Technical Trend

Light Sources and Ballast Circuits

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ABSTRACT

According to the machinery statistics by Ministry of Economy, Trade and Industry (METI), the total of domestic light bulb production in 2006 was 1,101 million (88.5% year-on-year). Production for general purpose illumination light bulbs and halogen light bulbs accounted for 122 million (99.2% y/y) and 45 million (96.3% y/y), respectively. The total of fluorescent lamp production was 988 million (114.9%) and the production of general purpose fluorescent lamps excluding backlights accounted for 367 million (101.7% y/y). Further, HID lamp production was 10 million (106.3% y/y). What is noteworthy regarding such lamp production is that, similar to the previous year, the sales volume (amount) of lamps for general illumination exceeded 100% against the previous year, indicating a steady shift to high value added products. Major lighting exhibitions in 2006 included the Light + Building Trade Fair held in Frankfurt in April and the Light Fair International 2006 held in Las Vegas, U.S.A. in May, both of which demonstrated signs of acceleration toward energy saving, high efficiency and resource saving. As for incandescent lamps, products filled with larger atomic weight gases aiming at higher efficiency/longer life are becoming the mainstream. As for new technologies, it was experimentally demonstrated that infrared radiation can be suppressed by processing micro cavities to metal plates made of tungsten, tantalum, etc. For fluorescent lamps, straight and circular fluorescent lamps achieving a longer life/higher luminous flux maintenance factor continued to be widely developed/launched again this year. For compact fluorescent lamps, energy saving/high efficiency products, multifunctional type products combined with LED and new shaped products were launched. As to HID lamps, ceramic metal halide lamps with high efficiency, improved color rendering, longer life and higher luminous flux maintenance factor were commercialized one after another. Numerous studies and analyses, on discharge models were reported. Further, studies on ultra high-pressure mercury lamps as light sources for projectors are becoming the mainstream of HID lamp related researches. For high-pressure sodium lamps, many studies on plant growing and pest control utilizing low insect attracting aspects were also reported in 2006. Additionally, for discharge lamps, the minimum sustaining electric power for arc tubes employed in electrode-less compact fluorescent lamps was investigated. For Hg-free rare-gas fluorescent lamps, a luminance of 10,000 cd/m² was attained by a 1 meter-long external duplex spiral electrode prototype using Xe/Ne barrier discharge. As to startup circuits, the commercialization of energy saving and high value added products mainly associated with fluorescent lamps and HID lamps are becoming common. Further, the miniaturization of startup circuits for self electronic-ballasted lamps has advanced. Speaking of the overall light sources and startup circuits in 2006 and with the enforcement of RoHS in Europe in July, the momentum toward hazardous substance-free and energy saving initiatives has been enhanced from the perspective of protecting the global environment. It is anticipated that similar restrictions will be globally enforced in the future.

1. Incandescent lamps

The total number of domestic light bulb production in 2006 was 1,101,047 thousand (88.5% y/y), of which 121,775 thousand accounted for general purpose illumination light bulbs (99.2% y/y) and 45,317 thousand for halogen light bulbs (96.3% y/y). Each category of general purpose illumination light bulbs decreased

against the previous year in terms of quantity and monetary amount¹⁾. Incandescent lamps have become widespread particularly in homes and stores as a light source owing to their warm light, adjustability, instant light-up capability, compactness and reasonable price. Their shipments had gradually decreased with the advent of circular fluorescent lamps. However, with the

development of krypton gas-filled light bulbs (argon gas is mainly used for general light bulbs) in 1990, incandescent lamp shipments began to slightly increase. Although it is an intelligent decision to choose a highly efficient light source such as fluorescent lamps as the main lighting source, it is also a fact that the light output is not the only efficacy of light source used for general lighting. The percentage of incandescent lamp shipments against the total shipments of all lamps is large, accounting for approximately 32%²⁾. This indicates that incandescent lamps are nevertheless indispensable for daily life.

However, in Cuba and Jamaica, the use of incandescent lamps in homes is being banned as a measure against global warming and they are being replaced by compact fluorescent lamps. In the Japanese lighting industry as well, the orientation toward resource-saving and energy-saving, together with miniaturization, high-efficiency and long-life, is becoming the norm, in response to the requirements under the current global environmental protection trend. Against this backdrop, higher efficiency of general purpose incandescent lamps is realized by changing the filler gas from krypton to the larger atomic weight xenon gas and improving coil designs, and next generation power-saving compact light bulbs are being merchandised³⁾ (Figure 1).

These next generation light bulbs are categorized as krypton light bulbs under the current product statistical classification. Xenon gas reduces heat loss by its low heat conductivity and suppresses filament evaporation. As a result, the product life has been doubled from the exciting 2,000h to 4,000h.

Reports on halogen lamp products introduced the exhibition items of "Light + Building 2006"⁴⁾. Most of the exhibits were products that are already being much discussed. There were exhibits that proposed the re-

placement of incandescent lamps to halogen lamps based to provide energy-savings in homes. A fuse embedded halogen lamp with aluminum reflectors was one of the new products exhibited at the fair⁴⁾ (Figure 2).

