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Physical Mechanism of Light emission from Discharge Cells in the Plasma Display Panel

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The plasma display panel is made of many small discharge cells, which consist of a discharge space between the cathode and anode. An electrical discharge occurs in the discharge space filled by neon and xenon gases. The electron temperature is determined from the sparking criterion, which theoretically estimates the electrical breakdown voltage in terms of the xenon mole fraction. The plasma in the cell emits vacuum ultraviolet lights of 147 nm and 173 nm, exciting fluorescent material and converting VUV lights to visible lights. The physical mechanisms of all these processes have been theoretically modeled and experimentally measured. The theory and experimental data agree reasonably well. However, new materials and better configuration of cells are needed to enhance discharge and light emission efficiency and to improve the PDP performance.

Keywords : Plasma display panel, Discharge cell, Light emission, Electrical Breakdown

I. Introduction

Images of the plasma display panel (PDP)[1] are transmitted through the lights, which are provided by the vacuum ultraviolet light (VUV) emitted from the excited xenon atoms and dimers. The more the excited xenon-atoms are the better the performance of the plasma display panel. Electron temperature at the electrical breakdown can be obtained in terms of the xenon mole fraction [1]. Most of the xenon atoms are excited by the electron impact excitation, where the electron temperature plays a pivotal role. There are two major vacuum ultraviolet emissions from excited xenon atoms and molecules. The spectrum of the atomic resonance radiation is very narrow, centering at 147 nm. On the other hand, the dimer spectrum has a broad molecular band centering at 173 nm. There is a weaker, vibrationally-excited molecular continuum extended from 147 nm to 173 nm. The intensity of dimer emission integrated around 173 nm is much stronger than that of the atomic resonance radiation [2,3], although the peak of the atomic radiation at 147 nm may be higher than that of the dimer emission at 173 nm. Therefore, we investigate the emission properties of the 147 and 173 nm VUV lights from the electrical discharge cells of the plasma display panel, including most of the important physical phenomena, i.e., the three-body collision, diffusion loss of excited atoms, etc.

II. Electron Temperature at Electrical Discharge in PDP Cells

The electron temperature T_e at the breakdown is calculated based on the sparking criterion [4] expressed as

$$\alpha_T d = \ln(1 + 1/\gamma), \tag{1}$$

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in a gas without electron attachment, where γ represents the secondary electron-emission coefficient of low-energy ion bombardment at the cathode. The total ionization coefficient α_T in Eq. (1) is known as Townsend's first ionization coefficient and d is the anode-cathode distance. The total ionization coefficient is a sum of the electron impact ionization of neon and xenon, and Penning ionization. Plasmas are generated from the ionization of neutrals, by the impact ionization of electrons, which have a higher kinetic energy than ionization energy. Electrons with energy levels higher than ionization energy collide with neutrals, ionizing, and creating additional electrons and ions. Therefore, it is easy to ionize neutrals with less ionization energy. Meanwhile, electron energy-gain in large-size neutrals is difficult due to small mean free-path. The electrons can easily get their kinetic energy in a light-atom gas mixed with heavy atoms. Once they have enough kinetic energy, they collide with heavy atoms of low ionization energy, producing additional electrons and ions. The ionization energy of heavy atoms is usually low, although their atomic size is large. Neon atoms are small and have a small collisional cross section but require large ionization energy. Xenon atoms are large and have a large collisional cross section but need less ionization energy. The electron temperature T_e at breakdown is obtained from the sparking criterion in Eq. (1), which can be written by [2]

$$(1-\chi)U^{1.77}+(1-\chi)\phi(\chi)\frac{q_N^*\varepsilon_N^*}{q_N\varepsilon_N}U^{1.36}+\frac{q_X\varepsilon_X}{q_N\varepsilon_N}\chi U =\frac{\sqrt{\pi}\ln(1+1/\gamma)}{10^{20}q_N\varepsilon_N\xi pd}. \tag{2}$$

