몬테카를로 방법을 이용한 AC PDP 셀의 진공자외선 광자 이동 특성 해석

論 文
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Analysis of Vacuum UV Photon Travel Characteristics in AC PDP Cell by Monte Carlo Simulation

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Abstract - Resonance radiation trapping has a great influence on the characteristics of vacuum ultraviolet(VUV) photon emissions in AC PDP cell. We calculate the spatial and spectral distributions of VUV photons, which are radiated by excited Xe in AC PDP cell by Monte Carlo method. Especially a dip in the spectrum at center frequency is discovered both in simulation and in experiment. We give a physical explanation of this phenomenon by the concept of frequency-dependent mean free path of VUV photons.

Key Words : AC PDP, VUV emission, resonance radiation trapping, Monte Carlo simulation

1. INTRODUCTION

Resonance radiation trapping is an important phenomenon in gas discharge physics. Since the absorption of resonance radiation by ground-state atoms is high, the photons of this radiation can escape from the confined gas after a large number of repeated emissions and absorptions. This phenomenon causes the degradation of the lamp efficiency and the dispersion of spatial distribution.

The plasma display panel (PDP), which is one of the leading technology candidates for flat panel display, utilizes the 147 nm vacuum ultraviolet (VUV) Xe resonance photons in Xe-He mixture gas to excite phosphor on the surface of the PDP cell. However, the radiation trapping of 147 nm VUV is predominant in the PDP cell because the absorption coefficient of ground-state Xe atoms is high. This modifies the spatial distribution of the VUV photons and reduces their number that excite phosphor and causes serious problems in the brightness of the PDP. Therefore, in order to improve the brightness efficiency of the PDP, it is necessary to analyze the characteristics of 147 nm VUV photon travel considering the resonance radiation trapping.

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In this paper, we calculated 147 nm photon distribution arriving at the PDP phosphor surface by using Monte Carlo simulation. Spatial and spectral distributions of photons were calculated in the PDP cell structure. Especially, the dip in the spectrum at center frequency was seriously studied. This phenomenon was found in case of an argon-mercury fluorescent lamp but sufficient explanation was not provided [1]-[2]. We could give a brief explanation of the dip in the spectrum at center frequency by using the concept of frequency-dependent mean free path.

2. SIMULATION MODEL

Simulations were carried out for a surface discharge AC PDP cell having a structure of Fig. 1. Electric discharge generated many initial photon seeds which were the excited Xe atoms. In simulation, they were given only at the position of x=540 μm and y=10 μm with delta distribution. The total number of photon seeds was 10 millions. We calculated the total number of photons reaching the top surface (y=150 μm) from all directions.

Fig. 2 shows the flow chart of Monte Carlo simulation. When one photon seed is generated, a random number is generated between 0 and 1 to decide whether the photon is quenched or not. If the random number is smaller than quenching probability, the photon is destroyed and a next photon seed is generated. If the quenching does not take place, three more random numbers are generated. One is for deciding emission frequency, another for emission direction and the other for travel distance. And the procedure is repeated until the VUV photon reaches one of the four boundary surfaces.

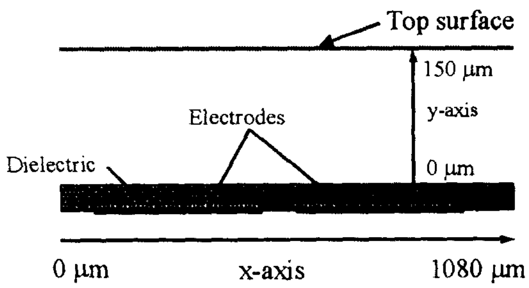


Fig. 1 Configuration of AC PDP cell used in the simulation

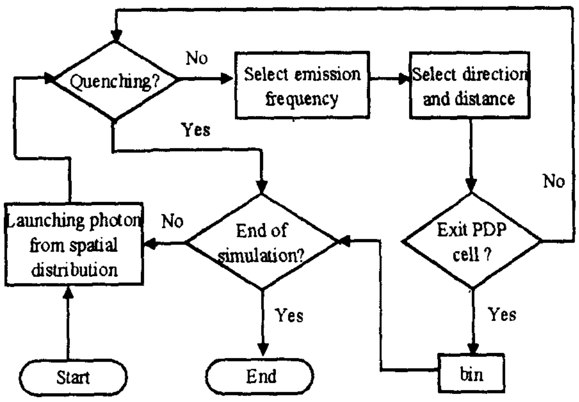


Fig. 2 Flow chart of the Monte Carlo simulation

2.1 Determination of emission frequency

Because typical Xe partial pressure in PDP cell (300 Torr, He-Xe mixture ratio 5%) is over 10 Torr, the pressure broadening is dominant [3]. Therefore, in this paper only pressure broadening is included in the lineshape of VUV photons and the Doppler broadening is neglected. The shift in line center caused by He, which is a foreign gas, is omitted for the simplicity of the lineshape model. The pressure broadening has the Lorentzian profile and the probability density function $P(\nu)$ of emission frequency ν is expressed as