As to new technologies, a report on micro cavity was made at 2006 Annual Conference of IEI-J. The reason for the low efficiency of incandescent lamps is that approximately 80% of the consumed electric power is used for infrared radiation and only approximately 10% for visible radiation. As a measure to improve efficiency, a tungsten micro cavity radiator, with 1 million or more 300-350nm cavities per 1mm² are processed on the surface, is being proposed. With these micro cavities, infrared radiation can be suppressed, thereby dramatically improving the luminous efficiency, and the use of this radiator as a filament is being considered as a new technology that can prolong the product life by setting the temperature to 2,000-2,100 K. It is also proven through experiments that infrared radiation can be suppressed by processing micro cavities to metal plates made of tungsten, tantalum, etc.⁵⁾ However, when being used as filaments, they must be processed into a coil-shape in order to produce light emission using a conventional commercial power supply, since the resistance of such high melting-point metals is low. A method to process micro cavities on the surface of filaments is not yet established and thus, this proposal has not been put to practical use.

On the other hand, attempts are being made to employ recent nanotechnology applied materials as light sources. Namely, the use of a carbon nano-tube (CNT) as an alternative material for filaments is being considered. CNT, a structure of cylindrically bonded carbon molecules, is a material possessing a high electron emission capability and melting point. In addition, CNT, being composed of carbon, is almost a blackbody mate-

Figure 1 Long-life small electric lamps (© Matsushita Electric Industrial Co., Ltd.)

Figure 2 Fuse embeded halogen lamp with aluminum reflectors (© OSRAM GmbH)

rial, thus the radiation is higher than filaments made by metals such as tungsten, if sufficiently heated. Yet, since both visible and infrared radiation becomes high, it remains necessary to review its luminous efficiency. The following effects of CNT have been proven through experiments. When CNT is heated by applying current, higher luminance is attained compared with a 40 W tungsten filament at the same voltage, and infrared radiation can be reduced with single-walled CNT in comparison to the blackbody. While it is an interesting finding that the infrared radiation can be reduced, the impact on visible radiation must be investigated. Further technological advancement is desired since there is still much to be reviewed before this technology can be put to practical use.

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2. Fluorescent lamp

According to the machinery statistics by METI¹⁾, the total number of domestic fluorescent lamps produced in 2006 was 988 million (114.9% y/y). The sales were favorable at 869 million (111.0% y/y) in terms of quantity and 318.3 billion yen (107.5% y/y). However, this growth is mainly attributable to the approximately 20% increase in both quantity and amount of fluorescent lamps for backlight use and the statistics for general purpose fluorescent lamps excluding backlights remained unchanged, namely, the total production was 367 million (101.7% y/y), sales quantity was 382 million (99.7% y/y), and sales volume was 209.9 billion yen (100.9% y/y). Meanwhile, for compact fluorescent lamps, which became a separate category since 2005, the sales quantity slightly increased to 24 million (102.0% y/y) and sales revenue slightly decreased to 26.0 billion yen (97.1% y/y).

With respect to new domestic products, many seeking longer life/higher luminous flux maintenance were developed/launched for straight and circular fluorescent lamps²⁾. For compact fluorescent lamps, high value-added products of higher efficiency and multi-functions, as well as new products aiming at expanding the lineup

of new shaped products were launched. Developments in straight, circular and compact fluorescent lamps are described below.

Luminous flux maintenance improved from approximately 70% at 6,000h to approximately 80% at 9,000h for straight FL20 and circular FCL30, 32, 40 lamps coated with UV protection material thereby reducing insect attraction³⁾. The UV protection consisted of ultra-fine particles applied to the first layer of the inner glass wall also acts to suppress Na deposition from the glass and prevent blackening/coloring.

The technology of thickening silica protection coating has contributed to the improvement of luminous flux maintenance²⁾. The technology is applied to straight FL20 and circular FCL30, 32, 40 lamps, and the luminous flux maintenance of circular fluorescent lamps has improved to approximately 80% from the conventional 70% at product life time of 6,000h⁴⁾. A similar technology is also applied to straight FL40 and FHF32, a dedicated type for high-frequency lighting, and the product life time of both types has reached 15,000h⁵⁾.

For fluorescent lamps with afterglow functions of FL20, FCL30, 32, 40 types, products with 25% improved persistence effect compared to the conventional types have been launched, whose product life time has also improved to 9,000h which is 1.5 times the conventional life time⁶⁾. In addition, their luminous flux maintenance levels have improved to approximately 80% at 9,000h from 70% at 6,000h.

For fluorescent lamps of FL20, FCL30, 32, 40 types, the inferior luminous intensity has improved by approximately 30% by processing a reflection coating to the upper half of the inner glass wall²⁾. The luminous flux maintenance level has improved from approximately 70% at a product lifetime of 6,000h to approximately 80% at a doubled life time of 12,000h⁷⁾ (Figure 3). Specifically, in terms of technology, the improvement in blackening/coloring was achieved by the optimization of the emitter coating quantity and the adoption of a spherical silica protection coating that suppresses the reaction between Hg and Na of the glass.

For straight FL20 and circular FCL30, 32, 40 types, products with warm light color, whose correlated color temperature is 2,500K which is lower than that of the commonly used light bulbs, were commercialized⁸⁾.

For compact fluorescent lamps, a product equipped with three LEDs inside the exterior globe, where the fluorescent lamp or LEDs can be selected by a switch (EFA15/13-N), has been commercialized for the first time⁹⁾. The total luminous flux of its fluorescent lamp is equivalent to a 60W type incandescent lamp, and the illuminance of the LEDs immediately below is equivalent to a night-light bulb.

