Special Arrangement of Phosphor Particles in Screen for Optimization of Illuminance (lm m^{-2}) of FL Tubes

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Abstract: The performance of lighted FL tubes is severely influenced by the depth of the gap between phosphor screen on inner glass wall and positive column which is defined by $F_{\text{vect}} \geq F_{\text{phos}}$. F_{phos} is vertical electric field of the surface bound electrons (SBE) on electric insulator in vacuum. The SBE on phosphor particles in the screen of the commercial FL tubes pushes back approaching electrons from phosphor screen to positive column. Naturally, there is the gap between positive column and phosphor screen. The depths of the gap ever study on the lighted FL tubes quantitatively. The depth by the gap by SBE is 3×10^{-3} m that gives rise to the slow build - up curve of illuminance from FL tube. Unexcited Hg atoms in the gap severely control the illuminance (lm m^{-2}) of FL tubes. The reliable FL tubes should have the depth of the gap less than 2×10^{-4} m. The formation of the narrow gap requires the special arrangement of (a) the low voltage CL phosphor particles and (b) PL phosphor particles side by side. The coil-EEFL tubes in the narrow gap allow the Ar gas pressures ($>7 \times 10^3$ Pa) for the high illuminance ($>10^3 \text{ lm m}^{-2}$) with nearly zero power consumption by the DC operation.

Keywords: FL Tubes, PDP, FFP, Superconductive Vacuum, Phosphor Screen, Illuminance, Depth of Gap

1. Introduction

In the study on the FL tubes, the phosphor screens have been considered as the transducer of the 254 nm UV lights to the visible lights since the invention of the FL tube [1]. With the consideration of the transducer, the study of the phosphor powder for the FL tube had made with the phosphor power in the planchette in air under the 254 nm UV lamp. The results under the UV lamp did not correspond to the results of the phosphor screen in the lighted FL tubes. The difference comes from the examined conditions. The UV lights (photons) do not have electric charge. The UV lights can penetrate in the phosphor particles in the deep layers with the optical scattering on the surface of the phosphor particles.

On the other hand, the UV lights in FL tubes are generated by the excitation of the Hg atoms by the moving electrons between cathode and anode of the internal DC electric power generator that is formed in the Ar gas space [2]. The Ar gas space of FL tubes quite differs from the solid, liquid, and vacuum devices. The Ar atoms in FL tube float in vacuum with the Maxwell-Boltzmann distribution. The vacuum between Ar atoms in the unlighted FL tube fills up the negative electric field from the orbital electrons of Ar atoms.

The presence of the electric field from Ar atoms can be detected by the measurements of the optical absorption spectrum and/or lighting spectrum by the spectrometer. As the atoms are under the electric field from the neighboring atoms, the energy levels of the isolated atoms split to sublevels. The splitting to the sublevels under the electric field is the Stark Effect. We have surely detected the sublevels from the Ar gas space in FL tube. In the FL tube, the Ar atoms do not split further levels by the Zeeman Effect that is caused by the magnetic field. The electrons from the cathode cannot step in the negative electric field of the Ar gas space in the FL tube. For the start of lighting of the FL tube, the negative field in the vacuum should be electrically neutralized for the moving electrons from the cathode. The neutralization of the vacuum is made by the presence of ionized Ar atoms (Ar^{1+}). The initial neutralization is made by the formation of the volume of the glow light (3G electron sources) at room temperature [2] and the corona light of the heated Ar gas space (4G electron sources) [3]. After the formation of the 3G or 4G electron sources, the electrons may step in the Ar gas space. The stepped electrons at nearby the electron sources ionize the Ar atoms. The ionized Ar atoms (Ar^{1+}) neutralize the vacuum at nearby the electron sources. The moving electrons under the vector electric field, F_{vect} , neutralize the entire vacuum of the

lighted FL tubes with the moving speed of the electrons from the cathode and to the anode. The moving speed in Ar gas space in FL tube is given by 10^5 m s^{-1} . The 3G electron sources are assigned as the volume of the glow-light [3]. The formation of the 4G electron source requires the volume of the heated Ar gas [4]. The heat source of the 4G electron sources requires the heated tiny spot on the W-filament coil. The continuous heating of the spot of the W-filament coil by the DC voltage shortens the operation life of the W-filament coil. The heated tiny spot on the W-filament coil with the BaO particles prolong by the application of the AC operation to the W-filament coil with the BaO particles [4]. The starting conditions of the lighting of the FL tubes and conditions of the lighted FL tubes quite differ from the solid, liquid, and vacuum devices. The generation of the UV lights in the lighted FL tubes is determined by the conditions of the moving electrons in the Ar gas space.

After start lights of the FL tubes, the vacuum between Ar atoms provides an advantage over the solid and liquid devices. The optical absorption spectrum of the Ar gas space proves the sharp energy levels by the Stark Effect. The sharp energy levels inform us that the floating Ar atoms do not receive the thermal perturbation from the neighboring Ar atoms. With other word, the lighted FL tubes provide the superconductive vacuum for the moving electrons [2]. The FL tubes are lighted with the moving electrons in the superconductive vacuum with meet with the floating Ar atoms in the vacuum. The moving electrons in the superconductive vacuum in the Ar gas space are the advantage of the lighted FL tubes.

