

## CHAPTER 1

# AN OVERVIEW OF THE DEVELOPMENT OF MAJOR LIGHT SOURCES: FROM LIGHT BULBS TO SOLID STATE LIGHTING

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This chapter reviews briefly the major development of light sources including incandescence light, fluorescence light, lasers, particularly, the semiconductor laser and high-brightness blue/white GaN-based LED. It shows that the nano-science, in a broader sense, has played a critical role in the subsequent commercialization of these great inventions by making them become commercially viable products. It also reviews some major events and national initiatives that took place worldwide in the last decade, particularly, in USA, Japan, China and Taiwan, in the development of this emerging solid state lighting technology. These historically significant events have contributed to the development of a much desired and more efficient lighting source which could address some of the major challenges facing us today, namely, energy, environment and protection of our earth.

### 1. Introduction

After over a century since the introduction of electric light sources, two traditional lighting sources which are still commonly used today- the incandescence light and fluorescence light, have failed to achieve an electrical power efficiency over 25%. As the energy becomes scarce, and our environment becomes endangered, a new and more efficient lighting source is critically needed.<sup>1</sup>

In the meantime, it is estimated there are about 2 billion population on the earth still do not have electricity, and therefore, do not have electrically generated light in their daily life.<sup>2</sup>

These two major challenges that the traditional lighting sources have failed to meet after they have been employed for over a century, namely, the low efficiency and low coverage of lighting on the earth. The emerging of GaN-based semiconductor lighting sources in the past decade promises to fulfill both of these challenges.<sup>3,4</sup>

In 1909, when the tungsten incandescence light bulb was first introduced commercially by GE, it had an efficacy of 10 lm/W. It took 30 years to reach this critical level of efficacy since the carbon filament light bulb was developed by Edison in 1879. For over a century, the incandescence light has been one of the major lighting sources. To date, the efficacy of the incandescence light bulbs is less than 20 lumen/W; only twice as much as what was achieved 100 years ago. There has been little progress made over the entire century.

Coincidentally, it took also about thirty years for LED to reach a level of brightness of 10 lm/W since the first LED was invented in early 1960. However, it is the high brightness GaN-based semiconductor blue and white LED light sources developed by Shuji Nakamura at Nichia in 1995 that opened a totally new chapter in the history of the development of lighting sources. These achievements have stimulated significant research interest and efforts in bringing this technology to commercially viable lighting products and this technology has been progressing in a truly amazing pace.

Today, an efficacy about 200 lm/W has been demonstrated<sup>5</sup>; an almost 20-fold improvement over what was first introduced a decade ago. At this level of efficiency, we could address those two most critical challenges that traditional lighting sources have failed to resolve, namely, to develop a highly efficient lighting source and to bring light to every corner of the world.

### ***1.1. Major milestones in the development of light sources***

If we list the major milestones in the development of light sources chronically, they are

- The incandescence light bulb developed by Thomas Edison in the late 19th century. This was the first time that electric lighting was introduced in the first 200 millennia of the human history;
- The invention of coherent light sources, particularly semiconductor lasers in the mid-20th century, This was the first time a light source with coherent properties was developed; and,
- The development of high-brightness blue/green GaN LED in the late 20th century, and later the high-brightness semiconductor-based solid state white light sources. This was the first time opening a new era of highly efficient and all solid state lighting sources.

All these breakthroughs have led to significant advancements of modern electronics, optoelectronics and material sciences and technologies, and made profound impacts upon how we live, work and communicate.

For example, the invention of incandescence light bulbs not only lit the world for the first time in the entire human history, but also created a major market for the electricity. It accelerated the development of electricity generation, transmission, and conditioning, and thus brought forth the infrastructure of a modern society that relies heavily on electricity.

The invention of lasers, particularly semiconductor lasers was the key component used in the modern fiber optical communication (the backbone of Internet), digital optoelectronics systems such as CD, DVD and laser printers. The development in these technologies has brought us the Internet and digital electronics that have made profound impacts upon our life.