Here U determines the breakdown temperature T_e by $T_e = \epsilon_x/\ln(1/U)$ and the Penning ratio $\phi(\chi)$ is defined by $\phi(\chi) = 7500\chi/[7500\chi + (1-\chi)^2 p]$. The subscripts N and X in Eq. (2) represent neon and xenon, and χ are the mole fractions of xenon, respectively. The symbol p is the gas pressure in units of atmosphere and d is the electrode gap in cm units. The neon atoms are excited to a metastable state with excitation energy of $\epsilon_N^* = 16.62$ eV. The increase rate of the excitation cross-section for this metastable state is $q_N^* = 4.3\times 10^{-19}$ cm^2/eV. The increase rate in the ionization cross-section and ionization energy for neon are $q_N = 2.5\times 10^{-18}$ cm/eV is, and $\epsilon_N = 21.56$ eV. We find $q_X\varepsilon_X/q_N\varepsilon_N = 14.7$ and $q_H\varepsilon_H/q_N\varepsilon_N = 0.57$ from data in a previous literature.

As an example, we consider PDP cells, assuming that the secondary electron-emission coefficient γ at the cathode is $\gamma = 0.05$, which is a typical value of the coefficient of secondary electron emission observed in our experiment. Assuming that the form factor of neon is $\xi = 3$, the right-hand side of Eq. (2) is calculated to be 2.1×10^{-2} for $pd = 0.03$ atm-cm estimated from our experimental observations, which indicate that the most-bright spot occurs at the distance of 0.16 mm from the mid point of the anode-cathode gap. The value $pd = 0.03$ atm-cm corresponds to 400 Torr ($p = 0.526$) in our experiment. Shown in Fig. 1 are plots of the electron breakdown temperature T_e versus the xenon mole fraction χ obtained from Eq. (2) for several different values of pressure p. As expected from Eq. (2), the electron breakdown temperature T_e decreases monotonically as the xenon mole fraction χ increases. The electron breakdown temperature T_e in Fig. 1 decreases as the pressure increases. Remember that the xenon ionization energy is much less than that of neon. Therefore, xenon atoms are dominantly ionized even for a relatively low concentration of xenon. The electrical breakdown in reality occurs in a local region, where the electric field concentrates, presenting the maximum temperature, which is considerably higher than T_e. On the other hand, the electron temperature T_e obtained from Eq. (2) represents the

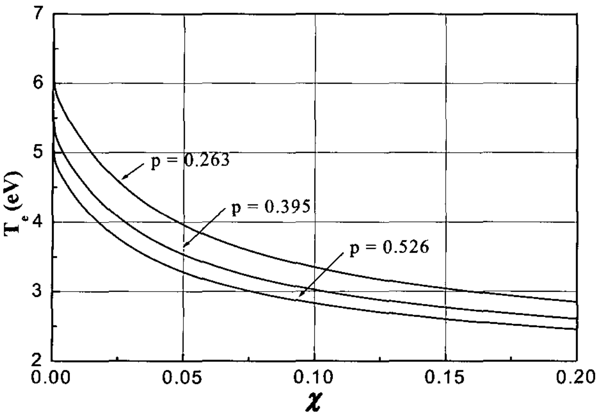

Fig. 1. Plots of the electron breakdown temperature T_e versus the xenon mole fraction χ obtained from Eq. (2) for several different values of pressure p.

mean temperature in the whole discharge volume, which is close to the electron temperature at the discharge during the sustain voltage pulse.

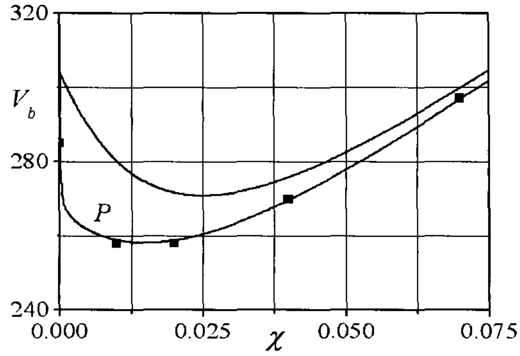

Fig. 2. Plots of the breakdown voltage V_b versus the xenon mole fraction χ. The closed rectangular dots are experimental data obtained for pd = 3.15 Torr-cm. The theoretical curve (labeled P) is simply the least-square-fit of experimental data assuming ξ/pd = 101. This line represents the breakdown voltage including the Penning effects. The upper line represents the breakdown voltage without the influence of the Penning effects.

