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Macroscopic cell experiments and three-dimensional modelling on electrode-shaping plasma display cell*

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A macroscopic cell and three-dimensional fluid model have been used to investigate the discharge characteristics in ac plasma display panel cells of electrode-shaping configurations. Four kinds of non-standard geometries (i.e. *D*-, *Δ*-, *W*- and *U*-shape electrodes) have been considered. The characteristics of the discharge current, the operating voltage and the discharge efficiency of different configurations have been discussed. It is found that the discharge efficiency can be improved by about 10%–30% compared with the standard geometry, while the operating voltage increases slightly in the non-standard geometries. There is a trade-off between improving the discharge efficiency and lowering the sustaining voltage in design of plasma display cells by electrode shaping.

Keywords: plasma display panel, discharge efficiency, simulation, electrode configuration

PACC: 5275, 5265

1. Introduction

The plasma display panel (PDP) is one of the leading candidates in the competition for large-size flat panel displays, suitable for high definition television (HDTV) wall-mounted monitors.[1] Most of the PDPs operate in a three-electrode coplanar configuration where each discharge cell is at the intersection of two parallel coplanar electrodes (sustaining electrodes) deposited on a glass plate (front plate), with a third, orthogonal electrode (address or data electrode) located on a facing glass plate (back plate). Because of the small dimension of an ac-PDP cell and the short duration of the micro-discharge, it is difficult and costly to make a systematic and parametric study of PDP cell design. The computer modelling is therefore currently an essential approach to understanding the PDP physics and optimizing the design parameters. The first one-dimensional (1D) fluid model of the PDP cells was developed by Sahni *et al* in 1978.[2] In the last 10 years the number of papers devoted to the modelling and simulation of PDP discharges has rapidly grown and the models have evolved from one dimension[2,3] to two dimensions (2D)[4−9] and more recently, to three dimensions (3D)[10−12] which allow the study of more complex electrode configurations. Another tool that is quite efficient in understanding the physical process of PDP discharge and in guiding the design of PDP cells is the macroscopic cell which is about 100 times larger than the real PDP and operates at pressure 100 times lower. The use of computer modelling together with experiments on the macro-cell has been proved to be very efficient for diagnostic and parametric studies of PDP cell and for the optimization of its operation. [1,13−17]

The luminous efficacy of conventional coplanar ac-PDP (standard geometry) is still low and an important research effort has been devoted to its improvement.[1] The efficacy of ac-PDP can be divided into contributions from successive conversion features: Vacuum-Ultraviolet (VUV) photon generation in the micro-discharge, VUV capture by phosphor coating, VUV to visible light conversion and visible light losses. The low efficiency of VUV production in the micro-discharge is mainly responsible for the low luminous efficacy of PDP. It is well established that the discharge efficiency is strongly influenced by the gas mixture composition and the discharge mode. The improvement of the PDP discharge efficiency can be achieved by several means, such as increasing gap of coplanar electrodes,[15−18] using RF excitation,[19] increasing the xenon content of the gas mixture,[20,21] and modifying the cell geometry or electrodes,[9,22,23]

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etc. Since the shapes of the sustaining electrodes of PDP cells influence the discharge characteristics strongly, we focus on the possibility of improving the VUV production efficiency by electrode shaping.

In this article, we investigate the discharge characteristics and the discharge efficiency in non-standard ac-PDP cells by using a 3D fluid model and macroscopic cell experiments. Four electrode-shaping configurations of PDP cells (i.e. *D*-, *Δ*-, *W*- and *U*-shapes) have been considered. The effects of the design parameters of PDP cells on the discharge characteristics and the discharge efficiency have been discussed. The experimental setup and the 3D model are described in Section 2. The results from experiments and simulations are shown in Section 3. And our conclusions are summarized in Section 4.