$$P(\nu)=\frac{1}{\pi}\frac{\gamma_p}{(\nu-\nu_o)^2+\gamma_p^2}, \quad (1)$$

where ν_o is the center frequency and γ_p is the half-width-at-half-maximum of the pressure broadening [4]. In this simulation, ν_o is 2040.82 THz(=147 nm) and γ_p is 1.7 THz(=0.12 nm). Since $P(\nu)$ is normalized, we can decide the emission frequency by a cumulative fraction of $P(\nu)$. Fig. 3 shows the procedure of the determination of emission frequency by random number R. A random number R [0, 1] specifies a value on the vertical axis of the figure, from which one obtains the emission frequency on the horizontal axis.

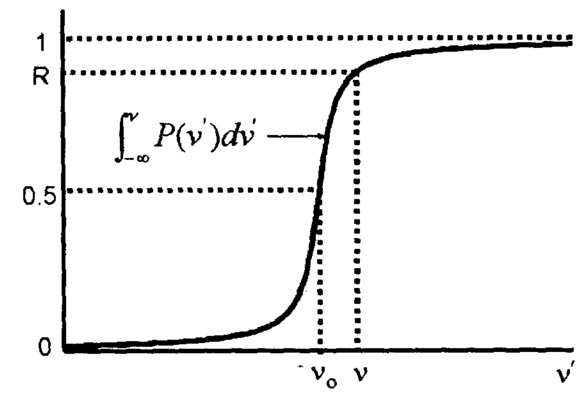


Fig. 3 Determination of an emission frequency ν by random number R

2.2 Determination of emission distance

After the emission frequency is decided, we must choose the radiation distance ρ of the determined frequency. The probability $T(\rho,\nu)$ that a photon of an emission frequency ν traverses a distance ρ without being absorbed is written as [3]

$$T(\rho,\nu)=\exp[-k(\nu)\rho], \quad (2)$$

where $k(\nu)$ is the absorption coefficient as a function of frequency. Since $T(\rho,\nu)$ has a value between 0 and 1, and is a monotonically decreasing function, we can determine the traverse length as we did the emission frequency. (see Appendix A) Then we can regard $T(\rho,\nu)$ as a random number U [0,1]. When we take the natural logarithm of both sides of Eq. (2), the traverse length ρ is written as

$$\rho=\frac{-\ln U}{k(\nu)}. \quad (3)$$

For the pressure broadening, $P(\nu)$ is proportional to $k(\nu)$ even in non-thermodynamic equilibrium [3]. Hence, $k(\nu)$ can be expressed as

$$k(\nu)=\frac{k_o}{1+[(\nu-\nu_o)/\gamma_p]^2}, \quad (4)$$

where k_o is a coefficient which is written as, in a pure gas, [3]

$$k_o=\frac{\lambda_o^2 g_2 N}{8\pi^2\tau g_1\gamma_p}, \quad (5)$$

where λ_o (=147 nm) is the wavelength of the center resonance line, τ is the spontaneous emission time, g_1 and g_2 are the statistical weights of the normal and excited atomic energy levels respectively, and N is the density of the normal atoms. Eq. (5) is derived in detail in Appendix B. In case of a He-Xe mixture gas the absorption coefficient is given in Ref. [5]. By inserting Eq. (4) into Eq. (3), radiation length is expressed as

$$\rho=\frac{1}{k_o}\left[1+\left(\frac{\nu-\nu_o}{\gamma_p}\right)^2\right](-\ln U). \qquad (6)$$

2.3 Determination of emission angle

Another random number between 0 and 1 is generated for deciding emission direction. A random number times 2π decides the two-dimensional radiation angle in radian.