Figure 3 Three-band fluorescent lamp with 12,000 h life time
(© Toshiba Lighting & Technology Corporation)

The most popular shape for compact fluorescent lamps is either A or G type, which is similar to that of incandescent lamps²⁾, EFT10/8 and EFT15/12, that are slimmer T type lamps with globes of 38 mm outside diameter, were launched¹⁰⁾. Both are alternative products for 40 W and 60 W type incandescent lamps in terms of luminous flux. Further, in Europe and the U.S., EFTC15/12 whose exterior globe is shaped for popular chandelier lamps, has also been launched¹¹⁾.

Progress in the miniaturization of compact fluorescent lamps with afterglow functions, namely EFA15/13 and EFG15/12, was observed⁶⁾.

The EFR25/22, which is an alternative product for 100 W type reflex lamps suitable for spot lights or down lights requiring higher illuminance, was launched¹²⁾. The maximum outside diameter of the reflector globe is 90 mm and the maximum intensity of light in the direction of its illumination is 300 and 280 cd for three-band incandescent light color type and daylight type, respectively.

Compact fluorescent lamps with correlated color temperature of 2,500 K were also launched in addition to the straight and circular types with the same correlated color temperature⁸⁾.

The EFA15/10, which achieved the highest efficacy with power consumption of 10 W among the alternative products for 60 W type incandescent lamps, was developed and commercialized¹³⁾ (Figure 4). While its shape and size are not much different from that of the conventional product¹⁴⁾ EFA15/12, the product lifetime has been improved to 10,000 h from 6,000 h owing to the increase in emitter coating quantity which was realized by introducing quadruple coils. It is said that the improvement in the efficiency of this product is due to the

Figure 4 Compact fluorescent lamp with power consumption of 10 W (© Matsushita Electric Industrial Co., Ltd.)

lengthened discharge path of the duplex spiral arc tube, specifically 1.2 times that of the conventional products. In addition, on and off performance has also been improved to 30 thousand times from the conventional 20 thousand times through adoption of an IC drive preheat circuit.

While all of the lamps described above are of the socket size of E26, in response to the rise of incandescent lamps of the socket size of E17, EFA15/13-E17 has been released as an alternative product for 60 W incandescent lamps¹⁵⁾. However, since this lamp is larger than the conventional krypton lamps, specifically its dimension is 55 mm (maximum outside diameter) and 109 mm (length overall) while that of the conventional krypton lamps are 35-34 mm and 58-81 mm, respectively, it is assumed that this lamp cannot be mounted in many cases in the appliances designed for the conventional lamps.

A self-ballasted EFP12, 20, which has a U-shaped 12 mm glass arc tube adopting a G23 socket, was commercialized¹⁶⁾. This product requires exclusive appliances, yet unlike the conventional compact fluorescent lamps that are mounted to E type sockets, the potential for slimmer and thinner appliance designs has been expanded.

Focusing on global trends, the world's largest lighting-related exhibition, namely the Light + Building 2006, was held in Frankfurt, Germany in April and an on-site report was made¹⁷⁾. Further, LIGHTFAIR INTERNATIONAL 2006 was held in Las Vegas, U.S.A. at the end of May¹⁸⁾.

The following describes the fluorescent lamps exhib-

ited at the above exhibition. For straight fluorescent lamps, the exhibitors primarily displayed T5 tubes. The broadened lineup, including products securing over 90% of the relative luminous flux at a circumference temperature range of 5-70 degrees C by adopting amalgam, long-life products, 8,000K high color temperature products, and special color lamps, attracted much attention. For T8 tubes, the competition for achieving longer product life and higher luminous flux maintenance level was severe, as symbolized by the 70,000h products. The technological challenges are said to lie mainly in the electrode structure, material selection and manufacturing techniques. Prolonging the product life of compact fluorescent lamps is also the trend, whereby two types of 42,000h lamps with luminous flux peak at 15 °C and 25 °C, respectively, were exhibited. High wattage products adopting amalgam were also announced. Compact fluorescent lamps of various wattages, sizes and shapes were exhibited, not only by manufacturers of Western nations but also China, Hong Kong and Taiwan. Products with new functions, such as those enabling continuous dimming down to 10% as well as restart from a dimmed condition and lamps that have four-level intermittent dimming capabilities from 100-5%, were also announced. Further, electrode-less compact fluorescent lamps with 15,000h product lives were introduced.

Next, I will report on academic trends. I will introduce Proceedings of the 39th Annual Conference of IEIJ at Kansai University in August and literatures on fluorescent lamps contributed to the Journal of Light & Visual Environment of the Illuminating Engineering Institute of Japan (IEIJ) in 2006. Meanwhile, there was no literature on fluorescent lamps contributed to Journal of the Japan Illuminating Engineering Institute of Japan (Japanese journal) of the IEIJ. This can be attributed to two reasons; first, a slowdown in overall research activities in this area and second, an increase in overall contributions to the English Journal.