The advantage of the moving electrons is restricted with the volume of the moving electrons in the Ar gas space. The electrons are particles that have electric charges. Each electron has the 1.6×10^{-19} Coulomb. The moving electrons strongly influenced by the localized electric fields in the Ar gas space. The lighted FL tubes contain Ar atoms and phosphor screen. Since the inner wall of the FL tubes is covered with the opaque phosphor screen, the moving electrons in the Ar gas space are invisible by the naked eyes. Then, the different results between the UV lamp and the FL tube had attributed to the clumped phosphor particles in the phosphor screen for the last 80 years. The clumped phosphor particles generate the pinholes and dark spots in the FL tubes with the visible sizes by the eyes. The number and sizes of the pinholes and dark spots had reduced by the adhesion of the SiO_2 microclusters (gel) on the surface of the phosphor particles. The adhesion of the microclusters on the surface of the phosphor particles has called as the surface treatment of the phosphor particles [5]. The produced phosphor screens with the surface treated phosphor particles still had detected the pinholes and dark spots. Then, the powders of the inorganic compounds at the low melting points were blended to the produced phosphor powder for the adhesion of the clumped phosphor particles on the inner glass wall of the FL tubes [5]. The added inorganic compounds are called as the binders. The surface of the current phosphor screens of the commercial FL tubes are heavily contaminated with the surface treatment and the blend mixture of the binders. The contaminated phosphor screen in

the lighted FL tubes conceals the remarkable advantage of the FL tubes.

We must clarify the different conditions between the examination of the phosphor screen under the UV lamp and the phosphor screen in the FL tubes. The UV lights from the UV lamp are the photons that do not have electric charges. The UV lights penetrate into the phosphor particles in the layers of the phosphor screen without perturbation of the electric charge on the phosphor particles.

On the other hand, the UV light in the FL tubes is generated by the excitation of the Hg atoms by the moving electrons in the positive column in FL tube. The positive column contains the moving electrons. The electrons are the particles with the electric charge of 1.6×10^{-19} Coulomb. The volume of the positive column in the given FL tubes is markedly changed with (a) the localized electric field and (b) magnetic field in the Ar gas space [2]. The moving electron in the Ar gas space generates the localized magnetic field. The number of the electrons in the lighted FL tube is $2 \times 10^{-4} \text{ A}$ ($= 0.2 \text{ mA}$). The generated magnetic field by the moving electrons is a negligibly small as compared with the electric field from the charges on the Ar atoms and phosphor screen in the lighted FL tube. The electric field from the Ar atoms scatters the moving electrons. The scattering range of the moving electrons by the Ar atoms limits in the volume of the positive column [6]. The electric charges on the phosphor screen generate the vertical electric field, F_{phos} , against the longitudinal vector electric field, F_{vect} , that is formed by the cathode and anode of the internal DC electric power generator in the Ar gas space [2]. The F_{phos} uniformly distribute on the entire phosphor screen. Consequently, the diameter of the positive column for the moving electrons in the Ar gas space under the F_{vect} is seriously restricted by the strength of the F_{phos} . Since the UV lights in the FL tubes are generated in the volume of the positive column, the illuminance (lm m^{-2}) of the lighted FL tubes is seriously influenced by the F_{phos} . The variation of the illuminance (lm m^{-2}) of the lighted FL tubes is not by the pinholes and dark spots. The variation in the illuminance of the FL tubes comes from the change in the F_{phos} . The change in the diameter of the positive column in the Ar gas space by the F_{phos} had ever reported in the study on the FL tubes.

The electric charges on the phosphor screens markedly influence to (a) the diameter of the positive column which the electrons move on in the Ar gas space, and to (b) the amount of the UV light on the phosphor screen in the FL tubes. Naturally there is a disparity between the experimental results by the UV lamp and the FL tube. The disparity comes from the electric charges on the phosphor particles in the FL tube. Recently, the details of the electric charges on the phosphor particles in the vacuum has quantitatively studied by the measurements of the voltage dependence (VD) curves of the cathodoluminescence (CL) of the phosphor screens in the vacuum [6]. The many commercial phosphor particles in the screen form the surface-bound-electrons (SBE) [7]. The contaminated small particles on the phosphor particles also form the SBE. The electric field from the SBE push back the approaching electrons to phosphor screen to the volume of the

positive column. The moving electrons never reach on the phosphor screen of the commercial FL tubes. Accordingly, there is the gap between positive column and phosphor screen in the commercial FL tubes. The reduction of the depth of the gap to a negligible depth has remained in the previous study [6]. This report will describe the longitudinal distribution of the electric charges on the phosphor screen in the FL tube for the reduction of the depth of the gap to the acceptable level.

Before the description of the details of the distribution of the electric charges on the phosphor screen, it is a better way to know the summary of the study on the phosphor screens of the FL tube. It is well known that the origin of the lights of the lighted FL tubes starts from the excitation of the Hg atoms by the moving electrons in the Ar atoms [1]. The excited Hg atoms by the moving electrons emit the invisible 254 nm UV lights. The excitation of the Hg atoms and the moving electrons in the lighted FL tube are covered with the opaque phosphor screen, so that they are invisible by the naked eyes. The excitation of the Hg atoms and the moving electrons in the lighted FL tube belong to the abstraction that is the belief in

the brain. It has believed in the past that the electrons from the cathode move on the entire volume of the Ar gas space in the FL tube until the anode collects the arrived electrons. This is the hypotheses. The volume of the Ar gas space that allows the moving electrons under the longitudinal vector electric field, F_{vect} , is severely restricted by the vertical electric field of the F_{phos} , against to the longitudinal F_{vect} [6, 7]. The restricted volume is named as the positive column. The approaching electrons to the phosphor screen in the commercial FL tubes receive the strong Coulomb's repulsion from the F_{phos} . The moving electrons never reach to the phosphor screen. Naturally there is the gap between positive column and phosphor screen. Figure 1 schematically illustrates the positive column that is given by the $F_{\text{vect}} \geq F_{\text{phos}}$ and the gap that is given by the $F_{\text{vect}} \leq F_{\text{phos}}$. The performances of the lighted FL tubes are determined by the ratio of the volume of the Ar gas spaces of the positive column of the $F_{\text{vect}} \geq F_{\text{phos}}$ and volume of the gap of the $F_{\text{vect}} \leq F_{\text{phos}}$. By the production of the commercial FL tube, the performance of the FL tubes is severely controlled by the depth of the gap [6].

