material is the growth conditions can be preserved. At the initial stages of growth, morphological disturbances may appear. During the first stage of epitaxial growth in vacuum, the substrate surface may improve since both sublimation and nucleation occur. By this, the effects of polishing damages in the original substrate are reduced. In fact, growth performed on substrates containing a layer grown by liquid phase epitaxy demonstrates the morphological stability. Smooth surfaces are accompanied by a high structural quality of the bulk material[23)]. In fact, direct proof that the epilayer structural quality even improves compared with the substrates is evident from ω-rocking curve measurements, Figure 8.

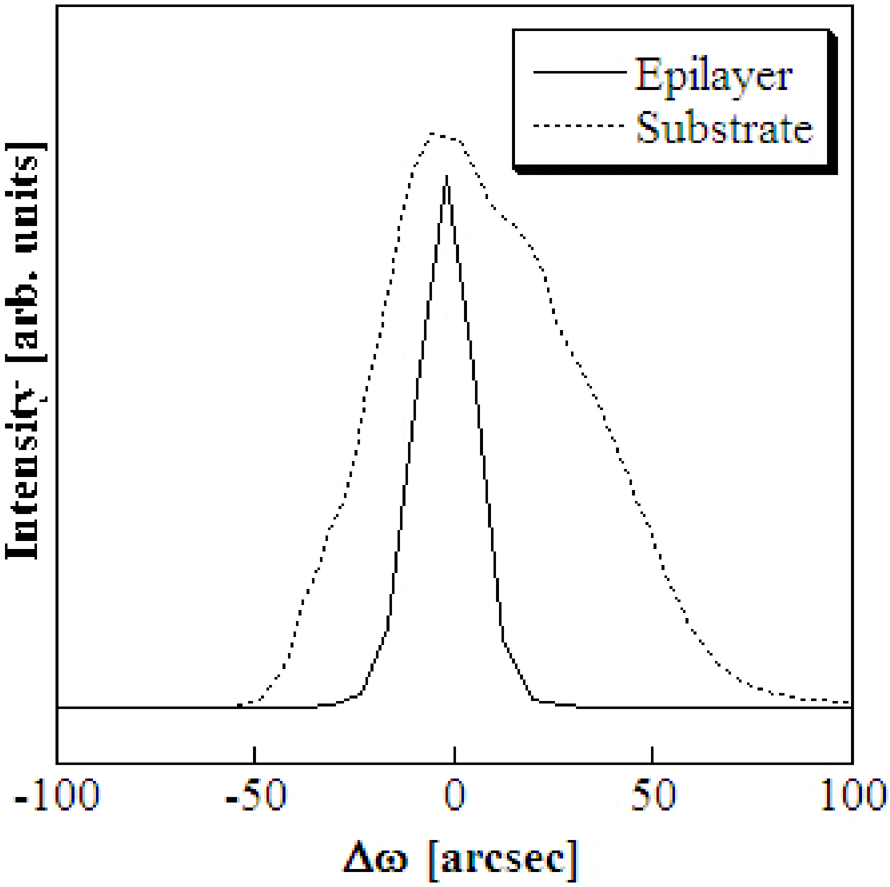


Figure 8. ω-rocking curve measurements from a substrate and the epilayer grown on the same substrate; layer thickness 100 μm.

Summary

The choice of growth technology is an important decision in development of LEDs since the structural quality has such strong influence on the optical recombination paths. In case of nitride growth the MOCVD is an established method, while the physics demonstrate an effect on the efficiency by the droop effect in blue LEDs. In case of SiC, the Modified Lely method is more difficult to control and the CVD method has difficulties in growth of thick layers that are needed in the new concept of fluorescent SiC. The feature of high structural quality while still maintaining high growth rates is very promising to achieve high optical efficiency of the fluorescent silicon carbide material prepared by the FSGP growth technology.

Acknowledgements

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Light Excitation and Extraction in LEDs

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Abstract

For realization of a white LED with broad visible spectrum, a combination of single spectral blue LED and phosphors is generally used. Our new approach is based on all-semiconductor material technology composed of a NUV-LED excitation source and fluorescent SiC (f-SiC) substrate that generate a visible broad spectral light. Since the f-SiC contains donor and acceptor impurities with optimum concentrations, a high conversion efficiency from NUV to visible light caused by the donor-acceptor-pair recombination is possible. This device is a promising candidate for general lighting applications because of the high color rendering index, high luminous efficacy, a high stability/reproducibility of color quality, and potentially low cost. Besides the f-SiC performance, high quality nitride-based NUV LED with high internal quantum efficiency and high light extraction efficiency to maximize external quantum efficiency are both indispensable to achieve the high luminous efficacy of white LEDs. In this paper, we describe basic technologies of the white LED, such as optical properties of f-SiC substrate, epitaxial growth of NUV stack on the f-SiC substrate, and moth-eye plane fabrication technique to enhance the light extraction.

Introduction

White light-emitting diodes (LEDs) are very promising devices for such huge lighting applications as the backlight source of liquid crystal flat display panels, the headlights of automobiles, and general lighting equipment. A combination of a blue-LED chip and yellow phosphor such as YAG:Ce1) has been greatly advanced, and their luminous efficacy has already taken over that of fluorescence tubes. However, there are still some problems with conventional white LEDs; a low yield of the color quality, a low total flux, and a low color rendering index. These problems are still serious obstacles for the expansion of white LED applications.

Because the conventional white LED mentioned above emits blue light and yellow light, the color rendering index is very low, mainly due to the lack of red1). Another white LED comprising a UV-LED and three-color phosphors has also been developed to improve the color rendering property2). However, this type of device has a low emission efficiency, because of the low efficiency of red phosphors. Thus, the color rendering index and emission efficiency are in a trade-off relationship. Figure 1 show a relationship between the luminous efficacy and color-rendering index (CRI) of current white LEDs. The very high luminous efficacies have been realized only in the low CRI range, and there have been no demonstrations in required range (CRI > 84, luminous efficacy > 130 lm/W) for the next general lighting applications. In addition, the combination of a single-spectrum LED and phosphors has an intrinsic instability of color against temperature change and divergence angle variation. Moreover, complicated assembly processes are required to set the phosphors uniformly on the LED chip.

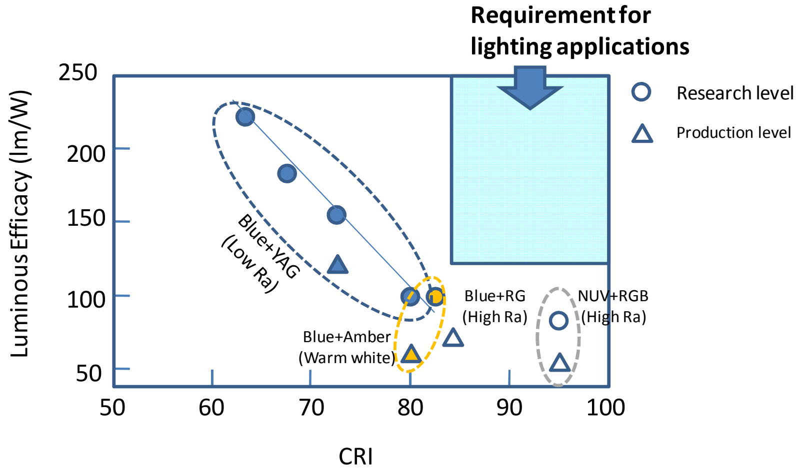


Figure 1. Relationship between luminous efficacy and color rendering index (CRI) for current white LEDs

Donor-and-acceptor (DA)-doped SiC is a promising candidate for fluorescent material used in a novel white LED[3]. This can be excited by nitride-based near ultraviolet (NUV) LEDs, which can be monolithically stacked on the SiC substrate. In this paper, we propose a new fluorescent material, a donor-and acceptor-doped 6H-SiC, and describe basic investigations about a monolithic white LED.

Optical properties of donor-and-acceptor-doped SiC

Figure 2 shows the photoluminescence spectra of nitrogen (N) and boron (B) doped and nitrogen (N) and aluminum (Al) doped 6H-SiC epilayers produced by a closed sublimation technique[4]. The pairs of the doped impurities correspond to donor and acceptor, respectively, and these broad light emissions are caused by donor-acceptor pair (DAP) emissions. The N-and-B-doped SiC emits yellow-orange light, while the N-and-Al-doped SiC emits blue-green light as shown in the figure. Therefore, by a combination of these two spectra, a full-range of visible spectrum similar to the sun-light spectrum can be produced. This means that the fluorescent SiC epilayers doped with donor and acceptor impurities are promising phosphor materials for high color rendering index. The CIE Chromaticity coodinates of these two f-SiCs are also measured as shown in Fig. 3. The chromaticity coodinates of x and y in N-and-B-doped SiC are 0.486 and 0.465, respectively, and those in N-and-Al-doped SiC are 0.137 and 0.085, respectively. B a mix of these two epilayers, pure white color can be generated.

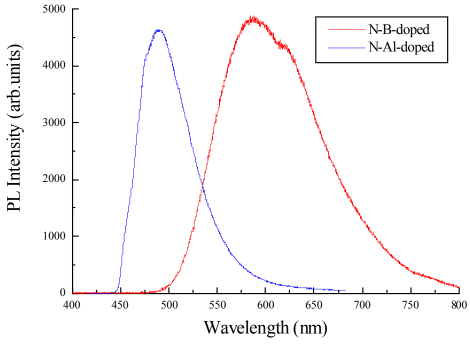


Figure 2. Photoluminescence spectra of f-SiC epilayers.

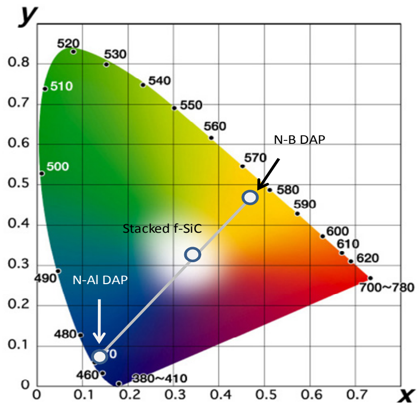


Figure 3. CIE chromaticity coodinate plot of f-SiCs

For high emission efficiency in f-SiC epilayers, high quality and appropriate doping concentrations are indespensable. Figure 4 shows the energy band diagram of f-SiC. The NUV light excitation generates electrons in the conduction band and holes in the valence band. These carriers are partly trapped in the donor and acceptor states, and partly trapped in the defect states. The former carriers recombine radiatively, and the latter carriers recombine non-radiatively. The internal quantum efficiency (IQE) should be determined by

$$\mathrm{IQE} = \frac{1}{1+{\tau_r}/{\tau_{nr}}} ,$$

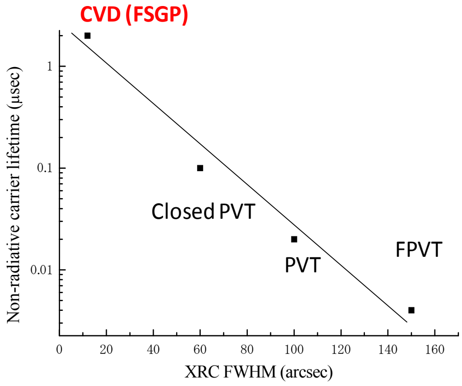


Figure 4. Relationship between non-radiative carrier lifetime and FWHMs of x-ray rocking curves.

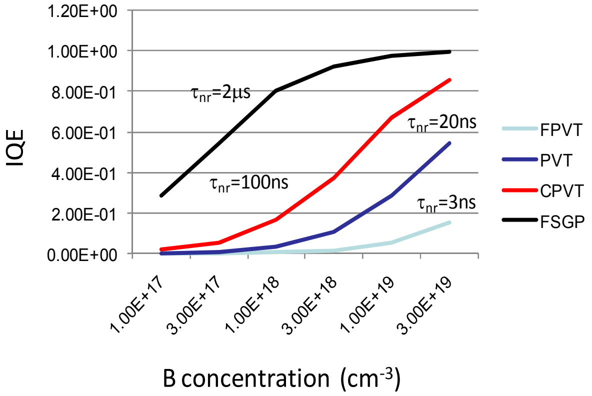


Figure 5. Estimated IQEs as a function of B concentration for f-SiCs with a variation of non-radiative lifetime.