In relation to the development of A-type compact fluorescent lamps with shape and light similar to incandescent lamps, a 7 mm thin arc tube, a key to lamp designs, and a compact inverter circuit that can be housed in the E26 socket, as well as lamp structures was reported¹⁹⁾²⁰⁾. In order to improve the luminous flux maintenance level of circular fluorescent lamps, overcoating materials were considered. It is demonstrated that an overcoating with a thickness of 2 μm or more is effective to suppress the reaction between Hg and Na in the glass and that silica is more suitable than alumina for the forming process by heat that is unique to circular fluorescent lamps²¹⁾. A basic study was conducted on the early evaluation method of solarization, which is caused by a trace component contained in the glass of the fluorescent lamp, and it was found that the application of

ultraviolet rays is more suitable than X-rays²²⁾. As to emitters that influence the product life of fluorescent lamps, in order to clarify the wear caused by vaporization and sputtering of the main component Ba, the Ba atom density was measured by a laser-induced fluorescence method, and it was found that the primary factor of Ba release is the vaporization at the anode²³⁾. Characteristics of a product equipped with amber LEDs for night-light and fluorescent lamp as a main light source, either of which can be selected by a switch, were introduced²⁴⁾. Compact fluorescent lamps that belong to a new category, namely those with a 12 mm U-shaped glass arc tube and inverter circuit housed in G23 socket, were developed, thereby achieving higher efficiency and thinner appliances compared to the conventional FPLs²⁵⁾. The mechanism of luminous deterioration during product life for cold-cathode fluorescent lamps used for the backlight of LCD TVs was studied, and it was proven that the impact of Hg absorption of blue fluorescent material is significant and that such deterioration can be improved by applying an overcoat to the blue fluorescent material²⁶⁾. The improvement in start-up capability of cold-cathode fluorescent lamps by filler gas was studied. As a result, it was found that start-up voltage can be lowered and luminous efficiency can be raised at the same time, by reducing the gas pressure with Ne95/Ar4/Kr1 composition²⁷⁾. For 135 kHz-driven electrode-less fluorescent lamps with an input of 150 W, the radial distribution of plasma characteristic was investigated by a double probe method, and it was found that the electron temperature is constant regardless of position and that the electron density reduces as the distance from the cavity increases²⁸⁾. By focusing on the fact that the electrode spot of fluorescent lamps shifts depending on the wear of the emitter during product life, an idea to regard the electrode filament as a serial circuit composed of resistance and inductance was introduced²⁹⁾. The development of a 240 W electrode-less fluorescent lamp that achieved a 20,000lm level, which is equivalent to a 400 W mercury lamp, was reported³⁰⁾. At the same time, full-bridge and half-bridge switching methods were compared for inverter circuit, and the backdrop of selecting the half-bridge method based on the temperature characteristics of the elements was presented³¹⁾. In addition, for cold-cathode fluorescent lamps, studies were conducted on the impact of cathode material and lighting frequency on start-up voltage³²⁾ and MgO which has a high secondary electron emission capability³³⁾³⁴⁾.

The minimum maintenance power (P_m) for arc tubes used for electrode-less compact fluorescent lamps was investigated and it was reported that the relationship between filler gas pressure (P_{gas}) and start-up frequency (f) can be described by the equation, $P_m =$

$A/(P_{gas} \cdot f)^2 + B$ (A, B are constants)³⁵. For Hg-free rare-gas fluorescent lamps, a luminance of 10,000 cd/m² was attained by a 1m-long external duplex spiral electrode prototype using an Xe/Ne barrier discharge³⁶. For circular electrode-less fluorescent lamps, it was reported that 30-100% dimming is possible by an IC circuit³⁷.

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3. HID Lamps

HID lamps operate by a discharge emission that occurs in high pressure vaporized metal. High pressure mercury lamps were developed in the mid 1930s and later, high pressure sodium lamps and metal halide lamps were developed through research aimed at improving color rendition and efficacy. HID lamps for gen-

eral lighting overcame shortcomings associated with restarting and start-up and are now being widely used as light sources for projectors, automobile headlights and so forth¹⁾²⁾.

For general lighting purposes, ceramic metal halide lamps, that offer high efficacy, excellent color rendition, long product life and good luminous flux maintenance factor, have been commercialized one after another³⁾ and introduced in both indoor and outdoor settings with the advancement of technology⁴⁾. In FY2004, these lamps grew to become an important product, accounting for 19% of total HID lamps used for lighting purposes⁵⁾. The market trend for ceramic metal halide lamps seems to be shifting to high value added products and future development is expected to focus on energy-saving (high efficacy) and reducing environmental burden⁶⁾.

As for HID lamps other than for general lighting, explanations on the current status of artificial accelerated weathering machines using metal halide lamps and precautions for tests as well as the recent progress were provided⁷⁾. In relation to plant growth lighting, the potential and challenges of new plant growing technologies using artificial light sources were mentioned⁸⁾. Recently, the effect of blue crime-prevention lights including HID lamps is becoming a topic of discussion by focusing on the psychological effect of color⁹⁾.

3.1 High pressure mercury lamps

Recent reports on high pressure mercury lamp technology are centered on research on ultra high pressure mercury lamps used as a light source for projectors.

Research on the problem of bursting, which is an underlying shortcoming of ultra high pressure mercury lamps, the effect of electrical power and current on the sealing-end temperature and destruction, as well as the stress on the sealing-end were examined by stress calculation using the finite element method taking into consideration the viscoelasticity of quartz glass. Consequently, it was proposed that the temperature inside the sealing-end should be 1,000 °C or lower in relation to lamp designing¹⁰⁾. In accordance with the miniaturization of front projectors, it was believed that the miniaturization and luminance enhancement of the light source was not possible due to the restrictions arising from the necessity of arc tube cooling. However, a report was made on the possibility of realizing such light source miniaturization and enlargement of electric power (luminance enhancement) by improving heat releasing capability with the use of a 4-layered reflector¹¹⁾. In addition, research was conducted on current waveform and electrode shape to control "flickering," which is often a problem for a front projector light source¹²⁾.