Figure 1. Schematic explanation of formation of positive column ($F_{\text{vect}} \geq F_{\text{phos}}$) and depth of gap ($F_{\text{vect}} \leq F_{\text{phos}}$) by SBEs on phosphor screen in lighted FL tube.

The Ar gas space in the gap has two negative actions to the performance of the lighted FL tubes. First is the surrounding the positive column by the Ar gas space that is the thermal insulator. Second is the optical absorption of the emitted UV lights from the positive column by the unexcited Hg atoms in the gap. The Ar gas at 1×10^3 Pa ($= 7$ Torr) is the good thermal insulator with 4×10^{-7} cal (m, s, deg) $^{-1}$. The Hg atoms must evaporate to the Ar gas space into the positive column from the Hg droplets on the phosphor screen. The heat source in the lighted FL tube is solely ionization of the Ar atoms by the change in the entropy. The temperatures of the positive column relate to the number of the ionization of the Ar atoms in the positive column. The ionization of the Ar atoms is solely made in the positive column. If you take the Ne atoms and/or adds some amount of Ne atoms (and other inert atoms) to the Ar gas space, the generated heat by the ionization of Ne atoms is a low. Accordingly, you cannot evaporate the enough Hg atoms in the positive column from the Hg droplets on the phosphor screen. The heating speed of the Hg droplets on the phosphor screen by the thermal radiation from the positive column is slow. The slow heating speed of the Hg droplets on

the phosphor screen gives rise to the slow build-up curve of the illuminance (lm m^{-2}) of the lighted FL tubes in the Ulbricht Sphere.

The excited Hg atoms in the positive column emit the 254 nm UV light by the electron transition from the excited energy level 6^3p_1 to 6^1S_0 ground state. The unexcited Hg atoms in the gap fill up the electrons in the 6^1S_0 ground state. The unexcited Hg atoms in the gap efficiently absorb the 254 nm UV light from the positive column by the resonance absorption. Subsequently, the unexcited Hg atoms in the gap considerably absorb the UV lights from the positive column before the reaching to the phosphor screen. Figure 2 schematically illustrates the UV lights arrive to the phosphor screen and optical absorption of the UV lights by the unexcited Hg atoms in the gap. The ideal FL tube should minimize the depth of the gap in the lighted FL tubes. The depth of the gap is given by the $F_{\text{vect}} \geq F_{\text{phos}}$. The variable factor in the lighted FL tubes is only the F_{phos} . The depth of the commercial HCFL tubes is 3×10^{-3} m ($= 3$ mm). We will reduce the depth of the gap to 3×10^{-4} m ($= 0.3$ mm) by the distribution of the different F_{phos} on the phosphor screen in lighted FL tubes.

Figure 2. Schematic explanation of part of UV lights generated in positive column reaches on phosphor screen and residual UV lights are optically absorbed by unexcited Hg atoms in gap of lighted FL tube.

2. Phosphor Screens in Present FL Tube

The study on the phosphor screen in the FL tubes has a long history [5, 7, 8, 9, 10, 11, 12, 13]. The phosphor screen is constructed with the layers of phosphor particles in the sizes of 10^{-6} m ($= \mu\text{m}$). The tiny phosphor particles are well crystallized particles with the polycrystals that have plural growing axes. The individual phosphor particles are small sizes beyond the resolution of the naked eyes. The sizes of the phosphor particles are observed under the optical microscope with the magnifications higher than 300 times, preferably 1×10^3 times. The sizes of the ideally produced phosphor particles distribute with the lognormal distribution [7]. However, the

commercial phosphor particles as the results of the references from 6 to 10 are not produced with the ideal conditions. Figure 3 (A) shows the photograph ($\times 500$) of the commercial phosphor particles of the typical Japanese phosphor company. The commercial phosphor powders do not produce with the ideal conditions as described in the reference 5. If the phosphor particles are produced with the ideal conditions, the phosphor powder contains the primary particles in the similar shape and nearly equal sizes [7, 8]. Figure 3 (B) shows the photograph of the ideal phosphor particles of the phosphor powder. We use the phosphor powder of the Figure 3 (B) in this study.

Figure 3. Photographs of phosphor particles of commercial PL phosphor powder (A) and ideal phosphor powder (B) for phosphor screen of FL tube.

If you use the commercial phosphor powders, you may detect the problems that contain the crystallized by-products in the phosphor particles. The crystallized by-products are generated by the drying process of the filtered phosphor

powder in the heated oven. The generation mechanisms of the by-products are below: If the phosphor particles are produced with the improper production process, the produced phosphor particles are covered with the thin layer with a few atomic

layers of the by-products of the flux and phosphor crystal. The thin layer of the by-products solves in a hot water higher than 70°C. As the produced phosphor powders do not have the removal of the by-products in the heated water higher than 70°C, the surface of the produced phosphor particles is covered with the thin layer of the by-products. In the drying process of the wetted phosphor powder in the heated oven, the by-products in the phosphor powder dissolves in the hot water in the drying powder in the oven. The solution gathers up in the drying powder. The dissolved by-products crystallize at the final stage of the drying process of the phosphor powder. You may detect the crystallized by-products in the large sizes under the optical microscope.