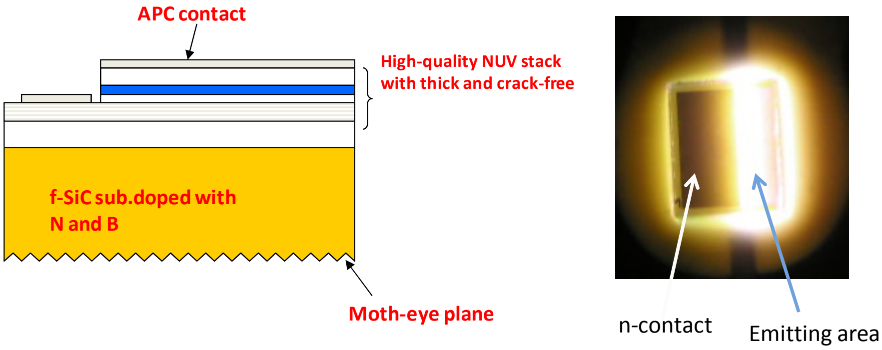


Figure 6. Schematic diagram and photograph showing the operation of warm-whte LED.

where τ_r is radiative lifetime corresponding to trapping time of holes to acceptor states, and τ_{nr} is non-radiative lifetime corresponding to trapping time of holes to defect states. The radiative lifetime is dominated by the doping concentrations of donor and acceptor impurities, and the non-radiative lifetime is determined by the quality of the crystal. The crystalline quality of SiC is greatly varied among several crystal growth techniques. We examined carrier lifetimes of several kinds of n-type 6H-SiC crystals. These carrier lifetimes correspond to non-ratiative recombination times in the above definition, because of the lack of acceptor impurities. In addition, the carrier lifetimes greatly correlate with full-width at half maximums (FWHMs) of x-ray rocking curve (0006 reflection), as shown in Fig. 4. The best quality SiC can be obtained by chemical vapor deposition (CVD) and Fast Sublimation Growth Process (FSGP)5), where the carrier lifetime is about 2 μsec. However, the SiC crystal grown by the most conventional growth method, physical vapor transport (PVT) method, has quite short carrier lifetime of 20 nsec. From the above equation, we can estimate IQEs for different kinds of f-SiC, which contains N and B impurities as a function of B concentration. Figure 5 shows the estimated IQEs with an assumption that N concentration is fixed at B concentration + 10^{18} cm^{-3}. While the low-quality f-SiC has low IQE even under the high doping concentration, the high quality f-SiC produced by FSGP exhibits very high IQE with relatively low doping concentration. To produce high performance f-SiC, an appropriate growth technique such as the FSGP method must be applied. The FSGP growth also satisfies the requirement of thickness of more than 200 μm, which is necessary for absorption of NUV excitation, because it has a very high growth rate of several hundreds of micrometer per hour.

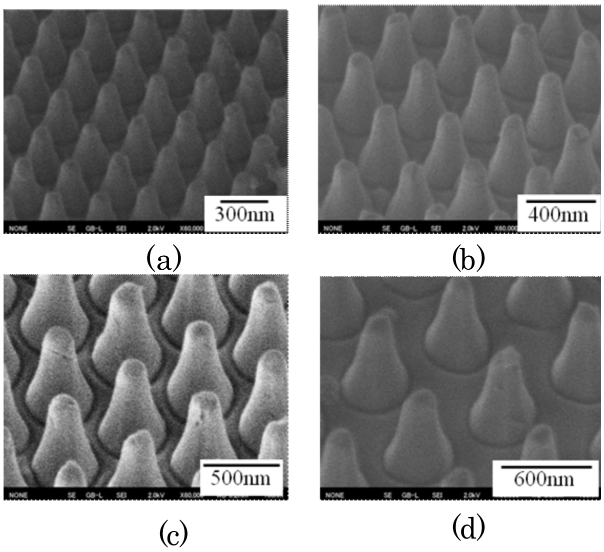
Although the high-quality f-SiC has not yet been developed, a warm-white LED was fabricated for the first demonstration by using a single N-and-B doped f-SiC grown by PVT method. Figure 6 shows a schematic diagram and a photograph showing the operation of the warm-white LED. The size of the chip is 500 μm × 500 μm, and the emitting area is almost the half of the chip. Warm-white emission with a peak wavelength of 580 nm was confirmed. This device is certainly proved to work with a combination of f-SiC substrate and nitride-based NUV stack, while the luminous efficacy seemed to be low. If the crystalline quality of both f-SiC and NUV stack is advanced, the performance will surely be improved for practical use in general light applications. In addition, a moth-eye plane on the backside of the f-SiC will improve the light extraction efficiency.

Moth-eye plane for high light extraction efficiency

Another critical issue toward the high performance white LED is improvement of light extraction efficiency. In the current nitride-based LEDs, textured or roughened surface and/or interface is commonly used for the improvement of light extraction efficiency. Figure 7 shows the schematic drawing of a typical nitride-based blue LED chip. A patterned sapphire substrate, which has a periodic texture with a pitch of several microns, is used for the nitride growth6). This plane can scatter the light propagating in the nitride epilayer laterally. As it results in the light scattering, light extraction from the top surface is increased. However, this scattering effect is still limited for further improvement, because the component of the total internal reflection in the epilayer can not be perfectly eliminated.

We proposed the moth-eye structure7,8), consisting of periodic corns with submicron-scale pitch to suppress the total internal reflection in an LED chip. The mechanism for the improvement of light extraction efficiency is not based on the light scattering but the light wave interference. The pitch of the moth-eye plane is as small as several times of the optical wavelength, and it is small enough for coherent length of the spectrum generated in LED chip. Therefore, strong interference effect for transparency of the light wave is caused. However, there has not been a production system for such small-scale patterning. We demonstrated a novel patterning technique based on low-energy electron-beam lithography (LEEPL), which is capable of high-throughput patterning7). In the LEEPL system, a stencil mask, having 200 nm-diameter through-holes with triangular lattice arrangement, is set between an electron gun and resist-coated substrate. This system is capable to expose a whole 2” wafer within 1 minute. After development of the resist, thin dielectric layer such as SiO_2 is deposited, and inverse hard mask pattern is formed by lift off process. Finally, dry etching is carried out to make the corn arrangement.

Figure 7 shows bird’s eye view scanning electron microscopy images of the moth-eye structure on a SiC substrate. The structure has uniformly aligned corns with well-controlled tapered sides. The pitches of the corns are varied from 300 nm to 600 nm, and the aspect ratio, which is the ratio of the height to the pitch, is fixed at 1. This moth-eye structure was formed on the backside of a SiC substrate in a nitride-based blue LED with a peak wavelength of approximately 450 nm, as shown in Fig. 6. This LED stack was grown directly by metalorganic vapor phase epitaxy (MOVPE). Since a flip-chip configuration was adopted for the blue LED, the blue light can be extracted from the backside of the substrate. The high-reflectivity APC alloy metal, which is an Ag-based metal with small amounts of Pd and Cu added, was applied to a p-type ohmic contact in order to enhance the backside light extraction[8)].



(a) (b) (c) (d)

Figure 7. Bird's-eye-view SEM images of moth-eye structure formed on SiC substrate.
(a) Pitch=300 nm, (b) Pitch=400 nm, (c) Pitch=500 nm, (d) Pitch=600 nm

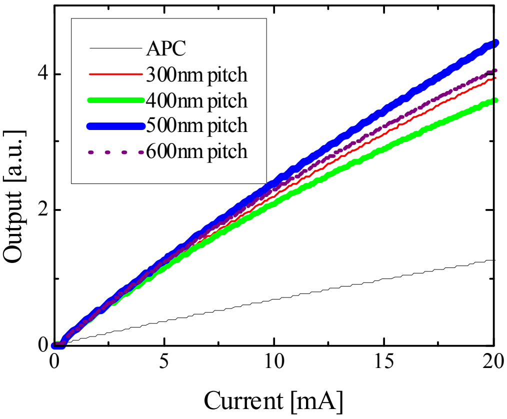


Figure 8. L-I curves of blue LEDs on SiC substrate with a variation of pitch of the corns.

Figure 8 shows L-I curves of blue LEDs on SiC with a variation of pitch of the corns in the moth-eye structure. The measurement was carried out using a wafer probing setup, so that all the detected light output goes through the moth-eye plane on the backside of the SiC substrate. As a reference, the curve for an LED without the moth-eye plane is also plotted. Compared with the reference LED, all the LEDs with the moth-eye plane exhibit significantly higher light output. The moth-eye structure is found to be very effective in enhancing the light extraction efficiency. The light output is definitely dependent on the pitch of the corns, and the LED with 500nm pitch has the highest light output. This behavior is qualitatively explained by that when the pitch is as narrow as 300 nm, the Fresnel reflection is suppressed by the gradual change in the refractive index on the surface. However, total internal reflection still occurs. With increasing pitch of the corns, the effect of Fresnel reflection suppression disappears therefore, the light output deceases at a pitch of approximately 400 nm pitch. Above a pitch of 400 nm, the number of interference modes that nearly satisfies the Bragg condition shown below increases. The Bragg condition for the interference modes is,

$$P\left(n_1 \sin\theta_1 - n_2 \sin\theta_2\right) = m\lambda,$$

where P is the pitch of the corns, θ_1 is the incidence angle, θ_2 is the extraction angle, n_1 is the refractive index of the substrate, n_2 is the refractive index of the atmosphere of air, m is an integer used to index the modes, and λ is the wavelength of light. From the interference equation, we can see that the number of modes increases with increasing pitch of the corns, P. The interference causes light extraction even above the critical angle of total internal reflection. However, the coherent length of blue light generated in the LED is in the range from 2 to 3 μm from the estimation of the spectral width thus, the interference strength decreases with increasing the pitch. Therefore, an optimal pitch for the highest light extraction efficiency should exist, and it may be around 500 nm. We found that the sample with a 500 nm pitch had the highest output power, which was 3.7 times higher than that of the reference sample without the moth-eye structure. Since the theoretical light extraction efficiency obtained from the flat SiC surface with an infinite area is 10%, the moth-eye LED is estimated to have a high light extraction efficiency of 37% even without the resin encapsulation. In an actual device with a finite area and surrounding side facets, the light extraction efficiency becomes higher owing the extraction from the side facets.

Summary

In summary, we propose a new monolithic white LED using a combination of the f-SiC substrate and nitride-based NUV stack. The f-SiC works as a phosphor for the emission of visible light, based on the recombination of donor acceptor pairs. Two types of f-SiC, where one is doped with N and B and another is doped with N and Al, can cover the whole visible spectral range. However, an optimization of the doping concentration and improvement of the crystalline quality are critical issues for high luminous efficacy in the white LEDs. The Fast Sublimation Growth Process is a promising growth method of radiative f-SiC, because it enables us to grow material of high crystalline quality and with long non-radiative lifetimes.

For further improvement of the white LED performance, high light extraction efficiency has been proved by the moth-eye plane on the backside of the SiC substrate. This technique improves the output power of blue LED of more than three times. This technique is also applicable to the white LED using the f-SiC substrate.

Acknowledgement

The authors would like to thank Professor Amano for his continuous advice on MOVPE growth of nitride epilayers. Part of this work was supported by and Department of the New Energy and Industrial Technology Development Organization (NEDO). The work concerning the moth-eye technology is supported by the Risk-Taking Fund for Technology Development of the Japan Science and Technology Agency.

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‘No Blue’ White LED

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Abstract

This paper explored the feasibility of making a white LED light source by color mixing method without using the blue color. This ‘no blue’ white LED has potential applications in photolithography room illumination, medical treatment and biophotonics research. A no-blue LED was designed, and the prototype was fabricated. The spectral power distribution of both the LED bulb and the yellow fluorescent tube was measured. Based on that, colorimetric values were calculated and compared on terms of chromatic coordinates, correlated color temperature, color rendering index, and chromatic deviation. Gretagmacbeth color charts were used as a more visual way to compare the two light sources, which shows that our no-blue LED bulb has much better color rendering ability than the YFT. Furthermore, LED solution has design flexibility to improve it further. The prototype has been tested with photoresist SU8-2005. Even after 15 days of illumination, no effect was observed. So this LED-based solution was demonstrated to be a very promising light source for photolithography room illumination due to its better color rendering in addition to energy efficiency, long life time and design flexibility. Additionally, the prototype is being implemented to treat a Porphyria patient.