Figure 5 680W ceramic metal halide lamp conformed to mercury lamp ballast, the world's first high wattage product (© GS Yuasa Lighting Ltd.)

3.2 Metal halide lamps

In recent years, the trend of HID lamps is toward metal halide lamps and it is no exaggeration to say that ceramic metal halide lamps are at the core. Ceramic metal halide lamps accounted for the majority of HID lamp products launched this fiscal year as well as those exhibited at the LIGHTING FAIR 2007 held in March. Ceramic metal halide lamps can be categorized into two types from the perspective of their usage purposes, namely those emphasizing color rendition and those emphasizing efficiency. The following are the new products launched this fiscal year.

New products emphasizing color rendition launched this fiscal year include a 150 W neutral white (5,500 K) lamp, which was developed for the first time as a ceramic metal halide lamp¹³⁾ and a 70 W lamp adopting a new standard socket (EU10) along with a triple tube structure that does not require a front glass on the appliance¹⁴⁾. New products emphasizing efficiency include a 180 W lamp that can be lit by an inexpensive mercury lamp ballast¹⁵⁾, a 400 W lamp with high efficiency of 110 lm/W and immediate light-up capability¹⁶⁾¹⁷⁾ and a 680 W lamp, the world's first high wattage product¹⁸⁾ (Figure 5).

Research reports on ceramic metal halide lamps were also popular among HID lamp reports made in the Journal of the Illuminating Engineering Institute of Japan and presented at Annual Conference of IEIJ in 2006.

Reports on the technology of 100 W, 250 W, and 400 W lamps with high efficiency and excellent color rendition¹⁹⁾²⁰⁾ were provided. Further, while the inconsistency in performance of lamps caused by the difficulty in proc-

essing the quartz glass for 20 W ultra compact lamps was a problem, explanations on the technology of the lamps and their systems that has overcome such problems owing to the adoption of ceramic arc tubes were provided²¹⁾²²⁾. Also, a report was made on the technology of 150-360 W ceramic metal halide lamps that can be lit by mercury lamp ballast. According to the report, higher efficiency and longer product life than the conventional quartz glass metal halide lamps were achieved by optimizing the arc tube shape, sealing-end structure and metal for the filler gas²³⁾²⁵⁾. The shape of transparent alumina ceramics varies in accordance with the design concept, and the shape significantly affects the lamp performance. A report on transparent alumina ceramics which is the most important material for lamps was made from the perspective of basic characteristics and manufacturing technology, as well as their underlying problems and recent development trends²⁶⁾.

With respect to ceramic metal halide lamps, a 680 W lamp, the world's first high wattage product compatible with 700 W mercury lamp ballast was developed²⁷⁾, and a 230 W lamp, compatible with 250 W mercury lamp ballast, that achieved high efficacy by reviewing the shape and dimension of the integrally formed arc tube and by optimizing the composition of iodide metal was developed²⁸⁾. Further, a report on the technology of a lamp realizing high efficacy of 125 lm/W through the adoption of new filler material and development of an unconventionally thin arc tube was presented²⁹⁾. A report on the development of functionally gradient material, which is an advanced cermet, and a ceramic metal halide lamp employing such functionally gradient material was made in media other than the Journal of the Illuminating Engineering Institute of Japan and 2006 Annual Conference of IEIJ³⁰⁾.

It was noteworthy that in FY2006, many reports on the analyses of discharge models of metal halide lamps were made. Such included, a) simulation of convection and diffusion in the discharge domain of metal halide lamps³¹⁾; b) research on the corrosion reaction between the various filler materials and molybdenum³²⁾; c) report on acoustic resonance occurring by combining with high frequency electron ballast³³⁾; and d) analyses on voltage, temperature, mass, velocity, heat generation and radiant intensity distribution when the discharge is DC-driven, through the development of computer simulation code for HID lamp designing³⁴⁾. Further, there was a report regarding the investigation on anode and plasma for HID lamps³⁵⁾ and on the intensity distribution of Dy for atoms and ions³⁶⁾. Also, a report was presented regarding an experiment on the distribution and temperature of rare-earth halide and mercury inside the arc tube during discharge conducted at the International Space Station in order to minimize the effect of

convection and diffusion³⁷⁾³⁹⁾.

Aside from reports on the analyses relating to discharge models, technologies on mercury-free metal halide lamps were reported⁴⁰⁾, and the behavior of color change/deterioration of cloth/paper lamp shades when a fine ceramic coating that absorbs ultraviolet rays is applied to the surface of the lamp outside the light source was investigated⁴¹⁾.

As to metal halide lamps for automobile headlight use, the development of partially covered HID lamps to secure high peripheral visibility for the driver and to reduce discomforting glare for oncoming vehicle drivers⁴²⁾ and investigation on the effect of headlight illumination on front vision at curves⁴³⁾ was reported. In addition, investigation on the spectral distribution, discomfort glare for oncoming drivers and color rendition against reflective traffic signs of mercury-free HID lamps was reported⁴⁴⁾.

3.3 High-pressure sodium lamps

Research on the use of high-pressure sodium lamps for plant growth as well as pest control taking advantage of the low insect attracting aspect has been the main focus, and many such studies were presented in FY2006 as well.

For plant growth usage, a demonstration on supplemental lighting systems using mercury-free high-pressure sodium lamps at a large-scale vegetable nursery growing site⁴⁵⁾ and the growth promotion effect on flowers, namely florist's chrysanthemum and petunia, were reported⁴⁶⁾⁴⁸⁾.