You may take a small amount (a few mg) sample from the dried phosphor powder in the storage container with the sharp tweezers. The sampled phosphor powder puts on the preparation glass plate of the optical microscope. A drop of the deionized water adds to the sampled phosphor powder on the preparation glass plate. Then sampled powder and deionized water mix up with the tweezers. Do not take out the extra

water and phosphor powder from the preparation glass plate. The by-products have a low density as compared with the density of the phosphor particles ($\sim$ around 5 g cm^{-3}). You may detect the by-products at the edges of the drying sample on the preparation glass plate. As you carefully observe the commercial phosphor powders under the optical microscope ($\times 300$), you may surely detect the crystallized by-products at the edges of the dried phosphor particles. Figure 4 shows the photograph of the crystallized by-products in the commercial phosphor powder. The by-products in the phosphor screens have usually detected by the observation under the optical microscope (>30). The detected by-products have attributed as the contamination of the dust in the air in the working room. It is not the dust. It is the by-products that are crystallized by-products in the drying process. If you wash well the produced phosphor powders with the hot water at 70°C for at least one hour, the contamination of the by-products go away from the produced phosphor screen. You may prepare the good phosphor screen in the ordinary laboratory.

Figure 4. Photograph of crystallized by-product in commercial PL phosphor powder.

The average size of the commercial phosphor particles is $5 \times 10^{-6} \text{ m}$ ($= 5 \text{ }\mu\text{m}$) by the microscopic determination [7]. It should be noted that if you determine the average particle size of the same phosphor powder by the commercial instruments of the determination of the particle sizes, you may obtain the different sizes that are the equivalent particle sizes with either the surface areas of the particles or the weights of the particles [7]. The study on the particles as the science should make the sizes by the microscopic determination. The particles sizes determined by the commercial instruments cannot use for the study of the phosphor powders for the practical use for the phosphor screen in FL tubes. The commercial instruments have the program for the determination of the primary particles. The size of the clumped 10 phosphor particles is 10

μm that is the upper side of the lognormal distribution of the phosphor powder. You cannot detect the clumped 10 phosphor particles by the commercial instruments. The commercial instruments exclude the clumped particles in the sizes larger than 20 particles that is larger than $13 \text{ }\mu\text{m}$ ($= 5 \times (20 \times 10)^3 \text{ }\mu\text{m}$). You may surely detect the 10 clumped particles under the optical microscope. Never use the commercial instrument of the determination of the phosphor particles in the quality control of the phosphor productions.

The phosphor screen is the optically opaque screen that gives the scattered lights from the surface of the polycrystalline phosphor particles in the screen. The scattered lights from the opaque phosphor screen are an advantage as the illumination source of the lighted FL tubes. The advantage

is the illumination on furniture in the room with the daytime scenery under the slightly overcast sky that the human eyes in the daytime activity adjust for 5 million years.

The disadvantage of the opaque phosphor screen in the FL tubes is the invisible of the Ar gas space and moving electrons in the inside of the lighted FL tubes. The studies on the phosphor screens of the FL tubes had made by the observation of the visible lights from the phosphor screen that is the concrete matter. The lights of the FL tubes actually originate from the excitations of the Hg atoms in the Ar gas space by the moving electrons in the vacuum between Ar atoms. The floating Ar (and Hg) atoms in the vacuum and moving electrons are invisible by the naked eyes. The studies of the floating Ar (and Hg) atoms in the vacuum and moving electrons have made by the hypotheses. The modern science has revealed the invalidated hypotheses. The Ar atoms float in the vacuum with the separation distance at $2 \times 10^{-7} \text{ m}$ [2]. The floating Ar (and Hg) atoms and moving electrons are invisible by the naked eyes that belong to the abstraction. If you studied and leaned the phosphor powders from the references [5, 9 to 13], you may have the same conclusions with them. You never produce the advanced FL tubes. In the reality, the FL tubes light up from the excitation of the floating Hg atoms in the vacuum by the moving electrons in the superconductive vacuum [14]. The phosphor screen transduces the UV lights that arrive on the phosphor screen.

3. Clumped Particles in Phosphor Screens

The theoretically and practically optimized phosphor screen in the lighted FL tubes had well studied by the number of the layers of the phosphor particles [15]. If the phosphor particles disperse well in the screening slurry, you may have the uniform phosphor screens. By the uniform phosphor screen, you may have the optimized phosphor screen in the lighted FL tubes. The optimal phosphor screen in the lighted FL tube is given by 3 layers of the phosphor particles theoretically and practically [7, 15]. So far as you use the commercial PL phosphor powders for the screening slurry, you have the thick optimal layers more than 3 layers, depending on the producers of the phosphor powders.

The well dispersed phosphor particles in the screening slurry can be made with the aging process of the phosphor past with the addition of the small amount of the solvent. The container of the phosphor past is tightly sealed with the cover, and the covered container keeps for the several hours. The surface of all phosphor particles wet with the solvent. This is the aging process. The aging hours are changed with the commercial phosphor powders, depending on the different phosphor producers. After the aging process, the appropriate amount of the solvent adds to the aged slurry for the preparation of the screening slurry. The individual phosphor particles perfectly separate each other in the phosphor slurry. The phosphor screen on the inside wall of the FL tubes is made with the screening slurry.