2. Experiments and simulations

2.1. Experimental setup

The macroscopic cell we used in experiments is a sealed glass vessel with internal dimensions 9 cm × 3 cm × 1 cm as described previously.[15−17] The filling gas is 4%Xe in Ne–He mixture at 665 Pa. The two sustaining coplanar electrodes are located outside the cell, on the 9 cm × 3 cm face. The each of the two 9 cm × 3 cm plates is 3 mm thick, with a relative permittivity of 8, and the two plates are supported by two other glass layers which act as dielectric ribs. To lower the operation voltage, a MgO layer has been deposited on the internal surfaces of the 9 cm × 3 cm plates. The coplanar electrodes are 2 cm × 3 cm in dimension, with a coplanar gap of $d = 0.8$ cm, corresponding to a real PDP cell in simulation with the coplanar electrodes of 200 μm × 300 μm and gap of 80 μm. The data electrode is made of transparent indium tin oxide (ITO), with a width of 1 cm and grounded. An ac square-wave voltage (with rising time on the order of 600 ns) is applied between the two coplanar electrodes to sustain the discharge. An intensified CCD (ICCD) camera with filters (infrared (IR) emission around 823 nm or visible emission around 640 nm) is used to measure the light emission from the discharge either in front of or form side of the cell.

2.2. 3D model and input data

The 3D fluid model simulator (SIPDP-3D) we used here is from Kinema Research & Software.[24] It is an extension of the 2D model (SIPDP-AC) presented in several publications (Ref.[1] and references therein). The assumptions and boundary conditions in the 3D model are the same as those in the 2D version. Compared with the SIPDP-AC, the SIPDP-3D simulator is also semi-implicit. The charged particle continuity equations and Poisson's equation are solved in 3D model by using a bi-CGSTAB (Conjugate Gradient Stabilized)[25] technique.

The cell dimensions in the simulations are 900 μm × 300 μm × 100 μm. We consider four non-standard configurations: (a) *D*-shape, (b) *Δ*-shape, (c) *W*-shape, and (d) *U*-shape, as shown in Fig.1.

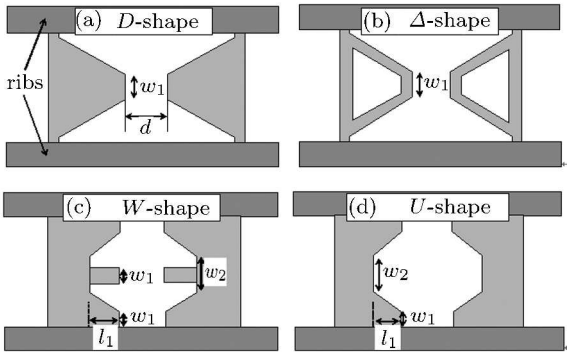


Fig.1. Schematics of non-standard configurations (a) *D*-shape, (b) *Δ*-shape, (c) *W*-shape, (d) *U*-shape.

In the simulations, the coplanar electrodes are 200 μm × 300 μm in dimension with a gap of $d = 80$ μm for all cases. The shapes of the coplanar electrodes can be altered by varying the design parameters, i.e. the values of w_1, w_2 or l_1 in Fig.1.

The gas in the calculations is mixture of 4%Xe in Ne at 6.65×10^4 Pa. The secondary electron emission coefficients for Ne^+ and Xe^+ ions on the dielectric layers are chosen in such a way that the breakdown voltage of the standard configuration in simulations is similar to that in experiments. For the present conditions, the coefficients on MgO layer are taken as $\gamma_{Ne} = 0.5$ and $\gamma_{Xe} = 0.05$, respectively. The sustaining voltage is rectangular wave pulse with a duration of 3 μs in the 3D simulations.

3. Results and discussions

3.1. Voltage margin and discharge current

We firstly test the operation voltage of different PDP configurations on the macro-cell. The margin

of the PDP cell, $(V_{\rm br} - V_{\rm min})$, is defined as the difference between the breakdown voltage $V_{\rm br}$ and the minimum sustaining voltage $V_{\rm min}$. The minimum sustaining voltage $V_{\rm min}$ is the minimum value of the applied voltage that can sustain a stable discharge in an addressed cell. We determine this voltage to be 10 volts above the off-voltage $V_{\rm off}$, below which the discharge will extinguish. The breakdown voltage $V_{\rm br}$ is the voltage at which the discharge can be turned on in an un-addressed cell. The minimum voltage should be as low as possible in a real PDP, while the margin should be as large as possible to ensure the reliable operation for all PDP cells.[1]

The measured voltage margins for the considered configurations on macro-cell are shown in Table 1, under the conditions of the design parameters set to be $w_1 = 0.4\,{\rm cm}$, $w_2 = 1.2\,{\rm cm}$ and $l_1 = 0.8\,{\rm cm}$.