In relation to pest control, pest control technology using yellow coated high-pressure sodium lamps was reported together with its effect on green tea, buckwheat and vegetables⁴⁹⁾⁵⁴⁾. The expectation of high-pressure sodium lamps is significant.

On the other hand, high-pressure sodium lamps are still very popular for road lighting. In this regard, the visibility of high-pressure sodium lamps was compared with that of fluorescent lamps from the perspective of crime prevention and it was reported that fluorescent lamps were superior⁵⁵⁾.

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4. Other discharge lamps and radiation sources

Studies of inductively-coupled electrode-less lamps were conducted, for enlargement initiatives, for the electrode-less fluorescent lamp system of 22,000 lm¹²⁾, for miniaturization initiatives, and the dependency of filler gas and driving frequency of the compact electrode-less fluorescent lamps on their minimum plasma sustaining power³⁾. From the perspective of property research relating to plasma, the measurement of electron temperature and electron density in a lamp filled with argon and mercury⁴⁾, analyses on electron density using a finite element method⁵⁾, relationship with the coldest point temperature in connection with mercury emission line⁶⁾, and analyses on radial intensity distribution⁷⁾ were reported. For startup circuit studies, performance of dimming circuits⁸⁾⁹⁾ and charge-pump-method circuits¹⁰⁾, control method that can follow-up on the environmental changes and circuit dispersion for submerged electrode-less disinfection lamp circuits¹¹⁾, and analyses by employing equivalent circuits to lamps¹²⁾ were reported. For mercury-free electrode-less lamps that use xenon, optimization of coil¹³⁾, enhance-

ment of luminous efficacy using re-integrated radiation by pulse modulation¹⁴⁾ and the relationship between xenon gas pressure and color rendition¹⁵⁾ were reported.

For capacity-coupled electrode-less lamps, the relationship of lamp current as well as power against the capacity of external electrode¹⁶⁾ was reported.

Regarding microwave discharge lamps, a study on microwave discharge by antenna excitation where the electrode of compact HID lamps are employed as the antenna was carried out and the following were reported: a) emission performance when applied to high-pressure mercury lamps¹⁷⁾ and metal halide lamps¹⁸⁾; b) shape of antenna and microwave electric power to start discharge¹⁹⁾; c) startup pulse frequency and duty as well as luminous efficacy²⁰⁾; d) electric and magnetic field distribution at the gap between electrodes by numerical analysis²¹⁾; and e) microwave electric and magnetic field distribution and lamp impedance²²⁾²³⁾. As to the application of microwave discharge, the development of a 4-inch wide-space vacuum ultraviolet light source²⁴⁾ and demonstration of the simultaneous radiation of microwave and ultraviolet rays using microwave electrode-less lamps for organic decomposition²⁵⁾²⁷⁾ were reported.

Excimer discharge lamps are widely used for industrial purposes as an ultraviolet light source and are also regarded as an important ultraviolet source for mercury-free fluorescent lamps. Optimal combinations of krypton and bromine for glow discharge²⁸⁾, planar excimer lamps using chloridized rare gases²⁹⁾, high-voltage capacity-coupled discharge with krypton and bromine at 13.56 MHz³⁰⁾, and micro gap argon discharge using gas-sink structure electrodes³¹⁾ were reported.

Dielectric barrier discharge lamps are the mainstream of lamps employing the excimer discharge method owing to their superior efficiency and cost. Reports were made on operational conditions for efficient vacuum ultraviolet emission by xenon gas³²⁾ and the relationship between generation/annihilation of quasi-stable atoms and vacuum ultraviolet radiation performance against time³³⁾. Many types of simulations were actively carried out and reported, namely those by one-dimensional fluid model for argon excimer³⁴⁾, one-dimensional model in order to express discharge voltage/current performance³⁵⁾, two-dimensional fluid model with consideration of ion and gas temperatures³⁶⁾ and those displaying the rise in gas temperature by rectangular wave operation³⁷⁾. As to emission materials, reports were made on OH and argon³⁸⁾, mercury (II) iodide and inert gas³⁹⁾, high-pressure neon and nitrogen⁴⁰⁾ and helium and neon⁴¹⁾. In addition, the impact of gas flow at micro gap discharge on emission was reported⁴²⁾. A startup method using nanosecond short pulse⁴³⁾ was reported. For startup circuits, piezoelectric transformer⁴⁴⁾ and pulse density modulation high fre-

quency soft switching inverter⁴⁵⁾ were presented. Moreover, a 40 W high power lamp⁴⁶⁾ and a $23 \times 23 \text{ cm}^2$ large area lamp⁴⁷⁾ were also introduced.

Dielectric barrier discharge is also applied to studies on mercury-free lamps, and an iodine-xenon mixed lamp was introduced as an ultra violet light source⁴⁸⁾. In addition, in order to examine the efficacy of a pulse discharge lamp using xenon, the positive column was expanded by voltage control, which was realized by establishing external electrodes⁴⁹⁾⁵⁰⁾, and then, the voltage of the operational pulse range was investigated when a double helical structure for external electrodes was employed with the lamp with xenon-neon mixed filler gas⁵¹⁾⁵³⁾. Further, plasma measurements were made for quasi-stable atomic density by infrared laser absorption spectroscopy⁵⁴⁾ and spatial distribution of quasi-stable atomic density by laser-induced fluorescence spectroscopy⁵⁵⁾⁵⁶⁾. For mercury-free emission materials, measures against nitrogen wear were reported utilizing an argon-nitrogen mixed gas discharge tube⁵⁷⁾.