In general, the commercial phosphor powders contain many clumped phosphor particles. If you prepare the screening slurry with the commercial phosphor powder that contains the clumped particles, the optimal thickness of the phosphor screen is more than 5 layers, depending on the amount of the clumped phosphor particles in the commercial phosphor powders. The optimization of the commercial phosphor screen had made with the inspection of the lighted phosphor screen by the naked eyes. It was not hard to find out the dark spots and pinholes in the lighted phosphor screens. The assignment of the dark spots and pinholes is made by the observation of the magnifier (> 3 times). The pinholes are assigned as the drop out of the large clumped phosphor particles after the baking process of the phosphor screen. The dark spots in the prepared phosphor screen are assigned as the clumped phosphor particles in the screen. The sizes of the clumped phosphor particles are the larger than $10 \mu\text{m}$ to $500 \mu\text{m}$. The produced phosphor screens from the commercial phosphor powders have many pinholes and dark spots in the phosphor screens in the lighted FL tubes. The improvement of the illuminance (lm m^{-2}) of the FL tubes had made by the removal of the clumped phosphor particles in the phosphor screens [9, 10]. They thought that the clumped phosphor particles came from the storage of the produced phosphor powder in the container. However, they did not figure out the mechanisms of the clumped particles in the container.

The clumping mechanisms of the phosphor particles are below. The storage container of the produced phosphor powder usually contains the air. The phosphor particles contact each other. The contact of the particles has a narrow gap at which adsorbs the water from the moisture in the air by the capillary condensation. The adsorbed water in the narrow gap dissolves the residuals on the phosphor particles. The water becomes the solution that has the high surface tension. The surface of the phosphor particles slowly covered with the thin layer of the solvent. The particles that are covered with the solvent gather up to the some sizes. The gathered particles are the clumped particles. As the phosphor powder puts in the container with the small amount of the water, the solvent of the clumped particles slowly dissolve in the water. This is the aging process. If you do not have the aging process before the preparation of the phosphor slurry, your phosphor slurry surely contains the clumped particles in the slurry.

4. Surface Treatment of Produced Phosphor Particles

The mechanisms of the formation of the clumped particles of the commercial phosphor powders have not studied in the past. The pinholes and dark spots in the phosphor screen are the visible by the naked eyes that give the concrete matter for the phosphor producers. The reduction of the clumped phosphor particles had empirically found that the adhesion of the SiO_2 gel (microclusters) on the surface of the phosphor particles [9, 10]. The adhesion of the SiO_2 microclusters had called as the surface treatments of the phosphor particles.

Figure 5 shows the photograph of the scanning electron microscope (x 2000) of the commercial phosphor particles with the surface treatment by the SiO_2 microclusters. The SiO_2 microclusters in the size smaller than $0.1 \mu\text{m}$ are the electric insulators. Accordingly, the entire area of the phosphor screen in the lighted FL tubes is electrically shielded by the cloud of the SBE on the SiO_2 microclusters on the phosphor particles [6]. The approaching electrons from the cathode of the internal DC electric power generator receive the strong Coulomb's repulsion from the SBE on the SiO_2 microclusters on the

phosphor particles. The moving electrons cannot approach to the phosphor screen. The electrons move on in the Ar gas space in which the $F_{\text{vect}} \geq F_{\text{phos}}$. The depth of the gap of the surface-treated phosphor screen does not change with the diameters of the FL tubes. The depth of the gap can be evaluated from the measurements of the build-up curves of the illuminance (lm m^{-2}) in the Ulbricht Sphere. The determined depth of the gap is $3 \times 10^{-3} \text{ m}$ ($= 3 \text{ mm}$). Figure 6 illustrates the gap in the FL tubes in the different diameters.

Figure 5. Photograph of scanning electron microscope (x 5000) of surface - contaminated phosphor particles by surface - treatment of commercial phosphor powder.

Figure 6. Diameters of positive column in lighted FL tubes with different diameters of FL glass tubes with constant depth of gap by SBE.

Figure 7. Photograph of ideal phosphor particles for phosphor screen in FL tube. Photograph is by scanning electron microscope ($\times 5000$).

We may produce the phosphor screen of the FL tubes by the $\text{Ca}_3(\text{PO}_4)_4(\text{Cl}, \text{F})\text{:Sb:Mn}$ white emitting phosphor powder without the SiO_2 surface treatment. Figure 7 shows the photograph of the scanning electron microscope of the $\text{Ca}_3(\text{PO}_4)_4(\text{Cl}, \text{F})\text{:Sb:Mn}$ phosphor particles without the SiO_2 microclusters. The $\text{Ca}_3(\text{PO}_4)_4(\text{Cl}, \text{F})\text{:Sb:Mn}$ phosphor particles in the screen have the SBE in the lighted FL tube. With this reason, the commercial 40W-HCFL tubes with the $\text{Ca}_3(\text{PO}_4)_4(\text{Cl}, \text{F})\text{:Sb:Mn}$ phosphor screen do not change the depth of the gap by the surface treatment. The study on the phosphor screens of the 40W-HCFL tubes had optimized the outer diameter with the invalidated luminous efficiencies ($\text{lm W}_{\text{tube}}^{-1}$) [2]. The optimized outer diameter of the commercial 40W-HCFL tubes with the $\text{Ca}_3(\text{PO}_4)_4(\text{Cl}, \text{F})\text{:Sb:Mn}$ phosphor particles is $3.2 \times 10^{-2} \text{ m}$ ($T - 10$) [14]. The diameter of the positive column in the 40W-HCFL tube, in which the electrons move on in the Ar gas space, is $2.2 \times 10^{-2} \text{ m}$ ($= (3.0 - 0.2 - 0.6) \times 10^{-2} \text{ m}$). If the depth of the gap of the 40W-HCFL tubes reduces to $3 \times 10^{-4} \text{ m}$, the illuminance (lm m^{-2}) will increase to the level more than 2 times. However, we cannot reduce the depth of the gap by the cleaning of the $\text{Ca}_3(\text{PO}_4)_4(\text{Cl}, \text{F})\text{:Sb:Mn}$ phosphor particles as the reason described above.