Keywords: LED, energy saving, design flexibility, photolithography

Introduction

‘Clean-room’ is a closed area where temperature, humidity and even particle numbers are under strict control. Thanks to it, microchips, having wide applications in electronics, communications, biology and even defence, are becoming more compact and multi-functional. There is no doubt to say that our life has been and will continually be affected dramatically by it. The processes in the clean-room could be divided into 3 main types: film deposition, photolithography and etching. The room dedicated for photolithography could be easily distinguished from the others because it is yellow. The yellow appearance is caused by filtering out of all the wavelengths below 500 nm from a normal fluorescent light source. The reason to that is to protect photoresist from exposure under illumination. Some of the photoresist available in the market have photosensitivity up to wavelength of 460 nm. The wavelength sensitivity of these photoresists could be found from datasheet of company Shipley.

A big problem for the yellow room is the bad color rendering, compared to an ordinary light source and sunlight. People working in photolithography room for a couple of hours suffer a difficult adjustment to normal light. In addition, people may meet problems when they need to make judgement according to colors. For example, the layout of multimasks is usually distinguished by different colors. When people do alignment of different masks, they refer to the different colors. Sometimes it is impossible to do alignment if badly rendered colors are used, which will be discussed more in section 3.3.

White light emitting diodes (LED) are emerging as a promising general illumination light source because they are energy-efficient, have a long lifetime, and are environment friendly. Inspired by this and aiming to improve the color rendering of conventional yellow fluorescent tube (YFT), this paper explored the feasibility of using a LED-based bulb as the illumination light source for photolithography room. A no-blue LED was designed, and the prototype was fabricated. The prototype and the YFT were measured and compared on terms of color rendering index (CRI), correlated color temperature (CCT), chromatic coordinates, and chromatic deviation (DC). The prototype was applied in the photolithography room for test, and no exposure was observed with resist SU8-2005 even after 2 weeks of illumination. The wavelength sensitivity of SU8-2005 could be found from datasheet of company Microchem.

Experiments

The prototype of the 'no-blue' LED was fabricated by RGB Lamps, and shown in Fig.1. It is designed using additive color mixing method [Schubert 2008]. The emission surface has a diameter of 4.2 cm.

Figure1. A photo of 2 no-blue LED bulbs made by RGB Lamps A/S.

The yellow fluorescent tube used in this study is 'L-D 36W/16 yellow' from Philips. The tube was over 1 meter long and too large to be fixed inside the integrated sphere.

The spectral power distribution (SPD) of both the no-blue LED and the YFT were measured inside a dark room at a constant room temperature of 25^0 C. The setup consists of an integrated sphere with a diameter of 1 m that was fiber-coupled to a spectrometer (Andor Shamrock SR-303i with an IDus DV-420A camera). The spectrometer used a 300 l/mm grating yielding a spectral measurement range from 270.6 nm to 838.7 nm, with a resolution of 0.5570 nm. The forward flux measurement setup was calibrated using a standard of spectral irradiance lamp (OL FEL-C S/N F-911 from Optronic Laboratories) and corrections for the absorption changes in the sphere setup were made by using auxiliary lamps.

The input port of the sphere was 7.62 cm (3") in diameter and the LED bulb was mounted just inside the sphere, while YFT was mounted outside of the sphere. The measured SPD was used to calculate colorimetric values e.g. color coordinates, correlated color temperature and color rendering indices for both the LED bulb and the YFT. The total luminous flux was calculated only for the LED bulb.

To visually compare the color rendering of the LED bulb and the YFT, they were mounted above a color chart from Gretagmacbeth. Details of this color chart could be found from

Norman Koren's website at < http://www.normankoren.com/color_management_2A.html >. As reference source a normal 60 W incandescent light bulb was used. Pictures were taken using a Nikon camera mounted on a tripod 1 m away from the color chart.

The prototype LED was brought into the photolithography room for test. The setup is shown in Fig.2: a 4'' Si wafer (marked as 1) was put in a single wafer box, and a 5'' quartz mask (as 2) was placed very closely on top of the Si wafer, then the LED bulb (as 3) was fixed above the mask. The distance between the mask and the emission surface of LED could be adjusted between 0~15 cm. All of these 3 items are put inside a black tube (functioning as a small dark room) to exclude any light from outside and to insure that the bulb does not influence other people's work. Two micrometers thick photoresist SU8-2005 was spinned on the surface of a batch of 4'' Si wafers. The illumination time was set from 1 day, 3 days, 7 days, 10 days, to 15 days for 5 different wafers. Each time, after the set illumination time, the illuminated Si wafer was baked and then developed in SU8 developer for 2 min.

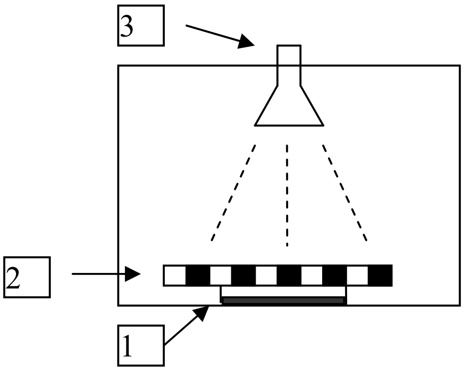

Figure 2. Schematic diagram of the photoresist illuminated by LED prototype. 1: 4'' Si wafer with 2µm thick SU8-2005 resist on top; 2: 5'' quartz mask with designed patterns; 3: LED bulb.

Results and discussions

SPD

The measured SPD for the no-blue LED and the YFT are shown in Fig.3 and Fig.4 respectively.

From Fig. 3, we can see that turquise (peak at 500 nm), yellow (peak at 600 nm), orange (peak at 620 nm) and red (peak at 650 nm) LEDs were used to make the bulb. Blue is not included in the design, therefore, this bulb is called 'no-blue' LED bulb. The spectrum starts at the wavelength of 450 nm and ends at the wavelength of 700 nm. So it can be applied for photoresists having photosensitivity up to wavelength of 450nm, and most of the photoresists are within such range.

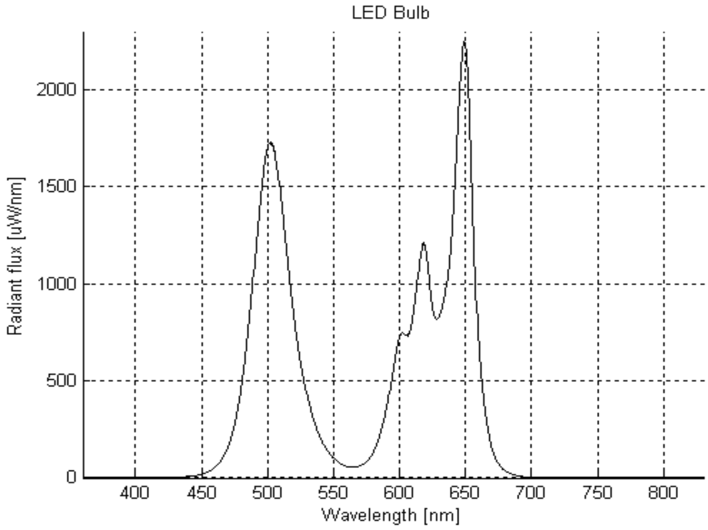

Figure 3. SPD of the no-blue LED bulb.

In fact the starting and ending wavelengths could be easily tuned on demand when designing the LED bulb, which is another big advantage the LED solution has.

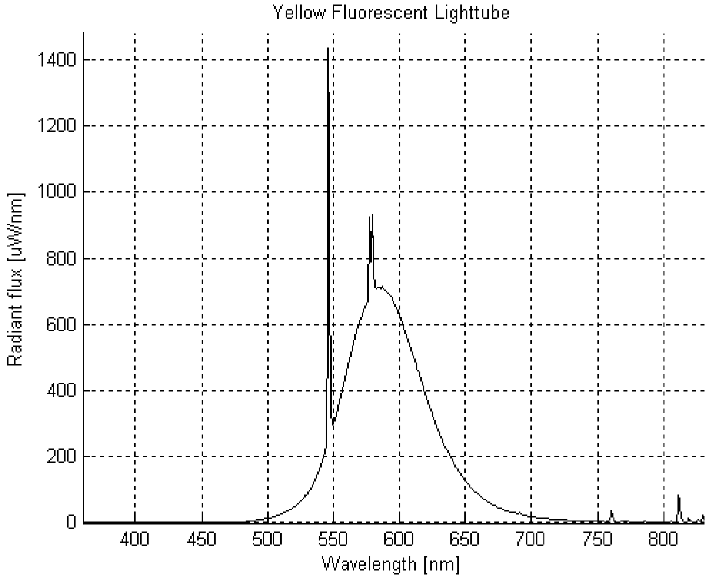

Figure 4. SPD of the YFT.

From Fig. 4, SPD of the YFT covers wavelength range from 500 nm to 700 nm. The two (or 3) sharp peaks at 546 nm and 578 nm in the spectrum are corresponding to the Mercury's gas lines with peaks of 546.074 nm, 576.9610 nm, 578.766 nm respectively. The broad peak is from Halophosphate phosphor, which is explained in Wikipedia's website at <http://en.wikipedia.org/wiki/File:Spectrum_of_halophosphate_type_fluorescent_bulb_(f30t12_w_rs).png>. All the wavelengths below 500 nm have been filtered out.

Colorimetry

Based on SPD, chromatic coordinates, uniform chromatic coordinates, DC, CCT, and CRI were calculated for both LED bulb and YFT. Luminous flux and radiant flux were only calculated for the LED bulb because the YFT is too large to be fitted into the integrated sphere.

The CIE 1960 (u,v)-uniform chromatic coordinate system is shown in Fig.5. It includes the coordinates of the LED bulb, YFT, the Planckian locus and single color (yellow, orange, turquoise, blue, green and red) LEDs. We can see from the figure that LED bulb is closer to Planckian locus than YFT.

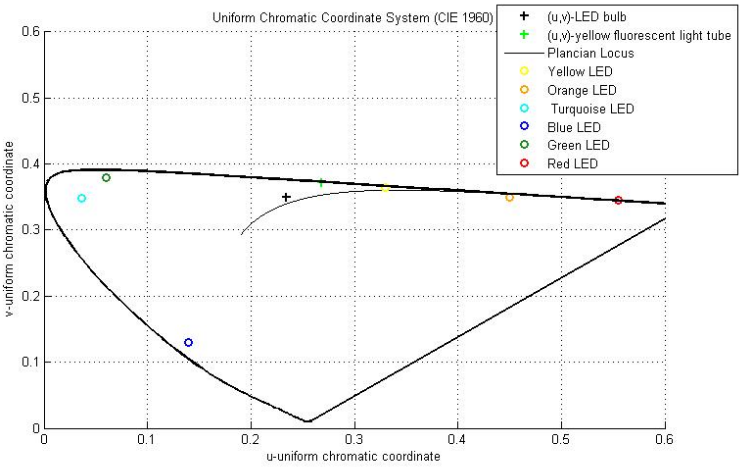

Figure 5. The CIE 1960 (u,v)-uniform chromatic coordinate system including the uniform chromatic coordinates of the LED bulb, the YFT, the Planckian locus and some typical LED locations.

The results of colorimetric values were listed in table 1. Both the LED bulb (DC of 0.0092) and YFT (DC of 0.0186) are too far from the Planckian locus to be perceived as white if 0.0054 standard is applied [CIE, 1995]. In such case, CRI does not have too much meaning.

It should be pointed out here that the no-blue LED can move closer to the Planckian locus by changing the relative intensity of different colors in a new design.

Table 1. Colorimetric values of the LED bulb and the YFT.

	LED bulb	**YFT**
(x,y)-chromatic coordinates	(0.4219,0.4209)	(0.5174,0.4780)
(u,v)-uniform chromatic coordinates	(0.2342,0.3504)	(0.2687,0.3724)
DC	0.0092	0.0186
Correlated color temperature (CCT)	3400	2490
Color rendering index (CRI)	12.7	29.8
Luminous flux [lm]	36.6	-
Radiant flux [mW]	150	-

Gretagmacbeth color charts

To compare how these two light sources render colors, a Gretagmacbeth color rendition chart was used as a very direct way. Comparing the 24 colors illuminated by a) an incandescent light bulb, b) YFT and c) LED bulb, we can see from Fig. 6:

1) All the blue colors (3, 8, 13, 18) are rendered much better by LED bulb than by YFT.
2) All the yellow colors are rendered better by YFT than by LED bulb.
3) Both LED bulb and YFT have difficulty to render light colors (19, 20, 21).
4) LED bulb has better rendering ability towards red colors (9, 15, 17) than YFT.
5) Three different colors (3, 4, 18) in (a) are rendered into same color (c) by YFT. The same goes for color (6, 14) and (10, 13).