With respect to new light sources, the following were presented; a) for a cluster light source, the dependency of molybdenum cluster emission on discharge gas⁵⁸⁾; b) for micro cavity light sources, those using tantalum⁵⁹⁾ and photonic crystal⁶⁰⁾⁶²⁾; and c) optical characteristics of metal mirror micro cavity including quantum dot⁶³⁾. Light sources using nanotechnology were also reported, namely, a) carbon nano-tube electrode arc tube⁶⁴⁾⁶⁶⁾; b) electron beam lamp combining carbon nano-tube electrode and electron beam permeable membrane⁶⁷⁾⁶⁹⁾; and c) spark emission with continuous spectrum from visible to near infrared rays of carbon nano-tube array⁷⁰⁾. The application of carbon nano-tube electrodes was reported with the study on reducing voltage at the start of discharge⁷¹⁾. Proposals on Smith-Purcell radiation by electric field radiation cathode using silicon⁷²⁾ and emission from silicon possessing discharge processed nano structures⁷³⁾ were made.

Other reports on vacuum ultraviolet and extreme ultraviolet discharge sources include: a) iodine vapor glow discharge⁷⁴⁾; b) xenon and tin emission⁷⁵⁾; c) afterglow emission from nanosecond volume discharge⁷⁶⁾; and d) microwave ECR plasma⁷⁷⁾. Further, for Z-pinch plasma⁷⁸⁾⁸³⁾, coaxial double nozzle electrodes⁸⁴⁾ and pulse power source⁸⁵⁾⁸⁶⁾ were reported, and for capillary discharge⁸⁷⁾⁸⁸⁾, plasma behavior by high-speed camera⁸⁹⁾ was presented.

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5. Startup circuits

The most noteworthy feature of the market trend in FY2006 was that, with the enforcement of RoHS in Europe in July, initiatives such as energy saving and green procurement from the perspective of protecting the global environment have become more vigorous. Moreover, due to the rise in prices of materials such as oil and steel, proactive approaches were taken toward lower prices and resource conservation.

In the fluorescent lamp related market, lighting appliances adopting exclusive high frequency startup lamps of double circular and T5 circular/square/double square types continued to be popular for home use, and value-added lighting apparatuses with crime-prevention, up/down, and ambience-creating functions were commercialized. For facility use, while the replacement of straight fluorescent lamps to exclusive high frequency startup lamps continued to progress, products with functions such as initial illuminance correction, daylight usage and automatic lighting control with human detector were launched in order to further promote energy saving. In addition to the progress in compact fluorescent lamps, the miniaturization of startup circuits advanced, such as commercialization of self electronic-ballasted compact fluorescent lamps (double-tube type) and so forth.

In the LED lighting related market, the usage of white LEDs has steadily shifted from supplemental to main lighting equipment in accordance with their greater output level and higher efficacy. The application of color LEDs to ambience-creating lighting appliances has also become popular.

As to HID lamps for general lighting purpose, the expansion in the demand for opening and renovating shops continued to be the driving force of the market. Accordingly, commercialization of lighting appliances using compact HID lamps with excellent color rendition was realized repeatedly. Compact HID lamps with size almost equivalent to halogen lamps and self electronic-ballasted HID lamps have been launched. Against the backdrop of energy saving demand, high efficiency lamps and their corresponding electronic ballasts as

well as dimming systems capable of controlling color temperature changes were commercialized. The demand for automobile use HID lamps continues to increase year on year, and many compact and highly reliable electronic ballasts have been developed.

As to electrode-less lamps, a number of electrode-less fluorescent lamp startup units were commercialized complying with the market demand for longer product life, and the lineup continues to increase each year.

Additionally, the demand for liquid crystal backlights using cold cathode lamps and LEDs has been increasing due to the trend of larger LCD TV screens and expansion of digital home appliances.

Described below are the details of the startup circuit related research papers presented at major conferences in 2006.

For fluorescent lamp startup circuits, proposals on new methods for input power factor improvement circuits aiming at reducing the number of parts and prices accounted for the majority, while other reports were related to protection circuit for end-of-life lamps and circuit efficiency improvements. Reports on the input power factor improvement circuits were, a) circuits that achieved high power factor by buck-boost voltage converting constant power inverter without electrolytic condenser¹⁾; b) proposal on single power stage circuit method, a combination of boost converter and a new inverter circuit, with reduced switching parts²⁾; c) electronic ballast with voltage supply type charge pump circuit without startup condenser³⁾; d) proposal on high efficiency circuit where input power factor improvement circuit (two sets of voltage supplies serially connected) and inverter circuit are partially shared⁴⁾; e) circuit with dimming function by combining current feedback control inverter and gap filling circuit⁵⁾; f) circuit with improved input waveform by the widening of the input current conduction angle by the two step-down choppers that operate according to the polarity of power source⁶⁾; and g) circuit with full-time dimming function attained by current phase control by serially inserting a magnetic energy regenerating switch between power source and load⁷⁾.