5. Deceleration of Moving Electrons with Distance from Cathode

The electrons move on in the superconductive vacuum in the Ar gas space. The electrons meet the Ar atoms that float in the vacuum. The moving electrons in the superconductive vacuum do not lose the kinetic energy by the Joule Heat. The moving electrons in the superconductive vacuum only lose some amount of the kinetic energy by each meeting with the Ar atom by the ionization of the Ar atom (Ar^{1+}). The initial kinetic energy is given by the F_{vect} between the cathode and

anode of the internal DC electric power generator, independent on the applied voltage to the electrodes of the external AC driving circuit [2]. The moving electrons are gradually attenuating the kinetic energy by the ionization of each Ar atom from the initial kinetic energy (e.g., 5 kV). As the moving electrons attenuate the kinetic energy to the excitation energy of the Ar atoms that is between 15 eV and 11.5 eV, the moving electrons excite the Ar atoms. As the moving electrons have the kinetic energy below 11 eV, the moving electrons recombine with Ar^{1+} to return Ar atoms.

The number of moving electrons in the internal DC electric circuit is calculated from the DC current in the positive column. The DC current in the internal DC electric circuit is $2 \times 10^{-4} \text{ A}$ [2], corresponding to the number of the electrons of 1×10^{15} electrons per second $\{= 2 \times 10^{-3} \text{ A} \times (1.6 \times 10^{-19} \text{ Coulomb s}^{-1})^{-1}\}$. We cannot analyze the individual electrons of 10^{15} electrons per second. The DC current at anode coincides with the DC current from the cathode [2]. Following calculations are made as the statistical results of the 10^{15} electrons per second.

As the moving electrons attenuate the kinetic energy until 16 eV, the moving electrons lose the kinetic energy by the ionization of the Ar atoms. The scattered electrons from the Ar atoms gain the kinetic energy under the F_{vect} . This is the case of the high Ar gas pressures in FL tubes. The commercial 40W-HCFL tubes contain the Ar gas pressure at 930 Pa ($= 7 \text{ Torr}$). By a neglect of the acceleration under the F_{vect} , we may calculate the minimum number of the ionized Ar atoms by one moving electron. The number of the ionized Ar^{1+} in the positive column per one moving electron is calculated as 312 Ar^{1+} ($= 5000 \times 16^{-1}$). Each of the ionization of the Ar atom generates the heat in the Ar gas space in the positive column by the change in the entropy. The moving electrons lose the kinetic energy for a moment by the scattering from the ionized Ar atoms in the positive column.

Here is a problem with the scattered electrons from the ionized Ar atoms. The F_{phos} is the constant on the phosphor screen. Therefore, the constant F_{phos} gradually pushes the scattered electrons to the center of the Ar gas space, giving rise to gradually widening gap in the lighted FL tubes with the distance from the cathode of the electron sources. Figure 8 schematically illustrates the widening mechanism of the gap in the lighted FL tube. The widening of the gap with the distance from the cathode is invisible by the naked eyes. The widening of the gap can be detected by the light intensities from the phosphor screen of the lighted FL tubes. The number of the unexcited Hg atoms in the gap increases with the distance from the cathode, resulting in the decrease in the illuminance (lm m^{-2}) from the phosphor screen. The decrease in the light intensities at the distance from the cathode had been explained by the electric resistance of the Ar gas space. This is a wrong assignment of the decrease of the light intensities from the phosphor screen. The decrease in the light intensities of the phosphor screen from the cathode is actually narrowing of the diameter of the positive column in the lighted FL tube. Figures 9 and 10 (A) illustrate the

narrowing of the diameter of the positive column with the distance from the cathode. The depth of the gap increases with the distance from the cathode. The unexcited Hg atoms in the gap increase with the deep gap. Figure 11 shows photograph (above) of the narrowing of the diameter of the lights from the phosphor screen of the commercial CCFL tube in 3.2×10^{-3} m outer diameter. The commercial CCFL tube is operated with external AC riving circuit with 2 kV with 30 kHz. As the phosphor screens of the FL tubes are produced with the commercial PL phosphor powders, you surely have the trouble of the narrowing of the positive column with the distance from the cathode. Since the FL tubes are operated with the AC voltages, the longitudinal center area of the phosphor screen of the FL tubes emits the lowest light intensity.

Figure 8. Schematic explanation of widening of depth of gap with distance from cathode by uniformly distributed SBE on phosphor screen.

Figure 9. Narrowing in diameter of positive column in FL tube by distance from cathode.

Figure 10. Diameters of positive column in lighted FL tubes. (A) is phosphor screen by commercial phosphor powder. (B) is improved phosphor screen by arrangement of low voltage CL phosphor particle (black circles) and PL phosphor particles.

Figure 11. Photographs of lighted screens of CCFL tubes; above FL tube has phosphor screen by commercial phosphor powder are bottom FL tube has improved phosphor screen.

6. Arrangement Side by Side of Low Voltage CL Phosphor Particles and PL Phosphor Particles on Top Layer of Phosphor Screen in FL Tubes

There are two kinds of the phosphor particles in the phosphor screen in the operation of the lighted FL tubes [2]. One is the surface-bound-electrons (SBE) and other is electrically neutral surface. The charges of the SBE ($-2000V$) on the phosphor particles only appear in the phosphor particles that the luminescence centers are directly excited by either incident electrons or the UV lights. The SBE disappears in the unlighted FL tubes. The electric insulators on the surface of the phosphor particles also have the SBE in the lighted FL tubes. All commercial PL phosphor particles inevitably have the SBE in lighted FL tubes. Figure 12 (A) schematically illustrates the repulsed electrons by the Coulomb from the SBE. Accordingly, the commercial HCFL tubes have the gap deeper than 3×10^{-3} m [9].