3. SIMULATION RESULTS

Fig. 4 shows an experimental setup from which we obtain the experimental spectral distribution of photons for various top surface heights as shown in Fig. 5. Photon seeds are generated by the electric discharge of PDP cell. We only count the photons which pass through the slit in the center of the top surface of Fig. 4. Since MgF_2 layer is transparent only in the wavelength region of VUV, photons of other wavelength regions are attenuated. Finally, the wavelength distribution of the VUV photons is obtained by spectrum analyzer.

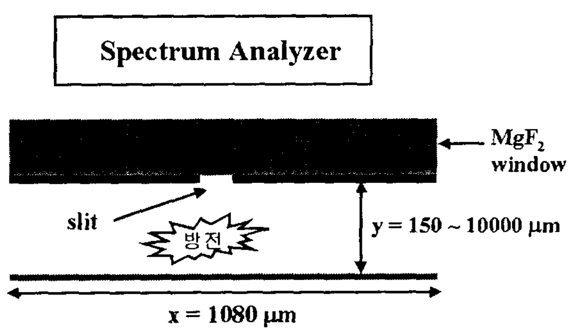


Fig. 4 Experimental setup

In Fig. 5 as the distance to the top surface becomes large, the total number of photons arriving at the top surface is reduced and the profile becomes broader. A noteworthy phenomenon is that, as the distance becomes large, the dip at the center frequency in the spectrum becomes relatively deeper. Fig. 6 shows the simulation results when the coefficient k_o is 1/170 (μm^{-1}). The simulation results show a tendency similar to that of the experimental spectral distributions of photons. Experiment and simulation results are not equal for various top surface hights because we have not yet considered the exact experimental conditions such as the distribution of initial photon seeds, physical parameters like the absorption coefficient, and the effects of foreign gas.

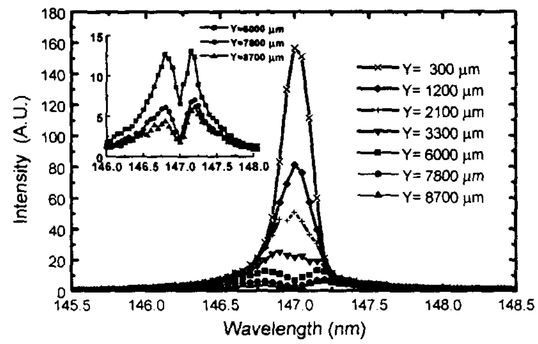


Fig. 5 Frequency distribution of photons reaching the top surface for various y-positions (experimental results)

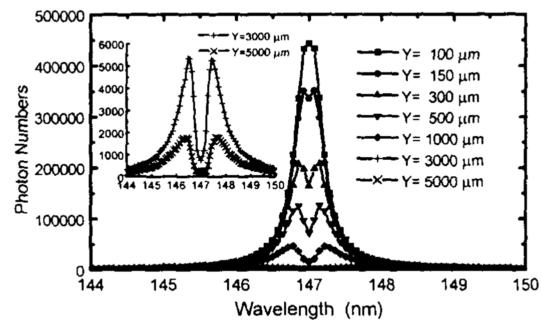


Fig. 6 Frequency distribution of photons reaching the top surface for various y-positions (simulation results, $1/k_o$ = 170 μm)

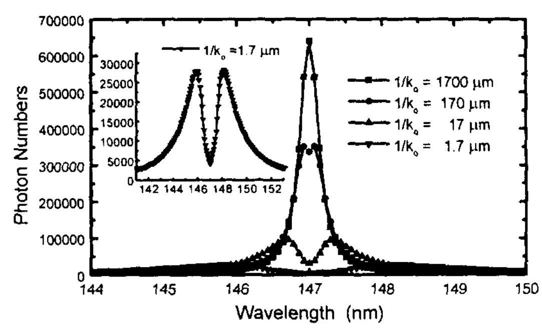


Fig. 7 Frequency distribution of photons reaching the top surface for various absorption coefficients (simulation results, y = 150 μm)

Fig. 7 shows the simulation results of spectral distributions when we vary the coefficient k_o. Though the distance to the top surface is fixed, the increase of the absorption coefficient gives more dip similarly to the case

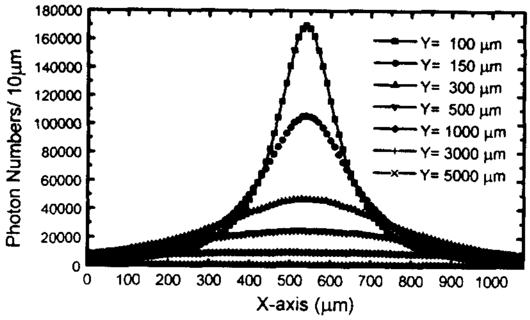


Fig. 8 Spatial distribution of photons reaching the top surface for various y-positions (simulation results, $1/k_o$ = 170 μm)

of increasing distance to the top surface.