Reports relating to protection circuits include those on a) circuit with protection functions against short-circuit of circuit parts, lamp damage and filament breakdown in non-resonant electronic ballasts⁸⁾; b) circuit with protection functions against end-of-life lamp, and circuit coping with high startup voltage, wide input voltage range and wide load range⁹⁾¹⁰⁾; and c) frequency analysis aiming at protection against abnormalities in current a feedback type parallel resonant circuit¹¹⁾. As to circuit efficacy improvement, reports were made on a) circuit for zero voltage switching by using input inductor at E-class inverter employing piezoelectric transformer¹²⁾; b)

circuits with improved efficiency through the optimization of coils for resonant inductor¹³⁾; c) a circuit that controls current by PLL method while detecting the phase at both ends of resonant inductor¹⁴⁾; and d) comparison of the stress of the switching parts for E-class and half bridge inverters¹⁵⁾. Reports relating to analyses by PSpice using lamp models were on a) verification of the impact of DC input voltage and operation frequency on circuit efficacy at the time of dimming¹⁶⁾; and b) comparison of voltage-current characteristics and transitional response at the time of output change between the lamp model and the actual apparatus¹⁷⁾. Presentations relating to self electronic-ballasted fluorescent lamps include those on a) single packaging of complementary MOSFET chips; b) adoption of miniaturized parts; and c) further miniaturization of inverter circuit employing measures against temperature rise¹⁸⁾²⁰⁾.

In relation to LED lighting circuits for general lighting purposes, studies were presented on a) LED features viewed from power source, required performance, current control functions and system composition²¹⁾; b) circuit enabling concurrent startup of 7 serially connected LEDs by generating 26V from 6V battery power source²²⁾; c) DC-DC converter designing method using midpoint tap inductor²³⁾; and d) miniaturization by 4 mm multilayer board that incorporates passive element used for LED drive²⁴⁾.

In relation to HID lamp startup circuits for general lighting purposes, many studies were made on a) investigation of acoustic resonance phenomena generated from high frequency operation unique to HID lamps; b) miniaturization; and c) simple circuit composition aiming at reduced pricing. In addition, studies on digital control using resonance boost startup pulse and microcomputers were newly introduced.

Reports regarding acoustic resonance phenomena include a) proposal of a high frequency startup method of 2.65MHz self-excited control that uses 2.5-3.0MHz band where EMI standard is alleviated²⁵⁾²⁶⁾; b) self electronic-ballasted HID lamp product (20W) realized by miniaturizing the circuit through the adoption of high frequency startup method²⁷⁾; c) investigation on the avoidance of acoustic resonance phenomena by high frequency rectangular waves²⁸⁾; d) investigation on the avoidance of acoustic resonance phenomena at 50kHz band by frequency modulation²⁹⁾; and e) investigation on acoustic resonance phenomena throughout the lamp's product life³⁰⁾. As to simple circuit composition, reports were made on a) reduction of the number of parts for switching function by dual purpose chopper circuit³¹⁾; b) reduction of the number of parts for switching function by bi-directional fly-back circuit³²⁾; and c) performance comparison among various dual purpose chopper circuits³³⁾. Reports on dimming circuits geared toward energy sav-

ing include those on a dimming control method with operational frequency 400kHz under both dimmed and non-dimmed operations were made³⁴⁾³⁵⁾. Moreover, reports on a) constant power control³⁶⁾³⁷⁾ and dimming control³⁸⁾ using microcomputers; b) designing method of resonance boost startup pulse³⁹⁾⁴⁰⁾; and c) startup pulse generating circuit by free oscillation utilizing polarity reversal of full-bridge circuit⁴¹⁾, were presented. Reports regarding HID lamp models include those on a suitable lamp model to examine step responses assuming instantaneous load fluctuation⁴²⁾ and a simulation model for transitional responses at startup⁴³⁾. As to HID lamp circuits for automobile use, reports on practical circuit designing were made, namely a) execution of control in accordance with the lamp condition from startup to stable operation; b) startup current control to satisfy the instantaneous luminous flux startup performance; and c) insulation designing for igniter circuits⁴⁴⁾.

With regards to startup circuits for non-electrode lamps, reports were made on high power startup circuit realized by the optimal designing of resonance circuit as well as improved performance against peripheral temperature⁴⁵⁾ and assessment of dimming performance by intermittent oscillation method⁴⁶⁾.

Reports on attaining high efficacy in relation to startup circuits for cold-cathode lamps used for LCD backlights include those on a) circuits that achieved low price and high efficacy by capacitance detection circuits, low frequency PWM dimming, voltage control at no-load and soft switching function⁴⁷⁾; b) circuit enabling maximum efficacy control irrespective of differing tube currents by executing dimming control by output voltage and high efficacy control by frequency⁴⁸⁾; and c) investigation on the relationship between voltage at the start of discharge and excitation frequency when using sine wave alternating current excitation⁴⁹⁾. For circuits using piezoelectric transformers, a report on a circuit that controls phases of input voltage and output current in order to cope with a wide load resistance range was made⁵⁰⁾ and a verification of the stability against peripheral temperature was conducted⁵¹⁾. Further, a circuit using an insulated transmission line boost transformer which is effective for harmonic noise control⁵²⁾ and a circuit reducing input current ripple through alternate lamp operation by three-phase drive system using lamp current transformer⁵³⁾.

For LED startup circuits used for LCD backlights, reports were made on a) current control method for a high power LED capable of coping with high input voltage⁵⁴⁾; b) circuit attaining high efficacy of driving system by dual-switch buck-boost converter⁵⁵⁾; and c) realization of high efficacy and high power factor over a broad range of output current through a driving circuit that incorporates an input power factor enhancement function⁵⁶⁾.

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