The invention of high-brightness white LED, still in the early stage of development, has already made significant inroad from back light modules used in LCD displays, automobile lights and head lamps, to architecture lighting with a flurry of new applications coming out everyday.

These efficient light sources are going to save enormous amount of energy, reduce greenhouse gases generation, and make our environment cleaner. In addition, a high efficient solid state light source offers the

possibility of bringing light to billions of population on earth living in the darkness without electric light in the entire human history.

In the following sections, we discuss the critical role that the nano-science, in a broader scope, has played in improving the efficiency of these light sources and making these inventions commercially viable lighting sources.<sup>6,7,8</sup>

## 2. Incandescence light bulbs

When Edison was trying to make an incandescence light bulb work, there were several other similar attempts by other inventors, however, none of them could succeed in making the incandescence light bulb last long enough. Edison persisted and invented a carbon filament placed inside an oxygen-free bulb which could burn for forty hours by 1879. Nevertheless, the incandescence light bulbs at the time had two critical problems for being useful as a consumer product, namely, the efficiency was too low and the life was too short.



Fig. 1. The Edison's incandescence light bulb in 1882. (Courtesy of GE Company).

If Edison's effort were to end here, the incandescence light might not become as widely used as it is today and Edison might not be credited as

the great inventor of the incandescence light bulb. (This story sounds similar to the development of GaN-based LED a century later.)

Two technical breakthroughs were critical to making this light source technology useful and become a commercial successful product:<sup>6,7,8</sup>

First, there was a young chemist, Irving Langmuir, who was recruited by Edison to work on improvement of the life and efficiency of the incandescence light bulb. Langmuir discovered the bulb life and efficiency could be significantly improved when he introduced an inert gas into the light bulbs,

In the course of his investigations, Langmuir realized the importance of the adsorbed layer on the surface chemistry and developed the vacuum system for his experiments. He performed fundamental studies of surface chemistry and invented the apparatus for making mono-layers adsorbed films that bears his name, Langmuir-Blodgett films. He pioneered the science of monolayer adsorbed films and invented the first gas-filled incandescence light bulb that is used today.

Langmuir's pioneering work on the surface chemistry of monolayer became the foundation of surface sciences, today, generally called nano-sciences. He was awarded a Nobel Prize in chemistry in 1932 for his discoveries and investigation in surface chemistry. In fact, he was the first industrial scientist ever to receive a Nobel Prize for the work that was motivated to improve the light bulb's life and efficiency.

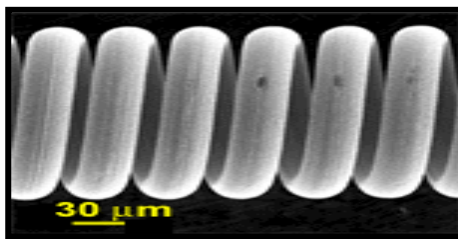


Fig. 2. The coiled tungsten filament used in the incandescence light bulb developed in 1909 by William Coolidge. (Courtesy of GE Company).

In the meantime, the effort seeking for a new filament material to improve the efficiency and life of the incandescence light bulbs led to the development of coiled tungsten filaments by Coolidge (Fig. 2). In 1909,

almost thirty years after the invention of light bulbs by Edison, the tungsten light bulb became a commercial product with an efficacy reaching 10 lumen/W which was about an order of magnitude improvement over that of the original Edison's light bulb.

As the incandescence light based on the principle of blackbody radiation, it was recognized that the efficacy of incandescence light could be improved by increasing the filament temperature at the expense of the operating life. Halogen lamps overcome this problem by introducing a small amount of halogen gas inside a quartz envelop to allow the lamp operated at a higher temperature, in the meantime, the tungsten evaporated from the surface will recombine with halogen gas and then redeposit onto the filament. This regenerative process employs a subtle surface chemistry to allow the lamp operated at a much higher temperature, thus improve the lamp efficacy while maintain a good life time; another wonder of nano-science!

The Halogen light has an efficiency of about 15-20 lumen/W. The efficacy of the incandescence lamp, however, has made little improvement in the last century in spite of intensive research effort. The incandescence light remains as a dominant light source used in the residential building in USA. The overall power conversion efficiencies of these incandescence lights are about 5%.