Fig. 8 shows the simulated spatial distribution of photons for various top heights. As the distance to the top surface becomes large, the distribution becomes much broader than the initial one. These results are due to the effect of the spontaneous emission, in which photon is absorbed by a ground-state Xe atom and reemitted to all directions. As the distance to the top surface increases, photons which are generated at initial photon seeds experience more absorptions and reemissions before they reach the top surface. Therefore, the spatial distribution of photons becomes more dispersive.

4. DISCUSSION

Among the above simulation results, the fact that the longer the distance is, the deeper is the dip in the spectrum at the center frequency is not easily understood. This phenonenon can also be found in case of an argon-mercury fluorescent lamp but sufficient explanation was not provided [1]-[2]. In color PDP cell the phosphor on the top surface may have VUV absorption coefficients that depend on wavelength. This may effect the brightness efficiency of the PDP cell and hence, the analysis of the spectral characteristics of VUV photons can be important.

4.1. Concept of frequency-dependent mean free path of photon

In Eq. (3) the random number U has a uniform distribution and its probability density function $f(U)$ is given by

$$f(U)=\begin{cases}1, & 0\le U\le 1\\ 0, & \text{otherwise}.\end{cases} \qquad (7)$$

Therefore, the expectation value of $-\ln U$ with the uniform probability distribution function $f(U)$ is given as

$$\int_0^1[-\ln U]f(U)dU=1. \qquad (8)$$

Then the expectation value of radiation length $\overline{\rho}(\nu)$ is expressed as

$$\overline{\rho}(\nu)=\frac{1}{k(\nu)}. \qquad (9)$$

$\overline{\rho}(\nu)$ is the mean free path of photons having emission frequency ν. When we insert Eq. (4) into Eq. (9), the mean free path of photons $\overline{\rho}(\nu)$ is expressed as

$$\overline{\rho}(\nu)=\frac{1}{k_o}\left[1+\left(\frac{\nu-\nu_o}{\gamma_p}\right)^2\right]. \qquad (10)$$

Fig. 9 shows the mean free path versus emission frequency. Mean free path has a minimum value $1/k_o$ at the center frequency ν_o. As the emission frequency deviates from the center frequency, the mean free path increases parabolically.

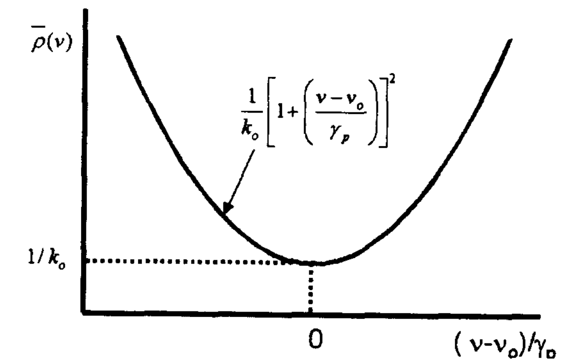


Fig. 9 Mean free path of photons versus normalized frequency $(\nu-\nu_o)/\gamma_p$

4.2. Explanation of the dip in the spectrum at center frequency

We can give a brief explanation to the dip in the spectrum at center frequency by means of the frequency-dependent mean free path. In Fig. 6 the dip does not occur when the position of top surface is at y= 100 μm. This position can be compared with the mean free path of photons of the center frequency. When the absorption coefficient ko is 1/170 (μm^{-1}), the mean free path of photons of the center frequency is 170 μm. This means that the photons which are emitted at center frequency can traverse 170 μm on the average. If the distance to the top surface is smaller than 170 μm, the seed photons of all frequency which are emitted by photon seeds can exit the top surface with one spontaneous emission on the average. Because photons of the center frequency have the largest probability of being emitted, the spectral distribution of y= 100 μm has the maximum at the center frequency (=147 nm).