Ⅲ. Cell Breakdown Voltage

The first issue in plasma generation is reduction of the breakdown voltage. As an example, we consider the electrical discharge system in high-pressure inert-gas, in connection with its applications to the plasma display panel [1]. One of the most important issues in the PDP study is also the reduction of the electrical breakdown voltage, which is the key element in enhancing the electrical efficiency of PDP operation. The electrical efficiency enhancement in turn prolongs panel life. The plasma display panel is operated with high-pressure gas, for which the breakdown voltage reduction may be accomplished by mixing a small amount of xenon with neon gas. A theoretical model of the breakdown voltage in a mixed gas is developed based on the Townsend criteria. We have carried out a preliminary experiment using an AC-PDP to verify some of the theoretical models. The experiment is carried out for neon gas mixed with a small percentage of xenon. The Paschen curves of the breakdown voltage are experimentally obtained in terms of the pressure parameter (pd) and the mole fraction.

Shown in Fig. 2 are plots of the breakdown voltage V_b versus the xenon mole fraction χ. The closed rectangular dots are experimental data for pd = 3.15 Torr-cm. The observation in this experiment indicates that the most-bright spot occurs at the distance of 155 μm from the mid point of the anode-cathode gap. The electric field line starting from this spot follows almost a semi-circular path to the cathode. The address electrode located beyond the discharge space helps to bend field lines in a semi-circular path. We therefore remind the reader that although the anode-cathode gap is measured to be d = 90 μm in coplanar geometry, the effective gap distance for discharge can be 500 μm or more, due to the curved field lines and the effects of the dielectric material on the electrodes. Therefore, the real effective value of parameter pd can be pd = 16 Torr–cm or more, even though the measured value is pd = 3.15 Torr–cm. The increase in the effective value of parameter pd from pd = 3.15 Torr–cm to pd = 16 Torr–cm is due to the increase in the effective gap distance from d = 90 μm to d = 500 μm. Note that pd = 16 Torr–cm is 0.022 atm–cm. The lower curve labeled P in Fig. 2 for pd = 0.022 atm–cm is simply the least–square–fit of experimental data assuming ξ/pd = 101. This line represents the breakdown voltage including the Penning effects. Due to the Penning effects, the breakdown voltage decreases very rapidly when a small amount of xenon is added to neon. The upper line in Fig. 2 represents the breakdown voltage without the influence of the Penning effects. Both the Penning effect theory and experiment indicate that the minimum breakdown voltage occurs at the xenon mole fraction χ = 0.015. The breakdown voltage decreases from V_b = 306 V to its minimum value of V_b = 255 V at χ = 0.015 and then increases again, as the xenon mole fraction χ increases from zero to unity. The breakdown voltage is reduced significantly by adding a small amount (1.5 percent) of xenon to neon. Comparing the two curves in Fig. 2, we also note that the Penning effects reduce the breakdown voltage 5 percent more and the location of the minimum breakdown voltage is shifted from χ = 0.0245 to χ = 0.015, which agrees remarkably well with experimental data.

IV. 147 nm Emission

The emission of the vacuum ultraviolet light (VUV) with 147 nm from the discharge plasma in the PDP cells is essential for efficient performance of the panel. The 147 nm VUV light emission from the PDP cell discharge is investigated in terms of the xenon mole fraction and the gas pressure p, including the important influence of the three–body collision of the excited xenon atoms in the resonance state and of the radiation trappings (or reabsorption) [2]. The emission intensity Y is analytically expressed in terms of the gas pressure and xenon mole fraction χ, and given by[2]

$$Y = \frac{\zeta\chi\exp(-\varepsilon^*/T_e)}{[1-\chi+(a_X/a_N)\chi]^2(1+\alpha_{cp}n_0\delta tp\chi)+\Delta/p^2}, \tag{3}$$

where the constants ζ and Δ are defined by

$$\zeta = \frac{2\alpha_{em}n_p\tau v_{th}q^*\varepsilon^*}{\sqrt{\pi}\alpha_v a_N^2 pn_0} \tag{4}$$

and $\Delta = a_{em}/a_{VaN}{}^{2}n_{0}{}^{2}$, respectively. In Eqs. (3) and (4), δt is the average flight time of a photon in the cell, $a_V a_N{}^2 = 1.5 \times 10^{-31}$ cm^6/s, $a_X/a_N = 3.5$ estimated from real atomic sizes based on the radii of neon and xenon atoms, a_{em} represents resonance light emission coefficient, $\varepsilon^* = 8.44$ eV is the excitation energy and the rate $q^*$of increase in the cross section is in units of cm^2/eV.