### 3. Fluorescence light

Perhaps few people realize that Edison was also an inventor of a fluorescence lamp and he even had a patent filed in 1896 for a x-ray fluorescent lamp and granted in 1907. This Edison's invention however never became a successful commercial product because X-ray is not economically feasible as a light source. It wasn't until 1938, a practical fluorescent lamp was successfully designed by GE and was subsequently marketed that year.<sup>9</sup>

A fluorescent lamp contains a small amount of mercury inside a tube filled with a low pressure inert gas like argon. The inside of the glass tube was coated with a phosphor layer. When the lamp is turned on, the discharge current induces electrons to collide and excite the mercury atoms. The UV emission from Hg atoms converts to visible light through

phosphors. The fluorescence lamps have efficacies ranging from 60-100 lumen/w and are the work horse in commercial indoor lighting. The overall power conversion efficiencies of various fluorescence lamps, however, are about 25%.

The incandescence and fluorescence lights are the dominant lighting sources used in residential and commercial indoor buildings and account for almost 90% electricity energy consumed for lighting. Non-building lighting such as street light and commercial outdoor lighting account for the rest of total electricity used for lighting. In general, the total electricity consumed for lighting is about 20% of the total amount of the electricity generated worldwide.<sup>10</sup>

#### **4. Coherent light sources: semiconductor lasers**

The invention of coherent light sources via the stimulated emission is a remarkable scientific and technical achievement. Among all the coherent light sources developed to date, the semiconductor laser represents one of the most important coherent light sources ever developed.

When the first GaAs semiconductor laser was operated at GE Research Labs by R.N. Hall and his co-workers in the mid-20 century, it was a rudimentary device (Fig. 3) operated at the liquid nitrogen temperature with a high threshold current density.<sup>11</sup> This device didn't become a commercially viable device until the invention of hetero-junction structures which allows the carrier confinement, and thus greatly reduces the laser threshold current.

More importantly, in the decades that followed, the development of molecular beam epitaxial (MBE) process and molecular engineering that provided a powerful instrument to allow the precise material growth atomic layer by layer in the nano-meter scale contributed significantly to the successful deployment of semiconductor lasers used today; another wonder of nano-science!

To date, GaAs-based laser devices are used in the fiber communication, digital devices such as CD/DVD and laser printers. It has made profound impacts to our life and to the way we communicate. Today, the most efficient semiconductor light emitting devices are semiconductor lasers in the infrared. This type of semiconductor light

emitting devices produces high power output on the order of hundred of watts in infrared. They are the preferred light sources which have replaced discharged flash-lamps for pumping solid state lasers. They are also used as the pump sources for the fiber amplifier; a critical component used commonly in the optical communication.



Fig. 3. The first semiconductor laser developed at GE. (Courtesy of GE Company).

## 5. GaN-based blue and white LED

When LEDs were invented in the late 60's, the output power was so low that they were used only as indicator lights in display panels. After nearly thirty year intensive development till mid-1990's, the efficiency of most LED devices were still very low, for example, GaP LED at 555 nm had an external quantum efficiency of 0.07%, and SiC LED at 470 nm 0.02% with the exception of GaAlAs red LED at 660 nm which had an external quantum efficiency of 12%.<sup>12</sup> Due to the lack of high power and high efficiency, major applications for LEDs till then were limited to the indicator light. In addition, lack of a high power LED in the blue and

green color has restricted the use of LED to less than full color applications.