As the distance to the top surface becomes larger than 170 μm, the photons near the center frequency can not reach the top surface at one time on the average and are absorbed by ground-state Xe. The excited Xe mainly reemits a photon near the center frequency. But in spontaneous emission, photons can be emitted to all directions with the same probability and this reduces the probability that the trajectory of the photon is toward the top surface. Therefore, a photon near the center frequency can not reach the top surface easily. But if an excited Xe emits a photon which has a frequency far from the center frequency, the photon has high probability to reach the boundary plane at one time of spontaneous emission because of its large mean free path. Therefore, when the distance to the top surface increases, the ratio of photons near center frequency to the photons that reach the top surface is reduced. This procedure can be shown graphically in Fig. 10.

The reason that the graph of spectral distribution has two maximum values at both sides of the center frequency (see Figs. 5 and 6) is as follows. The farther the frequency of photons is from center frequency, the longer mean free path the photons of that frequency have. Therefore, they have higher probability of reaching the top surface. But the farther the frequency of photons is from center frequency, the smaller emission probability the photons of that frequency have. This two factors have a conflicting effect on the number of photons with the specific frequency reaching the top surface. Two peaks in the spectral distribution appear at the frequencies at which the two conflicting factors are optimized. And the frequencies of the peaks are closely related to the distance of the top surface.

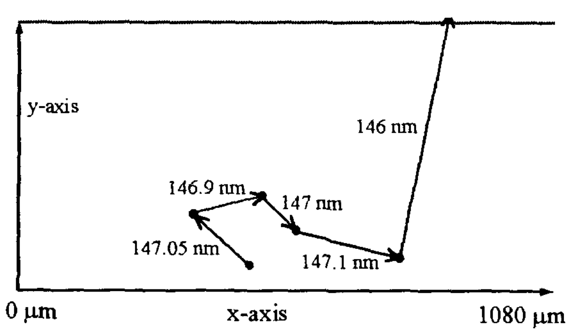


Fig. 10. *Procedure that a VUV photon exits PDP cell. Though excited xenons mainly emit photons near the center wavelength of 147 nm, the photons do not travel far from the emitted positions.*

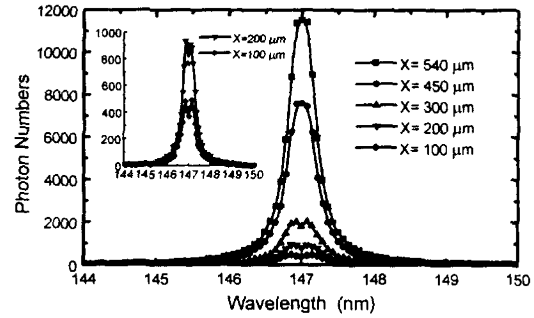


Fig. 11 Frequency distribution of photons reaching the top surface for various x-positions. Photons are counted within 10 μm width in x-axis. The y-position of the top surface is 150 μm and $1/k_o$ is fixed as 170 μm.

4.3. Relation between frequency distribution and the lateral detecting point

Fig. 11 shows the spectral distribution of photons at various x-positions at top surface with the y-position of the top surface fixed as 150 μm. The position of initial photon seeds is at the position of x = 540μm and y = 10 μm. As the x-position of detecting point deviates from that of the initial photon seeds, the dip in the spectrum becomes deeper. We can reaffirm the fact that the dip in the spectrum is related to the distance between initial photon seed and detecting position.

5. CONCLUSION

We studied the spatial and spectral distribution of VUV photons which reach the top surface of AC PDP cell by using Monte Carlo method. The spatial distribution of photons is broader than the initial spatial profile and the spectral distribution of photons is different from the profile of pressure broadening. Especially, the dip of center frequency in the spectrum becomes deeper as the distance between the initial discharge position and the top surface of PDP becomes longer. We gave a brief explanation of the dip in the spectrum at the center frequency considering the frequency-dependent mean free path. In conclusion, resonance radiation trapping must be seriously considered when we analyze the 147 nm resonance photons reaching the surface where phosphor emits visible light.

Appendix A

Decision of radiation length by $T(\rho,\nu)$ in place of a cumulative fraction of $K(\rho,\nu)$ which is the probability that a photon traverse a distance ρ