The Ar gas in the gap acts as the thermal insulation to the positive column, so that the gap controls the optimal temperature of the positive column. The high temperature of the positive column gives rise to the high illuminance ($lm\ m^{-2}$) of the lighted FL tubes. However, the vaporized Hg atoms in the Ar gas space in the gap work as the optical filter to the UV lights from the positive column. The eradication of the gap in the lighted FL tubes is expected in the improved FL tubes.

The low voltage CL phosphor particles have the electrically neutral surface in the lighted FL tubes [6]. The electrons from the cathode preferentially take the surface conduction on the neutral surface of the phosphor particles. Figure 12 (B) schematically illustrates the surface conduction on the phosphor screen by the low voltage CL phosphor particles. The electrons, which have the surface conduction, have a very low probability of the sampling of the floating Hg atom in the vacuum in the FL tube. Consequently, the FL producers do not consider the practical use of the low voltage CL phosphor powders.

We have reached an idea from the results in Figures 12 (A) and (B) for the eradication of the gap between positive column and the phosphor screens. If the low voltage CL phosphor particles arrange side by side on the top layer of the PL phosphor screen, the moving electrons may reach on the surface of the conductive low voltage CL phosphor particles. The electrons may accelerate on the surface conduction on the

low voltage CL phosphor particles. The size of the low voltage CL phosphor particles ($= 5 \times 10^{-6} \text{ m} = 5 \mu\text{m}$) is the wide enough for the acceleration of the electrons that have the diameter of $5.6 \times 10^{-15} \text{ m}$. The accelerated electrons on the surface conduction on the low voltage CL phosphor particles are strongly repulsed by the electric field from the SBE on the PL phosphor particles. The strongly scattered electrons may move the entire Ar gas space of the lighted FL tubes. The moving electrons in the longitudinal direction periodically reach on the surface of the low voltage phosphor particles. The accelerated electrons scatter the wide volume of the Ar gas space. Figure 12 (C) schematically illustrates the surface conduction on the low voltage CL phosphor particles and scattering of the accelerated electrons by the SBE on the PL phosphor particles. The average sizes of the phosphor particles are $5 \times 10^{-6} \text{ m}$ ($= 5 \mu\text{m}$). The periodical irregularity of the light intensities on the phosphor screen is beyond the resolution of the naked eyes. We may detect the constant light intensity from the phosphor screen of the lighted FL tubes. The diameter of the positive column in the total longitudinal length of the lighted FL tubes may apparently extend to the phosphor screen as illustrated in Figure 10 (B).

Figure 12. Schematic explanation of electron trajectories by distributions of negative charges of SBE (A), surface conduction on neutral surface of phosphor screen (B), and combination of low voltage CL phosphor particles and PL phosphor particles in phosphor screen (C).

The arrangements of the phosphor particles side by side at the top layer of the phosphor screen are made by the commercial tri-color rare earth PL phosphor powders. The experimental phosphor screens are made by the blend mixture of the commercial blue and green PL phosphor powders plus the cleaned surface of the Y_2O_3 : Eu red phosphor powder. We have confirm that the red phosphor particles have the $V_{\text{th}} = 110 \text{ V}$ in the VD curve of CL. The FL tubes were made by the glass tubes in $6.5 \times 10^{-3} \text{ m}$ ($= 6.5 \text{ mm}$) (T - 3) outer diameter with 0.70 m longs of the Pb-glass tubes. The Ar gas pressure in the testing FL tubes is $9 \times 10^3 \text{ Pa}$ ($= 70 \text{ Torr}$). The screening process of the phosphor screens and production process of the FL tubes take the ordinal production process, except for the sealing of the tip glass tubes. The tip glass tubes are sealed at

the softened temperatures of the Pb-glass tube, instead of the malted glass, by the use of the ring heater.

The arrangement of the individual phosphor particles on the phosphor screen at side by side is an impossible work in the practice with the involvement of a huge number of the phosphor particles. The calculated number of the phosphor particles per FL tube is 10^{22} particles. The followings are the statistical average of the involved phosphor powders. The moving electrons in the Ar gas space are only influenced by the electric charges on the phosphor particles arranged at the top layer of the surface of the phosphor screen. On other hands, the UV lights have no electric charge. The UV lights penetrate into the particles placed in the deep layers of the phosphor screen. As already mentioned, the best phosphor screen in the FL tube is constructed with 3 layers of phosphor particles [8, 16]. Therefore, at first the basic phosphor screen of 3 layers is made by the blend mixture of the blue and green PL phosphor particles. The screening density of the 3 layers of the phosphor screen is 3 mg cm^{-2} . After dry of the PL phosphor screen, the low voltage CL phosphor particles spread on the dried PL phosphor screen. Figure 13 (A) illustrates the phosphor screen prepared with the process described above. The production of the phosphor screens requires two steps of the screening process. A simplified screening process can be made with the blend mixture of the low voltage CL phosphor particles and PL phosphor particles by the control of the particle size distributions of each phosphor powder.

Figure 13. Ideal arrangement of low voltage CL phosphor particles on PL phosphor particles (A), and once screening of blend mixture (B).