In 1993, when the first high brightness blue GaN LED was commercialized by Nichia,<sup>13</sup> and two years later, the green GaN LED.<sup>14</sup> In the years that followed, Nichia further developed the high brightness white LED by mixing of blue LED with yellow phosphors. Since then, the field was revitalized and the outlook was totally changed. (Fig. 4)

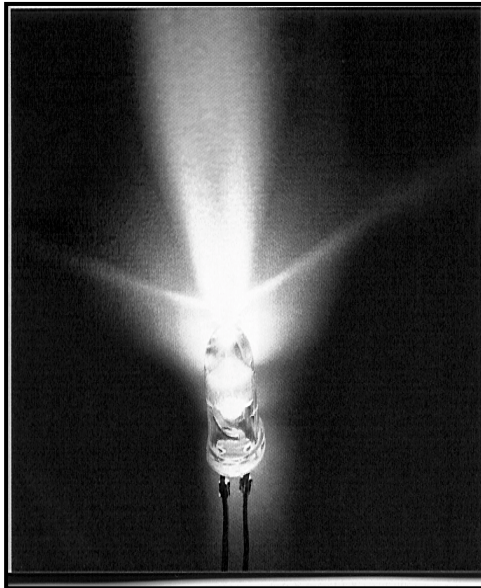


Fig. 4. The first GaN-based white LED developed by S. Nakamura at Nichia. (Courtesy of Nichia Company).

The applications of GaN LED have been rapidly expanded by the advancement made in the high power LED epi, device and packaging; all of these employ various advanced nano-technologies such as quantum-dots, quantum-rod, and photonic crystals. These sophisticated nano-technologies are found in the high power LED devices used in LCD backlights, automobile illumination, and the RGB white light sources in the projection display. In the future, we expect that nano-science and

technology will continue to play a critical role in realizing the ultimate goal of making a 200 lm/W device or beyond.<sup>5</sup>

## 6. DOE ALITE 1995

In 1995, US Department of Energy (DOE) organized a workshop, ALITE (Advanced Lighting Technologies) held in Washington DC that involved major lighting companies such as GE, Phillips and Osram to identify promising areas for pre-competitive research in the basic science of commercial light sources that might lead to major breakthroughs in the performance and efficiency. It was recognized at the time, that lighting consumes about 20% of the total electric energy generated in USA and the efficiencies of major light sources used over the century were merely 5-25%.

After intensive presentation and discussion among about 80 experts coming from world leading academic, industrial and research institutions, the ALITE Workshop reviewed all types of traditional light sources including incandescence lights, fluorescence lights, halogen and HID and other conventional light sources, the group concluded that in spite of the intensive R&D efforts, the technologies of three major conventional lighting sources, namely, incandescence, fluorescence and halogen, have not shown any significant improvements in the past thirty years.

In addition, the workshop further concluded at the time that the semiconductor light source is the only promising technology that mostly likely to make breakthroughs for achieving a much higher efficiencies. In the conclusion of the workshop, it was predicted that LED lighting would reach 10 lumen/watt by year 2000 and >100 lumen/watt by year 2005 with up to 100,000 hours of life. The output of the ALITE Workshop was published in a report (EPRI Report, TR-106022), called, “Vision 2000 Lighting Technology Roadmap” which could be seen as a white paper for the national solid state lighting project launched later.<sup>15</sup>

I left the workshop convinced that LED lighting is going to be an important technology for the GE lighting business and initiated a program at GE funded by the GE Lighting Business to look into the feasibility of using LED for general lighting applications in 1997. This was the very first funded project at GE on this emerging solid state

lighting technology after GE invented the LED in early 60s and then dropped the LED research program in early 70s. The reason for dropping the LED research program was “it will never be useful for general lighting applications” as concluded by the GE management.

At ALITE workshop, I also met Dr. George Craford who was heading the LED research program at HP. We had good exchange at the workshop discussing the possibility of using LED for lighting applications. After ALITE workshop, I made a special trip to visit him. We spent an afternoon together in his office at the HP Research Center in Palo Alto, CA, and continued the discussion in the following February 1996.