In Eq. (2), $T(\rho, \nu)$ represents the probability that a photon of an emission frequency ν traverses a distance ρ without being absorbed. From this, we can derive the probability $K(\rho, \nu)d\rho$ that the photon of an emission frequency ν is absorbed after traversing a distance between ρ and $d\rho$ from its emission point. From elementary laws of probability,

$$K(\rho, \nu)d\rho = T(\rho, \nu) - T(\rho + d\rho, \nu) = -\frac{dT(\rho, \nu)}{d\rho} d\rho, \tag{1A}$$

so that

$$K(\rho, \nu) = -\frac{dT(\rho, \nu)}{d\rho}. \tag{2A}$$

Inserting Eq. (2) into Eq. (2A), $K(\rho, \nu)$ is expressed as

$$K(\rho, \nu) = k(\nu)\exp[-k(\nu)\rho]. \tag{3A}$$

$K(\rho, \nu)$ is normalized, because

$$\int_0^{\infty} K(\rho, \nu) d\rho = 1. \tag{4A}$$

We can decide the radiation length by a cumulative fraction of $K(\rho, \nu)$ and a random number between 0 and 1 as we did the emission frequency in Fig 3. $Y(\rho, \nu)$, a cumulative fraction of $K(\rho, \nu)$, is defined as

$$\begin{aligned} Y(\rho, \nu) = \int_0^{\rho} K(\lambda, \nu) d\lambda &= -[\exp(-k(\nu)\lambda)]_0^{\rho} \\ &= 1 - \exp[-k(\nu)\rho] \\ &= T(0, \nu) - T(\rho, \nu). \end{aligned} \tag{5A}$$

As can be seen in Eq. (5A), we can also decide the radiation length by $T(\rho, \nu)$ and a random number between 0 and 1.

Appendix B

Derivation of absorption coefficient k_o Eq. (5)

From a very general expression derivable from thermodynamic principles (cf. Ref. [6] pp. 95-96, Eq. (28)),

$$\int_{-\infty}^{+\infty} k(\nu) d\nu = \frac{\lambda_o^2 g_2 N}{8\pi g_1 \tau}, \tag{1B}$$

where λ_o is the wavelength of the center resonance line, τ is the spontaneous emission time, g_1 and g_2 are the statistical weights of the normal and excited atomic energy levels respectively, and N is the density of the normal atoms. Since the probability density function $P(\nu)$ of emission frequency ν is normalized,

$$\int_{-\infty}^{+\infty} P(\nu) d\nu = 1. \tag{2B}$$

When $k(\nu)$ is proportional to $P(\nu)$, $k(\nu)$ can be expressed as

$$\begin{aligned} k(\nu) &= \frac{\lambda_o^2 g_2 N}{8\pi g_1 \tau} P(\nu) \\ &= \frac{\lambda_o^2 g_2 N}{8\pi g_1 \tau} \frac{1}{\pi} \frac{\gamma_p}{(\nu - \nu_o)^2 + \gamma_p^2} \\ &= \frac{\lambda_o^2 g_2 N}{8\pi^2 g_1 \tau \gamma_p} \frac{1}{1 + [(\nu - \nu_o)/\gamma_p]^2}. \end{aligned} \tag{3B}$$

From this, we can obtain Eq. (5)

감사의 글

본 연구는 서울대 PDP 거점 연구단의 지원을 받아 수행되었으며 이에 감사드립니다.

참 고 문 헌

[1] J. B. Anderson, J. Maya, M. W. Grossman, R. Lagushenko, and J. F. Waymouth, "Monte Carlo treatment of resonance-radiation imprisonment in fluorescent lamps," Phys. Rev. A, vol. 31, no. 5, pp. 2968-2975, 1985.

[2] T. J. Sommerer, "A Monte Carlo simulation of resonance radiation transport in the rare-gas-mercury positive column," J. Appl. Phys., vol. 74, vo. 3, pp. 1579-1589, 1993.

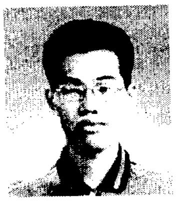
[3] T. Holstein, "Imprisonment of resonance radiation in gases," Phys. Rev., vol. 72, no. 12, pp. 1212-1233, 1947.

[4] B. E. A. Saleh and M. C. Teich, Fundamentals of Photonics. John Wiley & Sons, Inc., New York, USA, 1994.

[5] Y. Watanabe, S. Mikoshiba, K. Igarashi, M. Suzuki, and S. Murayama, "Trapping of Xe VUV photons in He-Xe mixture color PDPs," Japan Display '92, p. 890, 1992.

[6] A. C. G. Mitchell and M. W. Zemansky, Resonance Radiation and Excited Atoms, Cambridge University, Cambridge, UK, 1934.[1] A. Ghosh, S. Devadas, K. Keutzer and J. White, "Estimation of Average Switching Activity in Combinational and Sequential Circuits," ACM/IEE Design Automation Conf., pp. 253-259, 1992.

저 자 소 개



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