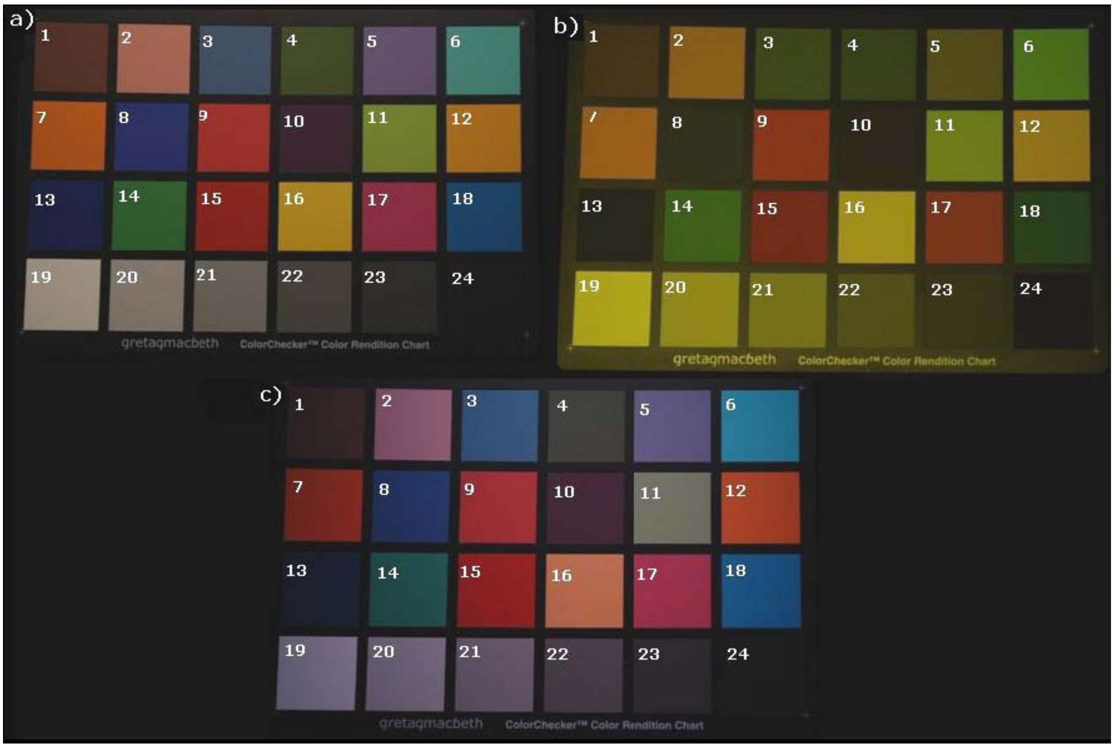

Figure 6. Photographs of the Gretagmacbeth color rendition chart illuminated by a) an incandescent light bulb, b) the yellow fluorescent light tube and c) the LED bulb.

When colors have important roles in photolithograph room, there is much less freedom to select colors for the YFT illumination than for the LED bulb illumination, which can render most of the colors in the color chart beside yellow. Therefore, we can conclude here that the LED bulb has better color rendering abilities for most of the colors in Gretagmacbeth color charts than YFT.

Photoresist exposure test

No patterns appeared on the photoresist after developing for the different illumination duration from 1 day to 15 days, which means the resist was not affected at all by the LED bulb. A photomask is made of dark and bright areas. Light can go through the bright area and then reaches the photoresist, while the dark area blocks light. If SU8 was affected by the LED bulb illumination from the bright area of the mask, the pattern from the mask should appear on some degree in the resist after development.

This test confirms the idea to use the energy efficient LED solution as an alternative illumination light source for photolithography room works.

Future perspective

The ‘no blue’ white LED was initially motivated to improve the working environment in the photolithography room. At a later stage, the prototype was implemented to treat patient suffering the disease called Porphyria. The patient of such a disease is extremely sensitive to the blue components in the white light, which opens up a new field for the applications of design flexible LED-solution. ‘Blue’ in English also means depression. According to a survey in Scandinavia, suicide is the second high death cause only after the top cancer, which is triggered by depression especially in the long and cold winter. There has been research on ‘light therapy’ to treat depression for a long time. It is expected that the emerging LED technology with more technological functionalities will promote the research in this area.

Conclusion

A prototype of no-blue LED bulb was designed and fabricated for photolithography room illumination with the aim to improve the color rendering of the conventional yellow fluorescent tube. The spectral power distribution of both the LED bulb and the YFT was measured. Based on that, colorimetric values were calculated on terms of chromatic coordinates, correlated color temperature, color rendering index, chromatic deviation for both of them. Gretagmacbeth color charts were used as a more visional way to compare the two light sources. Our preliminary results show that our no-blue LED bulb has much better color rendering ability than the YFT. Furthermore, LED solution has design flexibility to improve it further. The no-blue LED prototype has been tested with photoresist SU8-2005. Even after 15 days illumination, no effect was observed. So we can conclude, it is very promising to use LED based solution as a photolithography illumination light source. Based on this example, it is reasonable to expect that this LED-based solution will have more applications in wider areas due to its design flexibility in addition to better color rendering, energy efficiency, and long lifetime.

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See reference:

CIE-See International commission on illumination.

User Responses to Energy Efficient Light Sources in Home Environments

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Introduction

There is a well-known preference for the use of the incandescent light source in domestic homes. The warm and comfortable light from the incandescent is by that a visual preference according to light sources. The more energy efficient light sources available on the market are produced towards efficacy and are not in the same way as the incandescent suitable for human visual comfort. There is a need in domestic homes to create an environment that gives recreation, relaxation, and visual comfort as a calm contrast to a stressful weekday. From a health promotion perspective the light sources that are for sale on the market have an important role in psychological and physiological support of people all over the world. The incandescent light source emits nm within the long wavelength part of the spectrum in a high extent. Long wavelengths in electromagnetic radiation are highly represented in the natural light in early morning and the late afternoon. Long wave radiation gives good support for relaxation. Will LED light sources be accepted in domestic environments and replace the incandescent or are there obstacles for the transition that already can be seen? Visual preferences that guide the consumer when buying light sources to domestic environments have a strong connection to the amount of energy used for lighting purposes on a national and yearly basis, as well as globally and are by that of great importance.

Background

The predominant information about light sources is technical and not in a high extent related to human visual and physiological impact. There is a need of an increase in the knowledge about the interaction between man and artificial light sources and about the psychologically, physiologically and ergonomically direct impact from nanometers. In ‘The impact of modern science on lighting quality’ (CIE 2010, 122-123) Liljefors invite to adapt modern science in vision and the interaction between man and light as a foundation for the evaluation of the human impact from electromagnetic radiation emitted from light sources. In ‘Light response properties of intrinsically photosensitive retinal ganglion cells in non image-forming vision’ Yasuko. K et.al (2009) picture the distinctive light response properties of iPRGCs that is the physiological system behind the direct human physiological impact from light sources.

Aim and problem formulation

The aim of the study is to collect data about users’ opinions about the light emitted from energy efficient light sources according to gender and geographical origin, including there visual preferences according to the level of light on the work space and level of complementary ambient light, the color of the light and the subject´s use of light sources at home and their ability to judge the light emitted from light sources in the luminaries in Test Room 1 and 2. In this article the part of the study that concerns the subject´s opinions about the quality of the light emitted from the luminaries in Test Room 1 and 2 and the subject´s ability to identify the type of light source in the luminaries in the test rooms is interpreted.

Method

The test subjects were recruited by e-mail (due to convenience) which was sent to all students at the School of Engineering. From the group that expressed an interest in participating, 100 people were selected based on a desire to obtain as even a distribution in age and geographical origins as possible. 87 people from 23 countries completed all stages of the study. The group consisted of 43 men and 44 women. The average age was 31 years.

Formation of subgroups

The average values for the entire group's experiences were arrived at as a first step. The group was then divided into three subgroups: Scandinavians, Central Europeans and non-Europeans. Finally, the group was divided into men and women. The average values for the entire group of test subjects were compared with those of the subgroups. The average values obtained from each subgroup were subsequently compared with those of the other subgroups.

Material

Freely formulated responses were assessed and were interpreted according to written guidelines for assessing positive and negative weighting. Each positive or negative light descriptive word was assigned one point. Data on the test persons' experiences of light were collected through a combination of semantic scales and questionnaires with freely formulated responses. In the latter case, the number of positive and negative descriptive words was counted.

Design of the test rooms

All tests were conducted in six rooms. In two of these rooms, light colour, glare and individual preferences for lighting levels were evaluated with regards to levels of light on work surfaces and levels of ambient light. The other four rooms were labelled Test Rooms 1a and 1b and Test Rooms 2a and 2b. These four rooms will in this text be referred to as Test room 1 and Test room 2b. They were completely identical as far as the furniture was concerned, however Room 1a and 1b was designed with the same luminaries as Test room 2a and b, but was equipped with different light sources. The luminaries in Test Room 1a and 1b were fitted with LEDs, halogen bulbs and low energy efficient light bulbs, while Test Rooms 2a and 2b were fitted solely with LEDs.

Picture 1. Test Room 1.

Picture 2. Test Room 1.

Picture 3. Test Room 2.

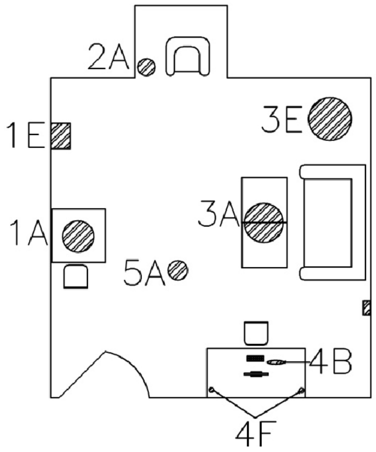

Figure 1. Coded floor plan.

Table 1. Lighting conditions in Test Room 1 and 2.

Test Room 1		**Test Room 2**	
1A	Pendant luminaire. Compact fluorescent 11W E27, 2700K	1A	Pendant luminaire LED 8W E27
1E	Wall luminaire. Compact fluorescent 2x7W, E27, 2700K	1E	Wall luminaire LED 2x4W E27
2A	Reading luminaire. Compakt fluorescent 7W, E14, 2700K	2A	Reading luminaire LED 1,6W E14 Warm white
3A	Pendant luminaire Compact fluorescent 8W, E27, 2700K	3A	Pendant luminaire LED 2W E27 Warm white
3E	Floor luminaire, LED, 1,6W, E27, Warm white	3E	Floor luminaire, LED 1,6W, E27, Warm white
3I	Wall luminarie Halogen 42W 230V, E27	3I	Wall luminaire LED 1,6W E27 Warm white
4B	Reading luminaire Halogen 35W, 12V, GY 6.35	4B	Reading luminaire LED 9W 18V 800 mA Warm white
4F	Ceiling luminaire Compact fluorescent 7W, GX53	4F	Ceiling luminaire LED 3W, 700 mA
5A	Ceiling luminaire Compact fluorescent 7W, E27, 825	5A	Ceiling luminaire LED 2W, E27, Warm white

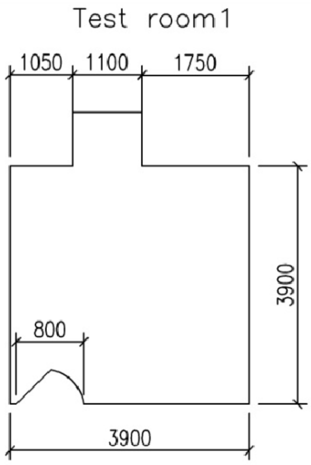

Figure 2. Floor plan 1.