### Ratio of Luminous Efficacy

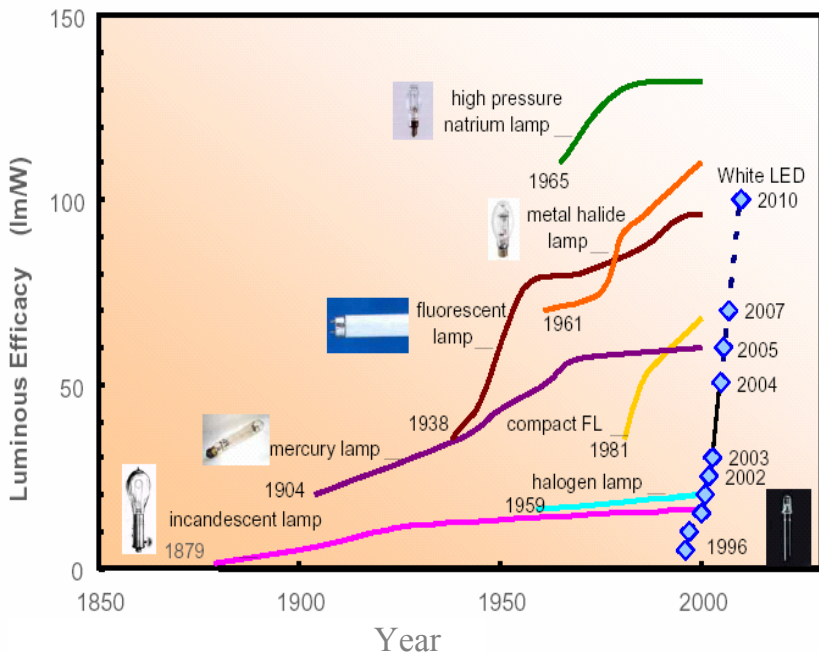


Fig. 5. The efficacies of major light sources evolved over the entire centuries. (Courtesy of Nichia Company).

In November 1996, HP and Philips announced in the news the formation of a joint venture called, LumiLEDs, to develop LED-based

lighting products and business. That was the very first business venture formed by a major international company devoted solely to the development of LED-based lighting sources. Personally, however, I was a bit disappointed for not having HP team up with GE to work together on this emerging lighting technology with a tremendous potential.

Almost at the same time, there were major technical breakthroughs taking place in Japan. Nakamura and his coworkers at Nichia published a paper, entitled, “High-brightness InGaN/AlGaIn double-hetero-structure blue-green-light-emitting-diodes”.<sup>13,14</sup> The research results were quickly commercialized as Nichia started to sell blue LED products. Nakamura and his coworkers further combined the blue GaN LED with YAG phosphors to generate white LED with an efficacy reaching over 10 lumen/W. This marked a new generation of high brightness LED and quickly transformed the LED into a new kind of light sources and opened a new era of solid state lighting! The evolution of various major light sources is shown in Fig. 5 in which the commercially available white LEDs sold by Nichia are used for comparison.

## 7. Japan MITI’s “21st Century Solid State Lighting Project” 1998

In 1997, trying to capitalize the leadership role after having invented this new lighting sources, Japan’s MITI (Ministry of International Trade and Industry) announced the plan for a 5-year, 5B Yuen (US\$40M) national project, “The 21st Century Solid State Lighting” to develop GaN-based LED white light for general lighting applications with a goal of 120 lumen/W by 2010 (Fig. 6). At the time, this goal seemed to be too aggressive to be realistic when the commercial product announced at the time by Nichia was only about 10 lumen/W.

In October 1997, I represented GE to visit Dr. Yoshi Tabata, then MITI’s Program Director, to understand the purpose and background of this national project. I was told that the targeted goal of 120 lumen/W was not an extrapolation from the technical roadmap, rather it was dictated by the Kyoto Protocol declared by the Japanese government to cut the total greenhouse gas emission at least 5% from the 1990 level in the commitment period from 2008-2012. MITI’s 21st Century Lighting



Fig. 6. The poster for the national project on “21st Century Solid State lighting Project” initiated by MITI, Japan in 1998; the first national project ever on this technology in the world.

Project was formally launched in the following year in 1998 with participation of most companies from the LED industry in Japan except Nichia.

The MITI’s solid state lighting project represented the first national effort in the world launched to develop efficient solid state light sources for general lighting purpose and was driven by the concern of environmental conservation by the Japanese government.