Table 1. Measured breakdown voltages $V_{\rm br}$ and minimum sustaining voltages $V_{\rm min}$ for different configurations on macro-cell. The design parameters are $w_1 = 0.4\,{\rm cm}$, $w_2 = 1.2\,{\rm cm}$ and $l_1 = 0.8\,{\rm cm}$.

geometry	$V_{\rm br}$/V	$V_{\rm min}$/V	margin/V
Std	268	184	84
D	285	196	79
Δ	310	213	97
W	303	196	107
U	330	212	118

One can see in Table 1 that the electrode shaping results in an increase in both $V_{\rm br}$ and $V_{\rm min}$. The minimum voltage is about 12–27 V higher than that of the standard geometry. The operating voltage of Δ- and U-shape electrodes are a bit higher than those of the others. The margin $(V_{\rm br} - V_{\rm min})$ of the electrode-shaping cells does not change too much. It is larger than that in the standard case except D-shape under the present conditions.

The 3D model has been performed for the similar standard and the four non-standard configurations on micro-cell. The calculated discharge currents at $V_{\rm s} = 220\,{\rm V}$ are shown in Fig.2, under similar conditions of the design parameters $w_1 = 40\,\mu{\rm m}$, $w_2 = 120\,\mu{\rm m}$ and $l_1 = 80\,\mu{\rm m}$. To compare with each other, the currents have been normalized. It is seen in Fig.2 that the discharge currents of non-standard cells rise up more slowly than the discharge current of the standard cell. Meanwhile, the full width of half maximum (FWHM) of the current waveform is larger in the non-standard configurations.

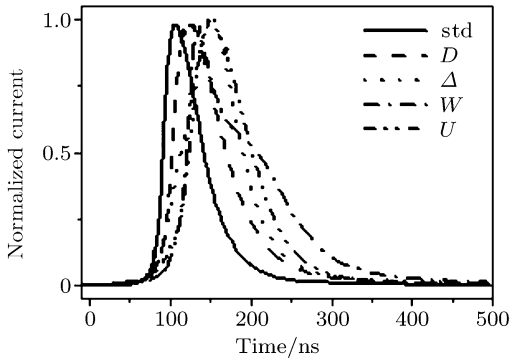


Fig.2. Schematics of non-standard configurations (a) D-shape, (b) Δ-shape, (c) W-shape, (d) U-shape.

The rising time $t_{\rm r}$ and FWHM of the currents are listed in Table 2.

Table 2. Rising time and FWHM of the discharge current in Fig.2.

geometry	$t_{\rm r}$/ns	FWHM/ns
Std	20	54
D	32	68
Δ	30	81
W	51	80
U	48	80

It shows clearly that the discharge of non-standard geometry has a longer duration than the discharge of the standard geometry, with $t_{\rm r}$ increasing 50%–100% and FWHM increasing 30%–50% respectively. The 3D modelling also shows that the current of Δ-shape cell is very low because the areas of the sustaining electrodes are small, typically being less than half of the areas of the other non-standard cells under the present conditions.

Moreover, the calculation also shows that in U-shape cell, the discharge starts on one side of the facing part (near the rib), then extends to the outer side of the electrode and to another side, forming much a longer path. This makes the current last longer than the others.