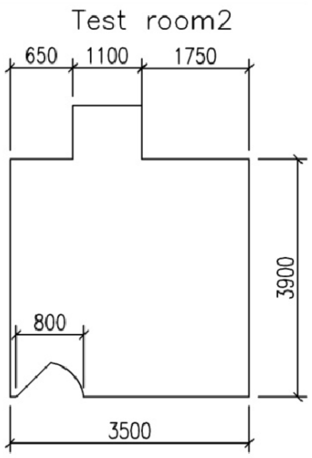

Figure 3. Floor plan 2.

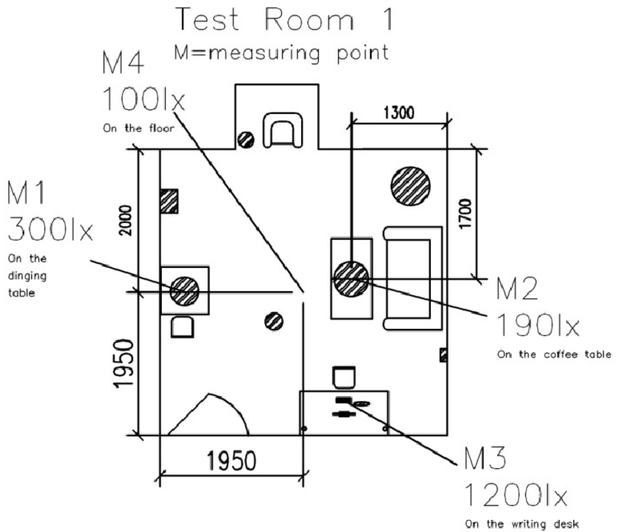

Figure 4. Measuring points Test room 1.

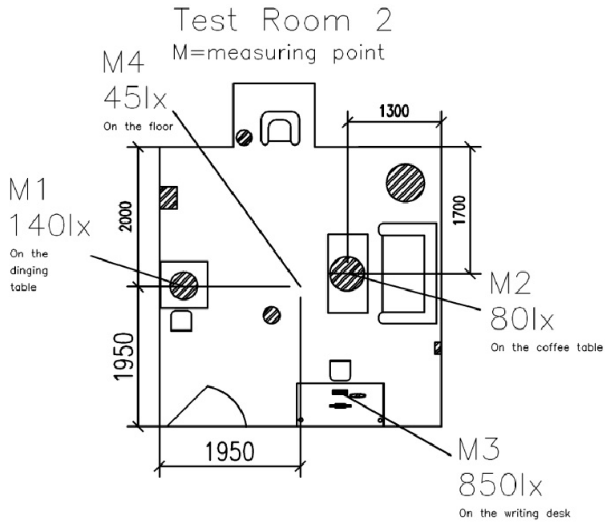

Figure 5. Measuring points Test room 2.

Table 2. Measuring points Test room 1 and 2.

Lux				
Measuring point 1 Dining table	Test Room 1	300	Test Room 2	140
Measuring point 2 Coffee table	Test Room 1	190	Test Room 2	80
Measuring point 3 Writing desk	Test Room 1	1200	Test Room 2	850
Measuring point 4 Middle of the floor	Test Room 1	100	Test Room 2	45

Procedure

The following is the procedure for conducting the study for the test subjects who began in Test Room 1. The allotted time was 50 minutes. The test subjects arrived and were each given a folder. They then carried out a test of visual comfort, after which they recorded the light sources they had at home on a questionnaire. They then received oral information about how the trial was to be conducted. An MP3 player in the room gave the test subjects information about the study's activity plan. Evaluation of the fixtures was carried out. Test subjects evaluated whether the light they were seeing in the room matched the light to which they were accustomed at home. They were then asked to state the way in which they were similar, and to describe the differences if the light did not correspond with the type they had at home. The test subjects were then asked to record their feelings of alertness, fatigue and wellbeing using a scale from 1-5 (a little – a lot). The trial was concluded after approximately 50 minutes.

The following is the procedure for conducting the study for the test subjects who began in Test Room 2. The allotted time was 50 minutes. The test subjects arrived and were each given a folder. They then conducted a study of lighting quality by describing the light in boxes 1-5 in their own words. They were asked to evaluate the quality of the light by assigning a score on a scale of 1-10, where 1=low and 10=high. The study of visual variation in the light on the wall included the test subjects being asked to look at the light source on the wall for one minute and then describe, in their own words, whether they felt that the light had changed during the time they had been observing it. They were asked to describe how the light had changed. The test subjects then carried out a glare test. A box with five different filters was placed on the floor. The test subject stood in a marked square, looking at the light in the box. The test subjects were asked to describe their experience of looking at the five alternatively lit surfaces on a scale of 1-10, with 1=uncomfortable and 10=comfortable. The test subjects received oral information about how the trial was to be conducted. An MP3 player in the room provided test subjects with information about the study's activity plan. Evaluation of the fixtures was carried out. Test subjects evaluated whether the light they were seeing in the room matched the light to which they were accustomed at home. They were then asked to state the way in which they were similar, and to describe the differences if the light did not correspond with the type they had at home. The test subjects were then asked to describe their feelings of alertness, fatigue and well-being on a scale from 1-5 (a little – a lot). The trial was concluded after approximately 50 minutes. The test subjects then continued to the next room, either Room 1 or 2, depending on where they had commenced the study.

Methods for data analysis

Data was evaluated by counting positive or negative words used for subject's opinion of the light emitted from the luminaries in Test Room 1 or 2. Data was compared between the subgroups. Data from the questionnaire used for collecting data about the subject's evaluation of the light sources in the luminaries in Test Room 1 and 2 was compared between the subgroups.

Results

P1=Comfortable, soft, cozy, nice, warm, relaxing, peaceful **P2**=Well functioning level of light, bright enough **P3**=Well functioning spread of the light **N1**=Uncomfortable, unpleasant, disturbing **N2**=Not well functioning level of light. Too high, too low, bad light **N3**=Not well functioning spread of the light						
Test Room 1	Positive			Negative		
Pendant kitchen luminary	P1	P2	P3	N 1	N 2	N 3
Entire group (87)	88	31	3	51	33	4
Scandinavians (38)	39	12	2	31	11	1
Europeans (22)	25	8	0	11	14	2
Non- Europeans (27)	24	11	1	9	8	1
All Men (43)	42	17	2	21	13	3
All Women (44)	46	14	1	30	20	1
Large wall luminary						
Entire group (87)	122	22	1	22	21	3
Scandinavians (38)	69	6	0	12	6	0
Europeans (22)	30	9	1	8	6	1
Non- Europeans (27)	23	7	0	2	9	2
All Men (43)	56	12	1	8	10	1
All Women (44)	66	10	0	14	11	2
Reading luminary						
Entire group (87)	46	15	2	60	62	4
Scandinavians (38)	36	9	0	24	25	0
Europeans (22)	4	3	1	17	19	2
Non- Europeans (27)	6	3	1	19	18	2
All Men (43)	22	7	1	22	31	2

P1=Comfortable, soft, cozy, nice, warm, relaxing, peaceful **P2**=Well functioning level of light, bright enough **P3**=Well functioning spread of the light **N1**=Uncomfortable unpleasant, disturbing **N2**=Not well functioning level of light. Too high, too low, bad light **N3**=Not well functioning spread of the light						
Test Room 2	Positive			Negative		
Pendant kitchen luminary	P1	P2	P 3	N 1	N 2	N 3
Entire group (87)	**55**	**25**	**3**	**83**	**41**	**2**
Scandinavians (38)	**33**	**10**	**2**	**44**	**15**	**1**
Europeans (22)	**7**	**6**	**0**	**28**	**13**	**1**
Non- Europeans (27)	**15**	**9**	**1**	**11**	**13**	**0**
All Men (43)	**26**	**13**	**1**	**30**	**20**	**0**
All Women (44)	**29**	**12**	**2**	**53**	**21**	**2**
Large wall luminary						
Entire group (87)	**92**	**7**	**2**	**45**	**36**	**7**
Scandinavians (38)	**47**	**2**	**1**	**28**	**12**	**3**
Europeans (22)	**24**	**2**	**0**	**13**	**16**	**2**
Non- Europeans (27)	**21**	**3**	**1**	**4**	**8**	**2**
All Men (43)	**37**	**3**	**2**	**15**	**20**	**4**
All Women (44)	**55**	**4**	**0**	**30**	**16**	**3**
Reading luminary						
Entire group (87)	**54**	**16**	**4**	**65**	**52**	**6**
Scandinavians (38)	**33**	**4**	**2**	**39**	**24**	**4**
Europeans (22)	**13**	**4**	**0**	**20**	**15**	**0**
Non- Europeans (27)	**8**	**8**	**2**	**6**	**13**	**2**
All Men (43)	**23**	**8**	**3**	**22**	**24**	**5**

P1=Comfortable, soft, cozy, nice, warm, relaxing, peaceful **P2**=Well functioning level of light, bright enough **P3**=Well functioning spread of the light **N1**=Uncomfortable, unpleasant, disturbing **N2**=Not well functioning level of light. Too high, too low, bad light **N3**=Not well functioning spread of the light						
All Women (44)	24	8	1	38	31	2
Floor luminary						
Entire group (87)	108	20	6	56	29	2
Scandinavians (38)	48	5	3	35	13	0
Europeans (22)	28	8	2	14	8	1
Non- Europeans (27)	32	7	1	7	8	1
All Men (43)	55	8	4	14	21	2
All Women (44)	53	12	2	42	8	0
Pendant luminary						
Entire group (87)	116	30	8	24	22	2
Scandinavians (38)	60	9	4	15	11	1
Europeans (22)	33	11	2	5	5	1
Non- Europeans (27)	23	10	2	4	6	0
All Men (43)	53	10	1	11	11	2
All Women (44)	63	20	7	13	11	0
Small wall luminary						
Entire group (87)	97	18	4	31	21	7
Scandinavians (38)	53	4	1	15	8	4
Europeans (22)	24	6	2	9	4	2
Non- Europeans (27)	20	8	1	7	9	1
All Men (43)	43	9	3	16	12	2
All Women (44)	54	9	1	15	9	5
Desk luminary						
Entire group (87)	79	43	9	38	25	2
Scandinavians (38)	46	17	3	19	12	1
Europeans (22)	17	12	3	10	6	0

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All Women (44)	**31**	**8**	**1**	**43**	**28**	**1**
Floor luminary						
Entire group (87)	**128**	**14**	**4**	**30**	**29**	**3**
Scandinavians (38)	**63**	**5**	**3**	**19**	**9**	**1**
Europeans (22)	**35**	**4**	**0**	**7**	**12**	**1**
Non- Europeans (27)	**30**	**5**	**1**	**4**	**8**	**1**
All Men (43)	**50**	**8**	**3**	**14**	**15**	**2**
All Women (44)	**78**	**6**	**1**	**16**	**14**	**1**
Pendant luminary						
Entire group (87)	**103**	**20**	**2**	**31**	**38**	**2**
Scandinavians (38)	**52**	**11**	**1**	**16**	**13**	**0**
Europeans (22)	**23**	**1**	**1**	**11**	**15**	**2**
Non- Europeans (27)	**28**	**8**	**0**	**4**	**10**	**0**
All Men (43)	**45**	**11**	**0**	**15**	**20**	**0**
All Women (44)	**58**	**9**	**2**	**16**	**18**	**2**
Small wall luminary						
Entire group (87)	**79**	**11**	**3**	**34**	**40**	**5**
Scandinavians (38)	**38**	**4**	**3**	**21**	**13**	**2**
Europeans (22)	**27**	**1**	**0**	**10**	**12**	**1**
Non- Europeans (27)	**14**	**6**	**0**	**3**	**15**	**2**
All Men (43)	**30**	**6**	**1**	**13**	**22**	**2**
All Women (44)	**49**	**5**	**2**	**21**	**18**	**3**
Desk luminary						
Entire group (87)	**109**	**42**	**5**	**31**	**22**	**5**
Scandinavians (38)	**64**	**14**	**2**	**16**	**8**	**0**
Europeans (22)	**30**	**10**	**0**	**9**	**6**	**3**