Prof. Tsunemasa Taguchi of Yamaguchi University was the PI leading this project and the project was jointly carried out by the New Energy and Industrial Technology Development Organization (NEDO) and the Japan Research and Development Center for Metals (JRCM) through a subsidy provided to NEDO by the Ministry of Economy, Trade and

Industry (METI). The Government provided a total funding of 6.2 Billion Yen between 1998 to 2004, and 2.5 Billion Yen, from 2004 to 2009.

The research topics in the 21st Century Lighting Project covered the following areas:

- Fundamental studies on emission mechanism in GaN-based compound semiconductors,
- Improvement of epitaxial growth methods for near ultraviolet (UV) LEDs.
- Large substrates for homo-epitaxial growth.
- Development of phosphors which generates white light excited by blue and near UV LEDs, and
- Realization of illumination source using white LEDs.

Japanese government's SSL initiative, not only focused on general lighting as the main target, it also focused on applications such as medical. One such project administrated by Ministry of Education, Culture, Sports, Science and Technology (MEXT) was "white LED to medical applications" which was to investigate high power white LED lighting systems for medical applications funded at 2.5B Yuen for five years from 2004 to 2009.

In retrospect, MITI's 21st Century Lighting Project is to be considered as one of the most significant national projects ever launched by any nations in the world.

## **8. USA Next Generation Lighting Initiative Alliance (NGLIA)**

In USA, the Office of Naval Research (ONR) organized a workshop chaired by Dr. Y.S. Park in 1998 in Washington on the GaN LED technology. The workshop invited experts from GE, HP, Sandia Lab., Cree Research and UCSB among others. This workshop was conducted to assess its potential for general lighting applications.

The US Department of Energy (DOE) initiated programs on solid state lighting research and development since 2000. In partnership with the private industry, the Next Generation Lighting Initiative Alliance (NGLIA) was established. The DOE initiative has made significant

progress since then. The NGLIA includes both organic and inorganic LEDs as the viable technical approaches in the program. The members include GELcore, Lumileds, Color Kinetics, Cree Inc., Dow Corning Corp., Osram Sylvania, Eastman Kodak and Air Products and Chemicals.

In the course of these initiatives, some significant accomplishments were made including: Lumileds Lighting in partnership with Sandia National Laboratories developed nano-photonics devices using quantum dots and demonstrated a quantum efficiency of 76%. Cree Inc. achieved 70 lumen/W with their commercial packaged LED operated at 350 mA in 2005; an increase of 43% in brightness compared with the current devices then.<sup>15</sup>

In 2006, President Bush signed National Energy Policy (NEP) called for “reliable, affordable and environmentally sound energy for America’s future.” The US Government allocated a budget of USD\$50M to fund the SSL program in the next seven years. In particular, DOE has set the following mission statement for the SSL research and development effort:

*“Guided by a Government-industry partnership, the mission is to create a new, U.S.-led market for high-efficiency, general illumination products through the advancement of semiconductor technologies to save energy, reduce costs and enhance the quality of the lighted environment.”*

## **9. China’s National SSL Program 2006**

In 2003, the Ministry of Science and Technology of China (MOST) together with the Ministry of Information Industry, and the Chinese Academy of Sciences and other government bodies plus eleven local government initiated a government committee for China’s SSL and formally launched the national SSL program.<sup>16</sup>

In February 2006, as part of government 11th five-year plan (2006-2010), MOST allocated RMB350M (USD\$44M) to support the national solid-state lighting program. The growth of the high technology sector is key to China’s future development, and LEDs are seen as an indispensable part.

One goal of the national SSL program is to stimulate domestic production through the use of public-private partnerships. Participation to the national program will include more than 15 research institutions and university research labs, as well as more than 2500 companies involved in LED wafers, chips, packaging and applications.

Another key goal of China's SSL program is energy savings. China is the second largest energy-consuming country after the US, and its energy consumption per dollar of GDP however is much higher than Japan, Europe or the US. The country has set an ambitious plan to quadruple its total GDP by 2015, but hold the increase of her energy consumption only by a factor of two.

Lighting is seen a key element for the increase of energy demand, especially as 14 million rural Chinese move to cities each year. The adoption of SSL will be an important element in reducing the growth of energy demand. China expects to be the largest market for LEDs and solid-state lighting in the world." From reports, it is apparent solid state lighting will become a rapid growing industry in Asia in general, and in China in particular.