Figure 13 (B) illustrates the phosphor screen that is composed with the blend mixture of the low voltage CL phosphor particles and PL phosphor particles. The distribution of the particle sizes of the CL and PL phosphor particles is an important consideration for the blend mixture of the CL and PL phosphors. Furthermore, the densities and shapes of the CL and PL phosphor particles are also the important factors that control (a) the structure of the phosphor screens and (b) the distribution of the low voltage CL phosphor particles on the top layer of the phosphor screens.

In general, the low voltage CL phosphor particles on the phosphor screen do not have negative charges on the surface of the particles as for the particles emit lights. On the other

hand, the PL phosphor particles have negative charges of the SBE on the particles. The CL phosphor particles preferably have the average particle size that is $0.5\ \mu\text{m}$ smaller than the average particle size of the PL phosphors (about $5\ \mu\text{m}$ by microscope determination). The small CL phosphor particles ($\sim 4.5\ \mu\text{m}$) preferentially arrange on the top layer of the dried phosphor screen. It should note that if the average size of the low voltage CL phosphor particles is smaller than $2\ \mu\text{m}$, the tiny phosphor particles move to the bottom layers of the phosphor screen in the drying process. The surface of the dried phosphor screen does not have the low voltage CL particles. Never use of the low voltage CL phosphor particles smaller than $3\ \mu\text{m}$ as the average size. The results of the blend mixture of the PL phosphor powders ($V_{\text{th}} = 2000\ \text{V}$) and the low voltage CL red phosphor ($V_{\text{th}} = 110\ \text{V}$) are applicable to the phosphor screens of the FL tubes in any diameters. Figure 11 shows photograph (bottom) of the coil-EEFL tube in $3.2 \times 10^{-3}\ \text{m}$ outer diameter, under the operation of 2 kV with 30 kHz. By

the referring the results in Figure 6, the coil-EEFL tube in $3.2 \times 10^{-3}\ \text{m}$ outer diameter in Figure 11 (bottom) certainly indicates the reduction of the depth of the gap in the lighted coil-EEFL tube, proving the idea of the arrangement side by side of the low voltage CL phosphor particles and the PL phosphor particles on the top layer of the phosphor screen. Figure 14 shows the photograph of the lighted phosphor screen under the optical microscope. Figure 14 (A) is the improved phosphor screen by this study. Figure 14 (B) is the phosphor screen of the commercial CCFL tubes. The low voltage CL phosphor particles are the $\text{Y}_2\text{O}_3:\text{Eu}$ red phosphor powder. The blend mixture of the white emitting phosphor powder contains the 30 weight % of the $\text{Y}_2\text{O}_3:\text{Eu}$ red phosphor powder. The entire phosphor screen emits the uniform intensity, proving the concept described above. The coil-EEFL tubes in any diameters are operated with the external DC driving circuit with the nearly zero of the electric power consumption [17].

(A) improved phosphor screen

(B) commercial phosphor screen

Figure 14. Color photographs of improved phosphor screen (A) and commercial phosphor screen (B) under short UV lamp.

The best candidate of the low voltage CL phosphor particles is the $\text{Y}_2\text{O}_3:\text{Eu}$ red phosphor. As the surface of the $\text{Y}_2\text{O}_3:\text{Eu}$ red phosphor particles is not contaminated by the insulator particles or insulator layer, the $\text{Y}_2\text{O}_3:\text{Eu}$ red phosphor particles have $V_{\text{th}} = 110\ \text{V}$. You must confirm $V_{\text{th}} = 110\ \text{V}$ before the use of the phosphor particles. Other candidate of the low voltage CL phosphor is the $\text{Zn}_2\text{SiO}_4:\text{Mn}$ green phosphor powder that has $V_{\text{th}} = 110\ \text{V}$. There are two kinds of the commercial $\text{Zn}_2\text{SiO}_4:\text{Mn}$ green phosphor powders; the low voltage $\text{Zn}_2\text{SiO}_4:\text{Mn}$ green phosphor powders with the $V_{\text{th}} = 110\ \text{V}$ and the PL $\text{Zn}_2\text{SiO}_4:\text{Mn}$ green phosphor powders with the $V_{\text{th}} = 2000\ \text{V}$. If the blend mixture of the PL phosphor powder contains 30 weight % of the low voltage $\text{Zn}_2\text{SiO}_4:\text{Mn}$ green phosphor powders in the average particle size in $4.5\ \mu\text{m}$, you may produce the lighted FL tubes shown in Figure 11 (bottom).

7. Conclusion

The eradication of the gap between positive column and phosphor screen is a pending subject of the study on the lighted FL tube for 80 years. As far the phosphor screens are made by the commercial PL phosphor powders having $V_{\text{th}} = 2000\ \text{V}$, the SBEs inevitably form in front of the surface of the phosphor screens in the lighted FL tubes. The gap is generated by the SBEs. If the phosphor screens are made by the low voltage CL phosphor particles having $V_{\text{th}} = 110\ \text{V}$, the moving electrons selectively have the surface conduction of the phosphor screen. The surface conduction of the moving electrons results in the weak illumination of the FL tube. It has found that as far the phosphor screens are made by the arrangement of the low voltage CL phosphor particles of $V_{\text{th}} = 110\ \text{V}$ and commercial PL phosphor particles having $V_{\text{th}} = 2000\ \text{V}$ at side by side, the

depth of the gap of the lighted FL tubes reduces to 3×10^{-4} m. The optimal blend mixing ratio of the low voltage CL phosphor particles is around 30 weight % of the PL phosphor particles. Thus we have successfully reduced the depth of the gap from the lighted FL tubes in this study.

Because the arrangement side by side of the phosphor particles will encounter the difficulty, the author would like to assist your experiments on the phosphor screens in the lighted FL tubes in your laboratory. After you have learned the knowhow, you may smoothly duplicate the experimental results.

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