The closed squares represent the measured data and the solid line represents the theoretical curve least–square–fitted to experimental data

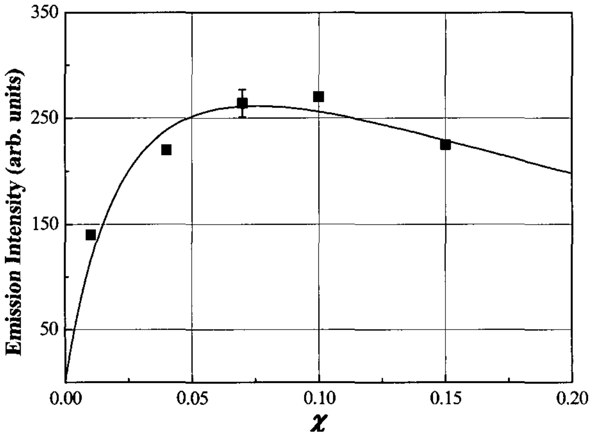

Fig. 3. Plots of the emission intensity versus the xenon mole fraction. The closed square (Ne–Xe mixture) dots represent the measured data and the solid lines are the theoretical curves least–square–fitted to experimental data for p = 400 Torr.

with K = 1.46 × 10^5, $a_{cp}n_0\delta t$ = 7.6 and Δ = 0.2. The ratio of the atomic cross section is given by a_X/a_N =3.5, because the radii of neon and xenon atoms in the ground state are r_N = 6 ×10^{-9} cm and r_X = 1.12 × 10^{-8} cm, respectively. The theoretical curve in Fig. 3 is numerically obtained from Eqs. (3) and (4). The reabsorption coefficient a_{cp} may be found from any data books, but the transit time δt of the photon in the discharge space may depend on many factors. Thus, the parameter $a_{cp}n_0\delta t$ is least-square-fitted to be $a_{cp}n_0\delta t$ = 7.6. Although five data points in Fig. 3 may not be sufficient for the determination of three parameters, the tendency of the emission intensity obtained theoretically agrees well with experimental data. The typical error bar of the experimental data is about ± 5 %, as presented in Fig. 3. The measured emission intensity decreases almost to zero prior to the application of the subsequent voltage pulse.

The theoretical model indicates that the emission intensity increases from zero, reaches its peak and then decreases, as the xenon mole fraction increases from zero. We observed from the theoretical study that the value of the xenon mole fraction corresponding to the peak emission intensity decreases as the gas pressure p increases. Therefore, the peak emission in a high gas pressure occurs at a small xenon mole fraction. The observation of the experimental data is remarkably consistent with the theoretical predictions. A simple scaling law of the emission efficiency for 147 nm VUV light is obtained by making use of the energy balance equation. Results from the theoretical model agree reasonably well with experimental data.

V. 173 nm Emission

Properties of 173 nm emission from the discharge cells in PDP are investigated [3]. A simple analytical expression Y of the total emission intensity is described in terms of the diffusion loss d_f, the three body collision η, the atomic excitation by atomic collision, the gas pressure p, and the xenon mole fraction χ. This analytical expression is expressed as the total emission of 173 nm photons from a discharge cell is given by

$$Y = \frac{\eta}{d_f + \eta}\kappa p\chi(1+2.5\chi)\sqrt{T_e}\exp(-\frac{\varepsilon^*}{T_e}), \tag{5}$$

where the constant K is defined by

$$\kappa = \frac{8.4\times10^7}{\sqrt{\pi}}q^*\varepsilon^* n_p n_0 \tau f_g \tag{6}$$