## **10. Taiwan's solid state lighting program**

Taiwan has become a leading producer of GaN LED with a production capacity of about 1.1B per month GaN chips and 1.25B per month of InGaAlP chips. Taiwan is now ranked as the world leading producer of both GaN and InGaAlP chips.<sup>17</sup> The MOCVD industry in Taiwan grew rapidly since 1998 with commercial MOCVD reactors installed in production estimated exceeding 300 units.

### **10.1. GaN-based solid state lighting research**

From 1997 to 2000, the GaN program at ITRI (Industrial Technology Research Institute) funded by the government focussed on the epitchnology for growing InGaN LED UV and blue LED, and LED chip processes, such as contacts, dry etching and chipping processes for high power and high efficiency GaN-based LED devices for display and lighting applications.

Since 2001, the ITRI research program started to address packaging technologies as well as lighting applications critical to energy conservation. Technologies on special package designs for lighting application as well as packaging technologies using flip-chip for high power devices were developed. The program has been coupled closely to the lighting industry and LED-based lighting equipment. Demonstrations using solid state lighting for replacement of conventional lighting sources for energy saving and environmental conservation have also begun in this phase.

ITRI played in key role in technology development and personnel training for the industry. The close interactions between ITRI and local industry had contributed to the rapid growth of the MOCVD industry during this period.<sup>18,19</sup>

### ***10.2. Next Generation Semiconductor Lighting Research and Development Consortium (2002-2005)***

One of the major industrial projects funded by the Ministry of Economic Affairs was the “Next Generation Semiconductor Lighting Research and Development Consortium,” formed in 2002 with participation of ten LED companies to develop advanced solid state lighting technologies with goals to achieve: (a) 100 lumen/W lab devices, and (b) 50 lumen/W proto-type commercial devices by 2005.

The consortium members were Epistar, Forepi, Ledtech, LiteOn, Opto-tech, Everbright, Kingbright, Tyntek, ParaLight, and Unity. Dr. Frank Chien of Forepi served as PI for this R&DC project.

This research and development consortium was successfully completed in 2005 by meeting its original technical goals. For the LED industry, this project was significant in that it was the first time, multiple companies worked together in a research project performing various tasks to achieve a common goal. It was a novelty to both the business culture and practice in Taiwan where most companies tend to work on research alone. Throughout the project, ITRI played a key role working with member companies in planning, organizing, facilitating and performing some of the technical tasks from the beginning till its completion.

The funding supports for solid state lighting programs come from Department of Industrial Technology, Ministry of Economics Affairs (DOIT/MOEA) for research and engineering, and from Commission of Energy, Ministry of Economics Affairs for solid state lighting demonstration, and lighting-based module technologies.<sup>20,21</sup>

## 11. Conclusion

As the world energy becomes scarce, and our environment becomes endangered, a new and efficient lighting source is critically needed to replace the traditional lighting sources which have electrical power efficiencies less than 25%. In the meantime, it is estimated there are about 2 billion population on earth still do not have the electricity, and therefore, do not have electrically generated light in their daily life. The traditional lighting sources have failed to meet these two challenges for over a century since they were introduced. The GaN-based semiconductor lighting source developed in the past decade promises to overcome both of these challenges.

In this chapter, we discussed major technological advancements in the history of the light source development including the invention of light bulbs in the late 19th century, the invention of coherent light lasers, particularly semiconductor lasers in mid-20th century, and the high-brightness blue/white GaN-based LED in the late 20th century. We showed that in each of these scientific breakthroughs, the nano-science and technology, in a broader sense, have played a key role in the subsequent commercialization of these inventions and made them into successful products.

We further reviewed several major events and national initiatives in USA, Japan, China and Taiwan for the development of viable solid state lighting sources to save energy, reduce green house gases and protect our environment and the earth.

Looking into the future, it is just as Edison proclaimed when he invented the incandescence light bulb that,

***“... Where this thing’s going to stop, Lord only knows...”***

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