P1=Comfortable, soft, cozy, nice, warm, relaxing, peaceful **P2**=Well functioning level of light, bright enough **P3**=Well functioning spread of the light **N1**=Uncomfortable, unpleasant, disturbing **N2**=Not well functioning level of light. Too high, too low, bad light **N3**=Not well functioning spread of the light						
Non- Europeans (27)	16	14	3	9	7	1
All Men (43)	33	17	5	18	14	1
All Women (44)	46	26	4	20	11	1
Two ceiling luminary						
Entire group (87)	62	18	12	42	27	6
Scandinavians (38)	38	5	7	20	10	3
Europeans (22)	11	7	2	12	10	1
Non- Europeans (27)	13	6	3	10	7	2
All Men (43)	28	11	8	18	12	2
All Women (44)	34	7	4	24	15	4
Ceiling luminary						
Entire group (87)	76	18	4	38	27	5
Scandinavians (38)	39	8	3	23	12	2
Europeans (22)	16	1	1	13	10	1
Non- Europeans (27)	21	9	0	2	5	2
All Men (43)	33	11	1	18	16	1
All Women (44)	43	7	3	20	11	4

P1=Comfortable, soft, cozy, nice, warm, relaxing, peaceful **P2**=Well functioning level of light, bright enough **P3**=Well functioning spread of the light **N1**=Uncomfortable unpleasant, disturbing **N2**=Not well functioning level of light. Too high, too low, bad light **N3**=Not well functioning spread of the light						
Non- Europeans (27)	**15**	**18**	**3**	**6**	**8**	**2**
All Men (43)	**47**	**16**	**4**	**15**	**9**	**3**
All Women (44)	**62**	**26**	**1**	**16**	**13**	**2**
Two ceiling luminary						
Entire group (87)	**50**	**12**	**6**	**41**	**40**	**6**
Scandinavians (38)	**23**	**4**	**4**	**26**	**19**	**4**
Europeans (22)	**15**	**6**	**0**	**9**	**9**	**2**
Non- Europeans (27)	**12**	**2**	**2**	**6**	**12**	**0**
All Men (43)	**20**	**5**	**5**	**20**	**21**	**3**
All Women (44)	**30**	**7**	**1**	**21**	**19**	**3**
Ceiling luminary						
Entire group (87)	**42**	**4**	**0**	**54**	**57**	**4**
Scandinavians (38)	**22**	**0**	**0**	**35**	**22**	**2**
Europeans (22)	**14**	**2**	**0**	**14**	**13**	**1**
Non- Europeans (27)	**6**	**2**	**0**	**5**	**22**	**1**
All Men (43)	**20**	**3**	**0**	**24**	**24**	**2**
All Women (44)	**22**	**1**	**0**	**30**	**33**	**2**

Test rom	**Number of subjects that evaluate the light sources in the luminaries correct. The lowest and the highest value.**	**Number of subjects that evaluates low-energy light bulbs and Led as incandescent. The lowest and the highest value.**	**Number of subject that evaluates incandescent as LED or low- energy light bulbs.**
Entire group			
1	25-53/87	5-37/87	37-40/87
2	5-34/87	16-35/87	

Test rom	**Number of subjects that evaluate the light sources in the luminaries correct. The lowest and the highest value.**	**Number of subjects that evaluates low-energy light bulbs and Led as incandescent. The lowest and the highest value.**	**Number of subject that evaluates incandescent as LED or low- energy light bulbs.**
Scandinavians			
1	9-24/38	9-20/38	12-19/38
2	4-17/38	6-15/38	
Europeans			
1	5-14/22	2-15/22	7-10/22
2	1-8/22	2-11/22	
Non- Europeans			
1	5-16/27	8-11/27	11-18/27
2	1-9/27	5-12/27	
All men			
1	11-28/43	8-20/43	15/22/43
2	3-21/43	4-18/43	
All women			
1	8-26/44	9-23/44	15/25/44
2	1-13/44	8-19/44	

Discussions of results

The results in this study are originated from the way the material in the luminaries modulated the light from the light sources. The ambition was to make the transition from applications equipped with different energy efficient light sources to the same applications solely equipped with LED and measure the experience.

Discussion of methods

The choice of research method is guided by the ambition to place as a priority the user's visual preferences. User responses can be used as a foundation for the development of lighting technique. In this study the subjects that have words for the experience of the light emitted from the luminaries in the test rooms is well represented. The subjects that have difficulty in putting words on their experiences are not represented to the same extent. If the level of visual awareness and the ability to put words on the experience was used as a method for selection of the test subjects the quality of data in the study could probably be higher. The study is based on artificial light only. The evaluation of the light emitted from artificial light sources will be different if the light is compared to daylight be different. In this case the study is done with the ambition to collect data about visual preferences connected specifically to artificial light and to the chosen types of light sources. It is important to have in mind in lighting studies that the visual experience of the light emitted from the light sources is relative and depends on the references in the eyesight.

Conclusion

The study reveals that visual comfort is an obstacle for the transition from the use of incandescent to the more energy efficient light sources in domestic environments. When the freely formulated answers and the words used for evaluation of the quality of the light emitted from energy efficient light sources in Test Room 1 and 2 were counted, the most frequently used words for positive response with just a few exceptions was concerning visual comfort. Visual support from the light was mentioned with less words and light distribution was mentioned with just a few words. The words used for the experience of visual comfort were comfortable, soft, cozy, nice, warm, relaxing, and peaceful. For the experience of positive visual support from the light the subject´s used most frequently the words, well- functioning level of light, bright enough and good enough. The words used for the positive experience of light distribution were well -functioning light distribution. The negative evaluation of the light emitted from the luminaries in Test Room 1 and 2 was mentioned in the same order as the positive. The most frequently used negative words concerned lack of visual comfort (uncomfortable, unpleasant, disturbing**)**. Then lack of visual support was mentioned (not well functioning level of light, too bright, too dark). With the least words the light distribution was mentioned **(**not well -functioning light distribution). With just a few exceptions both positive and negative evaluations followed the same pattern, visual comfort most frequently mentioned, visual support mentioned in some extent and light distribution rarely mentioned. When the results of the evaluation of the light emitted from the light sources and luminaries in Test Room1 and 2 is analyzed the subject´s point out the light in Test room 1 equipped with Led, Halogen and low energy light bulbs as having a higher level of quality than the light from the luminaries in Test room 2, only equipped with LED. This indicates that the subjects wish for quality in light is not met in the same extent in Test room 2. A possible explanation for the positive response among the subjects in Test room 1 is that halogen brings a certain amount of warmth, clear colors and visual variation to the room that is appreciated by the subjects.

The subject’s knowledge about the basic characteristics in the light emitted from energy efficient light sources is low in the study. The number of subjects that evaluate LED as halogen and halogen as LED shows the subject´s difficulties in judging the light source´ s but also the potential in the development in LED and the design of the luminary. The practical consequences of the study is that the users need of visual comfort and need for support for visual work tasks is pointed out by the subject´s use of words. LED is by the subject´s evaluated as in the applications in Test room 2, less comfortable, cozy, nice, warm, relaxing and peaceful and as giving less support for work tasks than the same luminaires equipped with a combination of LED, Halogen, low energy light sources. There is a challenge for Lighting Technicians to develop the LED replacement light sources in the direction towards general visual preferences. If not succeeded the light source can be an obstacle for the fast transition towards an increase in the use of energy efficient lighting sources.

This study is a first step towards a mapping of user responses to LED in domestic environments.

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Prospects for LED from a Historical Perspective

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Abstract

What are the prospects for LEDs, and will LED contribute to energy efficiency? Europe is in the middle of phase-out of inefficient lighting. Why is regulation necessary, considering that efficient technologies are cheaper in the long run? There are other efficient lighting technologies that can replace incandescent lamps, what is the role of LEDs?

These issues will be situated in a historical context of energy use. Also, a framework will be presented for the sake of explaining inertia in energy use. This framework focuses on two things: First, the stock of products in use, which changes slowly through adding of new products and scrapping of old ones. Second, that use is use of multifaceted products of which energy is just one facet.

Why regulate?

On 18 March 2009 the European Union decided to phase-out inefficient lighting technologies starting 1 September that year. In effect this is a phase-out of incandescent lamps beginning with 100 W incandescent light bulbs, and continuing with lower wattages and ending with a prohibition of 15 W in September 2012 (1).

This is just one of several policy measures taken in order to improve energy efficiency. Why are regulations necessary? Prices for electricity and oil have been rising in the long-term since the 1970s, not the least because of taxes on energy. When costs are rising one would expect that users of energy—households, industries, businesses—change their installations and behaviour in order to compensate for rising costs. For sure, overall improvements in energy efficiency have been made, but there are also tendencies in the opposite direction, of the use of more electric appliances, heavier cars, low cost air travel, etc. Narrowing down to residential lighting, why are householders replacing their incandescent lamps in such a slow manner?

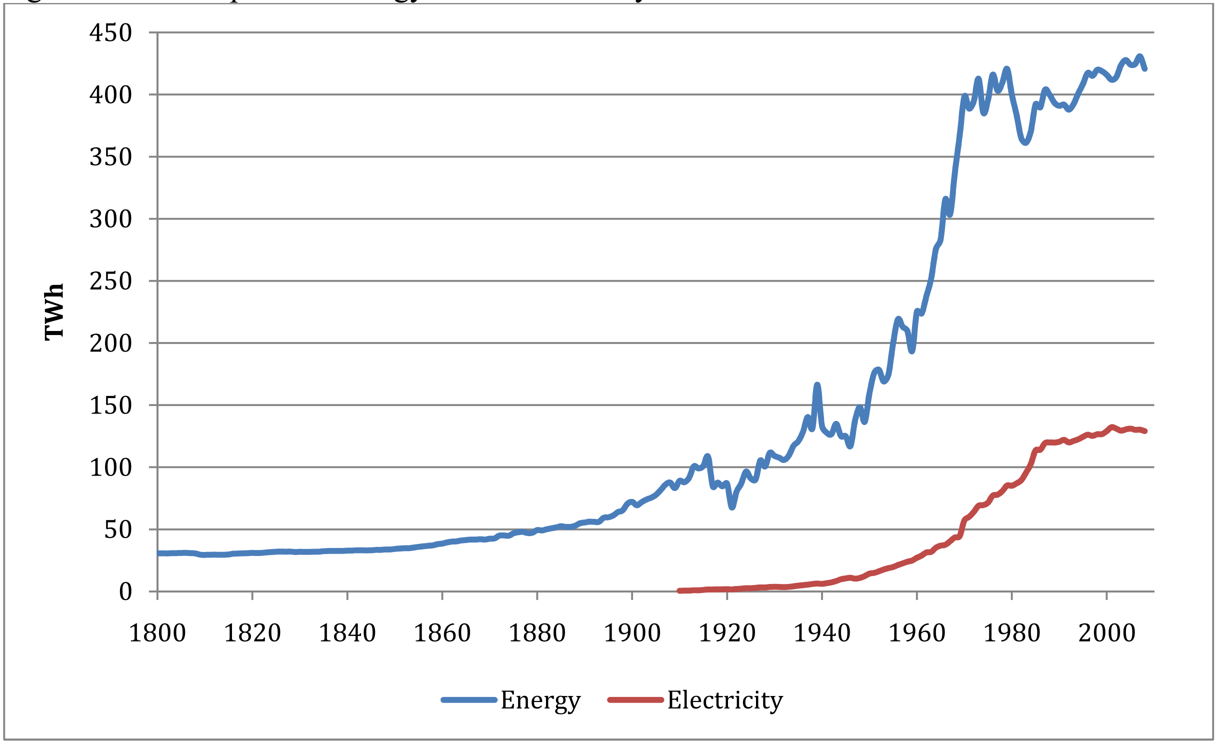
My proposition is that there are large stocks artefacts diffused all over society functioning as energy converters: Industrial machinery, vehicles, buildings, and electric appliances of different types. These stocks change slowly through the adding of new units and scrapping of old ones. Whether this change leads to higher energy efficiency or not is an open question because the renewal of the stock can follow a path-dependent pattern. I will show this with examples from Swedish energy history.

A growing attention to energy efficiency in the mix of characteristics

In the long-term perspective a change occurred in 1970s. At this point in time energy use stagnated in Sweden (and elsewhere in the industrialized world). In the mid 1980s even electricity consumption stagnated. These two long-term changes are of historical significance. Before the first and the second oil crisis in the 1970s energy use increased year after year incessantly as it seemed. For long energy efficiency was a non-issue, as prices decreased, both for electricity and for oil. Energy use could expand without limit it seemed. Then suddenly oil prices doubled as a consequence of OPEC price policy and oil embargos during the winter 1973–1974, and doubled again due to the shortages caused by the Islamic revolution in Iran and the war between Iraq and Iran 1979–1981. This hit hard on oil importing countries, and new policies were introduced. An era of conservation of energy began, and the use of energy became a matter of policy.