and symbol η is defined by

$$\eta = 10(1+3.3\chi)p^3\chi(\delta+\chi). \tag{7}$$

In Eqs. (5) and (6), the excitation energy ε^* = 8.32 eV, q^* the cross section rate of the metastable state is in units of cm^2/eV, τ is the discharge time and f_g is the fudge factor caused by the experimental condition. This expression provides a simple scaling law of the emission intensity for 173 nm photons. The solid curve in Fig. 4 for p = 0.526 obtained from eqs. (5) and (7) has been least-squares-fitted to the experimental data for p = 400 Torr with for K = 5.9 × 104, d_f = 0.05, and δ = 0.04. Other solid curves are obtained from Eqs. (5) and (7), simply using these parameters. The theoretical results obtained from Eqs. (5) and (7) agree markedly well with experimental data in the broad range of physical parameters. It is shown that the emission intensity Y of 173 nm photon decreases with an increasing value of parameter d_f. Reduction of the diffusion loss of the excited xenon atoms in the metastable level is extremely important for efficient emission of the 173 nm photons. The emission intensity Y of 173 nm photon increases drastically with an increasing value of the gas pressure p and the xenon mole fraction χ. Results from the theoretical

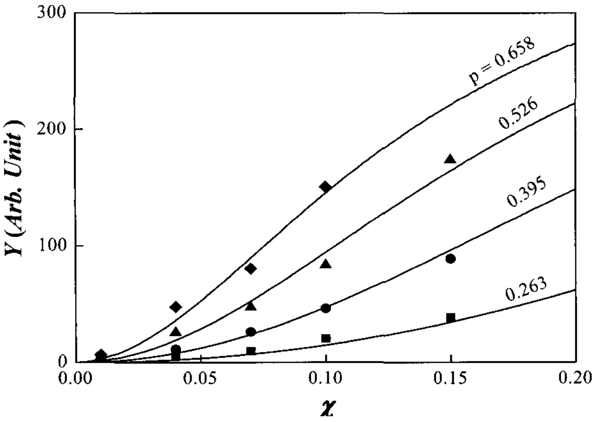

Fig. 4. Plots of the emission data for (a) the Ne-Xe mixture and p = 0.263 (200 Torr), p = 0.395 (300 Torr), p = 0.526 (400 Torr) and p = 0.658 (500 Torr). Curves are theory and dots are experimental data.

model agree remarkably well with experimental data.

Ⅵ. Conclusions

The plasma display panel is made of many small discharge cells which consist of a discharge space between the cathode and anode. An electrical discharge occurs in the discharge space. The most important parameter during the electrical discharge is the electron temperature determined from the sparking criterion. The electrical break down voltage can be estimated from the electron temperature in terms of the xenon mole fraction. The plasma in the cell emits vacuum ultraviolet lights of 147 nm and 173 nm. These VUV light excite fluorescent material, converting to visible lights. The physical mechanism of all these processes have been theoretically modeled and experimentally measured. The theory and experimental data agree reasonably well. However, the discharge and light emission efficiency is very low. New materials and better configuration of cells are needed to improve the PDP performance. Nevertheless, the commercial marketing performance of the plasma display panel is very good and is expected to be better in future.

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PDP 방전 셀에서 빛이 방출되는 물리적 메커니즘

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플라즈마 디스플레이 패널은 양극과 음극사이의 방전공간을 가진 많은 방전 셀로 구성되어 있다. 네온과 제논가스로 채워진 이 방전공간에서 전기방전이 일어난다. 전자온도가 방전조건에 의하여 정해지며 이온도를 통하여 제논의 함량에 따른 방전전압을 이론적으로 계산할 수 있다. 방전 셀 내의 플라즈마가 147 nm와 173 nm의 극자외선을 방출하고 이 자외선들은 형광물질을 여기하여 가시광선을 방출한다. 이러한 모든 과정에 대한 물리적인 메커니즘의 모델을 만들고 실험에서 측정된 데이터와 모델이 예시하는 결과를 비교한다. 실험 데이터는 이론 결과와 비교적 잘 일치하는 것을 관찰할 수 있다. PDP의 방전과 동작을 더욱 개선하기 위하여 새로운 물질이 필요하고 더 좋은 셀 구조가 요구된다.

주제어 : 플라즈마 디스플레이 패널, 방전 셀, 광 방출, 전기방전

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