3.2. Discharge efficiency

The VUV photon production and transport in the macro-cell do not follow the similarity laws and we have not tried to measure VUV emission to characterize the discharge efficiency in producing VUV photons in macro-cell experiments. However, we know

that the VUV efficiency is directly related to the efficiency of electron energy deposition in xenon excitation. A large part of this energy contributes to VUV emission. On the other hand practically most of the xenon excitations occur during the current pulse and, the discharge properties during the current pulse are expected to follow the similarity laws.[14] The generation of xenon excited states in the afterglow due to electron-ion recombination is possible in a real, high pressure cell. But this is significant for current and plasma density larger than those observed under PDP conditions. Since most of the energy put into xenon excitation is converted into UV emission under PDP operating conditions, we can conclude that the infrared emission of xenon (e.g. the 823 nm line) is directly correlated with the UV emission. This allows us to be able to use a 'relative infrared emission efficiency', $\rho_{\rm exp}$, to characterize the discharge efficiency instead of the absolute measurement of VUV emission efficiency in the macro-cell experiments. It has been proved that the discharge efficiency increases monotonically with this ratio. This ratio can therefore be used to compare the relative efficiencies of different configurations.[15,16] In this way, the uncertainties and errors in measurement of discharge energy can also be avoided. The relative infrared emission efficiency in macro-cell experiments is defined as the ratio of the total xenon infrared emission (~ 823 nm) to neon visible emission (~ 640 nm) integrated in space and time over one current pulse:

$$\rho_{\rm exp} = A \times \frac{\text{IR Xe emission}(\sim 823\,\text{nm})}{\text{visible Ne emission}(\sim 640\,\text{nm})}$$

where A is an arbitrary constant that can be adjusted for comparison with model results. The value is set to be 0.75 in this paper.

To compare with the experimental results, we calculated the 'Xe excitation efficiency' ($\eta_{\rm Xe}$ = the energy dissipated in xenon excitation / total energy in discharge) and the 'relative xenon upper excitation efficiency', $\rho_{\rm model}$, in the simulations, defined as

$$\rho_{\rm model} = \frac{\text{energy deposited in excitation of Xe upper states}}{\text{energy deposited in Ne excitation}}$$

where "Xe upper states" corresponds to the excitation states above the resonant and metastable states of Xe. Since these parameters are strongly related to the efficiency of VUV production in the discharge, $\rho_{\rm exp}$, $\rho_{\rm model}$ and $\eta_{\rm Xe}$ are good parameters that can be used to evaluate the discharge efficiency for the different electrode designs relatively.

Figure 3 shows the calculated and the measured discharge efficiencies as a function of the sustaining voltage for the different configurations under the conditions of Fig.2. One can see in Fig.3(a) that from 3D model, the discharge in the electrode-shaping configurations is more efficient than in the standard geometry. Typically, the discharge efficiency of non-standard cells is 10%–30% higher.

The similar results also have been found in macro-cell experiments as seen in Fig.3(b). The experimental results also show the discharge efficiency increasing in non-standard configurations. Generally, the efficiency decreases slightly with the increase of the sustaining voltage in both non- and standard geometries. Both the simulated and the measured results agree very well with each other and have the same tendency.

As is well known, the discharge efficiencies of PDPs can be increased by decreasing the electron energy or the electric field.[1] The anode region (plasma column) is therefore more efficient than negative glow for Xe excitation and hence for VUV production. The longer the discharge path extends, the higher the discharge efficiency will be. Therefore a higher efficiency can be obtained in non-standard cells, which tends to achieve slower rising and longer duration of the discharge current.

On the other hand, the energy deposition in xenon excitation and the discharge efficiency are not uniform in the space above the electrode surfaces. Figures 4(a) and 4(b) show the local distribution of the energy deposition into Xe and the relative discharge efficiency for the standard configuration from 3D simulation. Generally speaking, Xe atoms are excited more in the region near the centre of the cell than near the ribs. However, the local efficiency of Xe excitation is relatively high in the central region above the anode surface as well as in the region near the ribs in the outer

side of anode, forming a shape of letter "W." Since the amount of the energy deposited into Xe is very small in the region on the outer side of anode, only a small part of the Xe excitations come from this region. Practically, the central region of the cell is the most important part for the discharge efficiency and the total UV production. The non-standard PDP cells are designed in such a way that there exists a relatively large area where Xe excitation is more efficient. The discharge efficiency of these cells is therefore higher than that in the standard case. This is also the reason why the T-shape electrodes could be used in an efficient ac-coplanar PDP cell design.[23]