Concerning electricity supply, and specifically for Sweden, there was also a radical change. Erection of dams and hydropower stations for the purpose of distributing electricity to end-users—primarily industries, the state-owned railway organization and other big users but also householder's lamps—began in the early 20th century. As electricity is relatively efficient in comparison with other energy carriers, and possible to apply for many different end-use artefacts, consumption increased fast and steadily. High investment costs and economies of scale are associated with this technical system, prices and thus end-user costs for electricity decreased radically from the 1920s, and this reinforced the tendency towards rapidly increasing use of electricity. Investments in hydropower capacity were especially intense in the 1950s and 1960s, when dams, machinery and cables became bigger, more powerful and longer than ever before. At this point in time, however, hydropower ran into resistance from river savers, and the protests gained mass support and became an issue in the political system. In 1970 the fight about one of the few unexploited rivers was won by the river savers, and it was later decided by the parliament not to exploit the remaining four untouched rivers. In effect, this meant that hydropower capacity came to a halt.

Figure 1. Consumption of energy and of electricity in Sweden 1800–2008. TWh.



Sources: 1800–1969 (16); 1970–2008 (17).

Also nuclear power came to a halt, albeit at a later date. After some preparatory efforts Swedish electricity supply companies began investing in nuclear power in the 1960s, and the first reactor were put in operation in 1972. However, a critique of nuclear technology appeared, among others from the Nobel laureate in physics, Hannes Alfvén, who convinced one of leaders of a political party to oppose the operations of nuclear reactors already built and under construction. This party came to power in 1976 and this initiated a heated debate around nuclear power and energy policies in general. After the Three Mile Island accident the debate came to a climax before a referendum in 1980. Even though the outcome of this referendum is a matter of interpretation (and still is) the critique influenced prospects of further investments. After 1986 no reactors have been installed, while two have been shut down, so to the halt in hydropower was now added a halt to nuclear power.

In hindsight a change occurred in the 1970s that has lasted and even been pronounced in later years. For long energy had been a supply issue, where the main problem was how to satisfy the need for cheap energy in industry and transport, preferably without importing fuel from abroad. But now the use of energy came to attention, at first as immediate responses to price hikes in oil. This change was not a clear-cut shift of attention from supply to use. Rather that attention was given to both sides, and still is, albeit climate change has pushed energy efficiency more to the forefront. It must be concluded that when energy supply became scarce, energy efficiency came to the fore, when supply was abundant efficiency at the user end was a non-issue.

Energy is never used directly but always by way of an artefact— a paper machine, a car, a dwelling, a luminaire and lamp. There are stocks of machines, vehicles, buildings and appliances that demand energy. These things are not only energy converters they also have other qualities important for the buyer and user. Kelvin Lancaster introduced the notion of “characteristics” of goods to economic theory (2). His point was that goods were not homogeneous but made up of several aspects, or qualities, or properties. A car, for instance, can be judged according to its energy use characteristics, but also according to its size, speed, weight, design, comfort etc. What energy conservation policies did was to raise energy to a more prominent position among the characteristics of products. Previously ignored or downplayed energy was more and more paid attention by manufacturers and users.

Path dependence and user’s relation to a heterogeneous stock of light sources

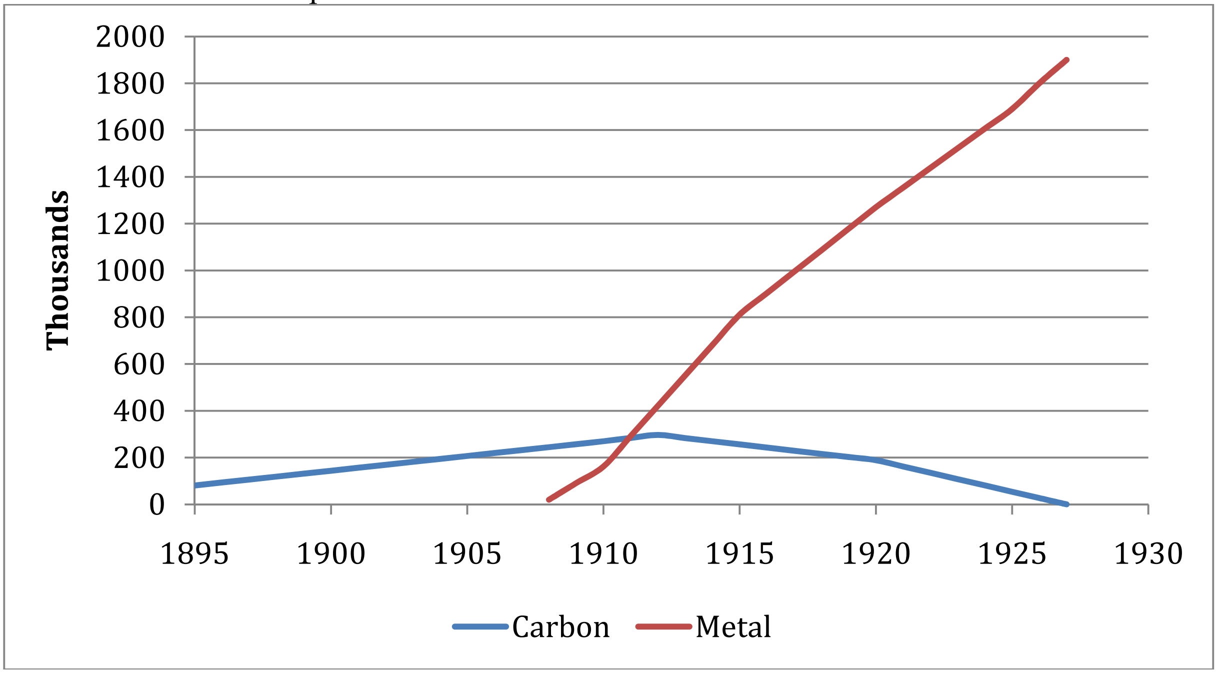
When we think of the stock of lamps in the homes of approximately 4.216 million households in Sweden, as it has been disclosed through the monitoring campaign initiated by the Swedish Energy Agency, we can see several types of lighting technologies beside each other. The main types are incandescent lamps, halogen lamps, fluorescent tubes, and compact fluorescent lamps. To this may now be added a small portion of LED-lamps. Why are the old still here?

Even though the halogen is basically an incandescent lamp it should be regarded as a different type. Because of its regenerative process it has a longer life, a higher efficiency, a whiter light and superior optical properties. The fluorescent tube is definitely a radically different lighting technology. It is not so obvious why we should consider CFLs as a special type. The CFL is a miniaturized fluorescent tube, either U-shaped or in a spiral, sometimes covered by a bulb. A CFL has built-in electronics and a size and sockets suitable for ordinary light-bulb fittings. What makes the CFL different is that it is intentionally made to replace the incandescent lamp, adjusted to the existing stock of luminaires. The necessity of such an adjustment indicates a sort of conservatism, or path dependence.

Path dependence means that both supply and demand follow old patterns. Path dependence does not mean that there is no change at all, rather that change follow a well-known pattern. Manufacturers tend to keep on manufacturing the kind of lamps that they have been manufacturing, and buyers tend to keep on buying lamps that they are using. When Paul David presented the idea of path dependence he pointed at self-enforcing mechanisms in both production and in use. Growing volume of typewriters with a qwerty keyboard exploited increasing returns to scale in manufacturing. Acquaintance among professional typists with that keyboard is an example of self-enforcing mechanism in use, and an example of increasing returns to adoption in the aggregate. Typists trained for a certain keyboard had switching costs, as knowledge residing in finger movements must be un-learned and re-learned for another type of keyboard (3).

The incandescent light bulb is an old innovation. The original Edison incandescent lamp with carbonized filament had a very low rate of efficiency—only 2.6 lumen per Watt. It had an exclusive character and had limited success among ordinary households in competition with kerosene and gas until the metal filament was introduced in the early 20th century. In just a few years the number of lamps with tungsten filament outnumbered the older type in Sweden. While the Edison-lamp never sold more than 297,000 (1912), the new light bulbs sold in increasing numbers, reaching 811,000 in 1915 and 1,619,000 in 1925 (4). These new incandescent light bulbs were more efficient, about 12 lm/W, did not blacken and could be used for more hours (5).

Figure 2. Sales of carbon filament and metal filament incandescent lamps in Sweden 1895-1927. Thousands of lamps.



Source: (4).

Why did the metal filament lamp grow so fast? We do not know. Efficiency and life cycle costs may not have been decisive, it could just as well be that the smoked glass of the carbonized filament lamp made users discontent as they experienced declining brightness over time. On the other hand, the Edison lamp may have prepared the ground, in terms of fixtures and outlets, without which expansion for the new types would have been more difficult.

The metal filament lamps marked a step upwards in efficiency. However, improvements in efficacy came to halt at this level—today it is still around 9–14 lm/W (6). Due to mass production the price could decrease, and due to acquaintance it became the standard lamp among householders. Later came the fluorescent and the halogen. Even though inventions and market introduction were made earlier, the fluorescent did not become common in Swedish homes until the 1970s, and the halogen even later (7). The efficacy of fluorescents has always been very much higher than that of incandescent lamps', never below 30 lm/W, today in the range of 60–100 lm/W. Also halogen lamps have been more efficient, today ranging from 10-30 lm/W (8). The CFL, invented in the 1970s at General Electric, were introduced to the general public in the 1990s, but it is not until the 2000s that they have made any significant penetration (9). The efficacy of a CFL is lower than that of a regular fluorescent tube—60-70 lm/W, or so—but compared to the ordinary light bulb they replace they constitute a clear shift upwards in energy efficiency. Despite these newcomers in residential lighting technology the incandescent has kept its position as the most common light source.

Figures from the monitoring study performed by the Swedish Energy Agency 2005-2008 show that more than 60 per cent of all lamps in Swedish households were incandescent lamps. Halogen comprised 16, CFL 13 and fluorescent tubes 10 per cent (10).

Why this conservatism? When new more efficient lighting technologies appear on the market, why does not everyone buy them? One barrier would be low awareness among ordinary people of energy, or limited knowledge about "Watt" and "kWh". This has perhaps been so, but by now information cannot have escaped anyone, especially as the CFL is called "low energy lamp" ("lågenergilampa") in Swedish stores. Information can overcome one type of barrier, but there may be other barriers, so to speak, behind awareness and knowledge. What about habits? But habits can change. If habits do not change, what is the cause of that? One answer would be that habits have hardened in a lighting culture. The point is that the culture says what a good light is, and this cannot be changed by information.

Harold Wilhite initiated a comparative study of lighting use in Norway and Japan. This was published in 1996 and has become a classic by now. The project team, with members from Norway and Japan, interviewed 18 households in Oslo and 16 in Fukuoka in the early 1990s. Astonishing differences was revealed in this comparison. While Norwegians wanted to create a cosy home the Japanese wanted brightness. Norwegian households preferred several shaded floor lamps, small table lamps and spot-lamps. While there were 10 lamps in a Norwegian living room there were only 2 or 3 in Japanese. Ceiling fixtures and fluorescent light were considered as absolutely inappropriate in a Norwegian living room, but were used in bathrooms and kitchens. The Japanese households, on the other hand, associated incandescent light with insufficient brightness, and often used fluorescent tubes fixed in the living room ceiling. In bathrooms several Japanese respondents said that incandescent lights were appropriate because they lighten up without delay (11).

Thus we can talk about a Nordic lighting culture where households use many small luminaires with a warm glow for the sake of a cosy atmosphere. The existence of this lighting culture was confirmed by a study reported to the European Commission. While the average number of lamps per household was 24 in the EU in 2007, the average was 42 in Sweden; The average wattage for incandescent lamps was 54 in the EU but 32 in Sweden, and for CFLs 17W in the EU but 8W in Sweden (12).

However, even cultures can change. The phase-out in EU (and in the USA 2012-2014) (8) will change lighting set-ups in many millions of homes in Europe and America. What does the stock look like before and after the phase-out, how fast will incandescent disappear, and what is the prospect for LED when these changes are taken into consideration? Some figures from Sweden will be presented here.

How fast is renewal of the lighting stock, and what are the effects of the phase-out?

We do not know so much about the lighting stock. The studies made so far are not representative of the whole household population. The number of households covered is small, from a statistical reliability point of view, due to the fact that data collection is cumbersome as the hours-of-use is essential information to collect. The most comprehensive study made so far, is that already mentioned by the SEA 2005-2008. Data from this source is shown in Table 1.

Table 1. Unweighted averages on Swedish household's use of electric lighting 2005-2008.

	Small houses	**Multi-dwelling houses**
Number of lamps	55.2	31.2
Wattage per lamp (W)	29.3	26.6
Hours-of-use per day and lamp	1.60	1.94
Number of households (000)	1,978	2,238
Electricity for lighting (TWh)	1.87	1.31
Lighting/all electricity (%)	22.7	19.0

Sources: (10), (13), (14). "Small houses" include detached houses and houses with two dwellings. "Multi-dwellings houses" often contain shops, offices and other non-residential spaces, but the main purpose is residential.

It must be emphasized that the real stock can be different. The sample is small in relation to the population of households, and the geographical distribution of the sample is quite narrow (concentrated to an area in the south-middle of Sweden including Stockholm westwards, "Mälardalen"). On the other hand data covers several types of households in regard to housing, age, number of people, etc., and it is very detailed comprising observations on each appliance (including each lamp) every ten minutes for a month or a year. So, data is accurate and contains a lot of information, but it is not representative. With this in mind, we can let data give us a hint of what the national consumption of electricity for lighting would look like. From data in Table 1 it can be calculated that there are 179 million lamps in total.

Table 2. The distribution on lamp types in Swedish households, and assumed lifetime and price level for each type. Per cent, hours, Euro.

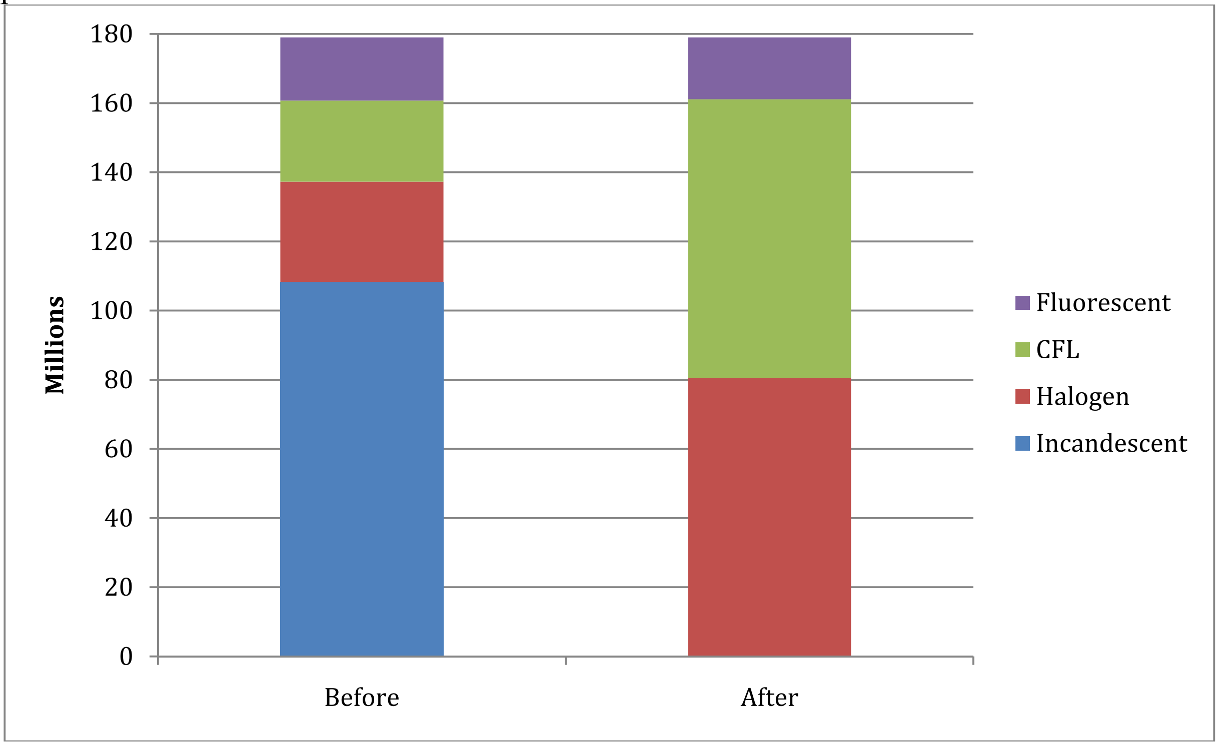
Lamp type	**Share, %**	**Life time, h**	**Price level, €**
Incandescent	60.5	1000	1
Halogen	16.2	3000	4
CFL	13.1	7000	6
Fluorescent tubes	10.2	10000	6

Sources: (10), (15). Currency rate assumed: 10 SEK=1€. 1 USD ≈ 0.75€ in May 2010.

Lifetime and price level varies from one variant and from one brand to the other. Prices presented are common prices in stores and on the Internet in Sweden in May 2010. Life times used are common assumptions in the literature (6, 9). Assumptions on lamp's life are necessary due to the secrecy of sales of lamps. *Belysningsbranschen,* a trade association for Swedish lighting manufacturers and lighting consultants, does not disclose any information on sales. However, in a press release from the SEA we are told that *Belysningsbranschen* said that "sales of incandescent lamps decreased with 36 per cent" in the autumn of 2009 compared to the autumn of 2008. Halogen lamps increased with 85 per cent and CFL with 90 per cent (15). This indicates that halogens and CFL will replace 108 million incandescent lamps.

With data presented in Table 2 it is possible to calculate the rate of turnover. Before the phase-out (with over 60 per cent incandescent lamps) the rate was 43 per cent per year. After the phase-out, assuming 0 per cent incandescent lamps, 45 per cent halogens, 45 per cent CFL, and 10 per cent fluorescent tubes in the new stock, the rate becomes 14 per cent. Despite this decrease in the rate of renewal, the value of sales actually increases somewhat, from 113 to 119 million Euros—on the condition that prices remain the same. On the other hand sales of electricity will decrease. When halogen and CFL replace incandescent lamps it can be estimated that the average wattage per lamp will decrease from 28 to 18, and total energy consumption for electric lighting will decrease from 3.2 to 2.1 TWh. If prices for 1 kWh are 0.15€ then income for electricity suppliers will decrease from circa 483 to 308 million Euros—a transfer from suppliers to consumers of about 175 million Euros.

Figure 3. Possible change of domestic stock of lighting in Sweden. Before and after the phase-out.



Sources: (10), (13), (14).

The problem for the future prospects for LED lamps is that the phase-out started with a LED supply limited to a low lumen range. As of Spring 2010 a consumer can find LED lamps up to 100 lumen only, at affordable prices. Brighter lamps are very expensive and seldom found in ordinary stores. It can be argued that LED lamps will appear in the coming years that are able to compete with halogens and CFLs. However, the CFL have the lead and will be bought during the phase-out. LED lamps can perhaps cover 10 per cent of the stock in the coming years, in which case lamp sales would decrease to 108 million Euros due to longer life, electricity use to 1.9 TWh and electricity sales to 281 million Euros due to lower wattage. LED lamps will have to wait five years for halogen lamps, and ten years for CFLs, to be scrapped. However, this may be fortunate, as it gives manufacturers the time to develop LED modules acceptable to consumers.

These changes in the national residential lighting stock are based on certain assumptions described above. The real effects of the phase-out may turn out differently. However, one thing is for certain— the incandescent lamps will disappear within the next few years. The Nordic lighting culture, which had the warm glow of the incandescent lamp as a fixed point for the definition of the good light, must change. The question is whether lamps that get as close as possible to the light of the incandescent lamp will prevail in the long run, or if the Nordic lighting culture will radically change or disappear.

Monica Säter’s study (this volume) shows that test subjects preferred halogen before LED light sources (18). Nevertheless, subjects gave positive judgements on the LED-light in five out of nine cases and, surprisingly, Scandinavians were more positive to the LED-light than Europeans. This indicates that a Nordic lighting culture can change when the lighting stock changes due to the phase-out. Bladh (19) studied the acceptance of LED and CFL in one Swedish household. All incandescent light sources were replaced with either CFL or LED-lamps, as if the phase-out was carried out in a single stroke. Even though this household adhered to the Nordic lighting culture it accepted the new lights, including LED-lamps with a bluish light at the bed. Six months after the radical change of the lighting set-up, all new light sources were still there and they had no intention of return to the old lamps or replacement to halogen lamps.

These studies indicate that the Nordic lighting culture is not rock-solid. There are no signs of hoarding of incandescent lamps in Sweden that would indicate a strong adherence to the existing culture. This has to do with the rather passive way lighting is used. Other technologies, especially those associated with mobility and communication (cars, motorcycles, computers, mobile phones) engages the user in a fundamentally different way than passive technologies like ventilation, dishwashers and lighting. With some technologies the user can be active and in that activity develop his or hers capabilities and/or communications with other people. Other technologies do not offer such explorations in active use, but has more to do with comfort and design.

Furthermore, the fact that several lighting technologies exist side-by-side point at the possibility that LED will add to the lighting stock, extend millions of lighting set-ups with more lamps added to the existing ones. LED-lights may be used as decorative lights in gardens, as Christmas lights on house fronts etc. The low lumen range of LED-lamps available now (in 2010) in ordinary stores, indicates that their role as replacements is not here yet, and as additions to the stock LED-lamps will not contribute to energy efficiency.

Conclusions

This paper analysed the use of lighting in terms of a changing stock of lamps. All kinds of durable goods give rise to a stock of units, and it is this stock that is used. In focus is the relation between users and the stock, at the individual level between one household and a part of the total stock put into one dwelling or near that dwelling. A stock changes through replacements and extensions. When old units are scrapped new units take their place. New units can also be added to the existing stock, thus extending it.

This frame of analysis can be used on many end-user products and for different purposes. Here energy efficiency and lighting are in focus. For the former a long-term view was applied, explaining why energy efficiency is on the agenda and how stocks change. Many durable goods are energy converters. They are many ‘things’ or, as Kelvin Lancaster said, durables are composed of several “characteristics”, of which their energy converting aspect is one. The energy characteristic was given attention from 1970s on, when man-made scarcity of oil induced a change in policy from supply to conservation. Whether scrapping and replacement in stocks of such energy converters improves the overall level of energy efficiency is an open question. Other characteristics than energy can be more important for the user.

The domestic lighting stock is peculiar in the sense that in homes we will find several lighting technologies beside each other. Despite newer and more efficient types of lamps the incandescent lamp is still here, but now the object of a phase-out in the EU. This heterogeneity is a sign of conservatism and a failure for energy efficiency. It is argued in this paper that replacement of worn out lamps follows a path dependent pattern. One mechanism of path dependence is that habitual use of lighting has hardened in a lighting culture, a Nordic lighting culture when it comes to Sweden, where the warm glow from the incandescent lamp suits the intention of creating of a cosy atmosphere with many small lamps. Another mechanism is the existing fittings and luminaires that make it impossible or difficult or inappropriate to buy certain lamps. The CFL is a proof of this, as this type of lamp is intentionally adjusted to fittings shaped for incandescent light bulbs.

Data from the monitoring study performed by the Swedish Energy Agency of 400 households in Sweden, in which electricity use was metered in detail, was used as an illustration of the stock-approach. It was shown that the phase-out would eliminate 60 per cent of all lamps, that the total value of lamp sales would increase a little despite a radical decline in the rate of renewal, and that the total value of electricity would decline significantly leading to a transfer of money from electricity suppliers to consumers.

The prospects for LED-lamps were considered to be one of delay. As halogen and compact fluorescent lamps already are available in stores today, they will replace incandescent lamps scrapped from the stock. The supply of LED-light, at affordable prices, is limited and cannot take the role of replacement. It is probable that LED can be the second generation of energy efficient lighting. The quality of LED-light can change in the future, or preferences can change when the lighting stock changes with increased shares for halogen and CFL.

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