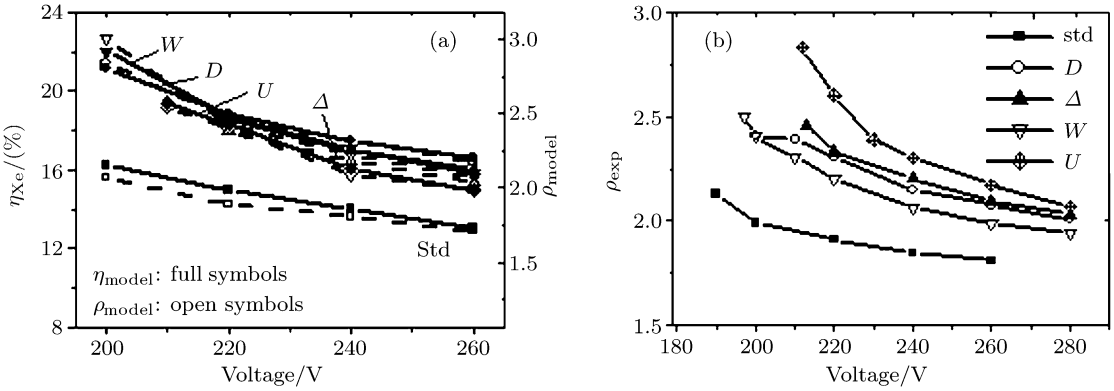


Fig.3. The (a) calculated and (b) measured discharge efficiencies as a function of sustaining voltage for different electrode-shaping configurations under the conditions of Fig.2.

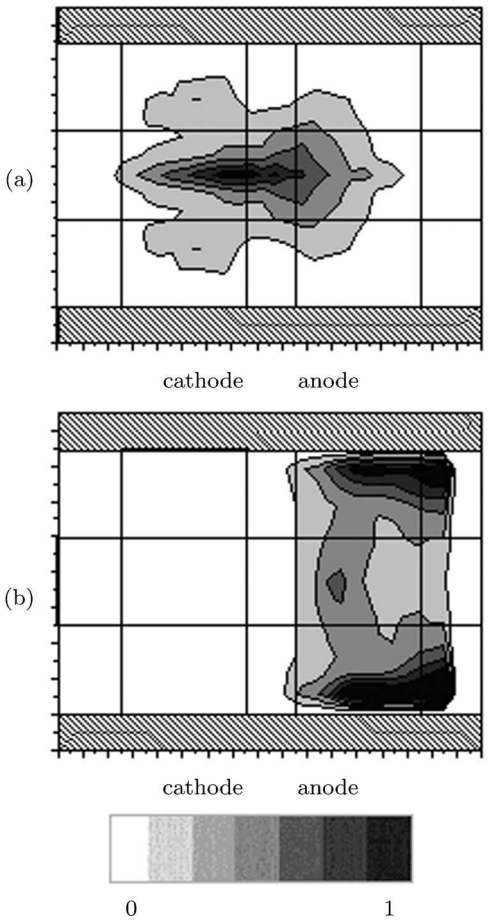


Fig.4. Time-integrated (a) energy deposition in Xe and (b) local discharge efficiency from 3D model. They are spatially integrated in the direction of front-view.

3.3. Effect of design parameters

The shape of the coplanar electrodes can be controlled by adjusting the design parameters, i.e. w_1, w_2 and l_1 in Fig.1. We test different electrode geometries in D- and U-shapes.

Figure 5 shows the measured discharge efficiencies as a function of the sustaining voltage for different design parameters of D- and U-shapes in macro-cell, with $w_1 = 0.8$, 0.4, 0.2 cm for D-series and $l_1 = 0.4$, 0.8, 1.2 cm for U-series ($w_1 = 0.4$ cm and $w_2 = 0.8$ cm), respectively. The curves are plotted from the minimum sustaining voltage of each cell. It is seen in Fig.5 that with w_1 decreasing (in D-series) or l_1 increasing (in U-series), the discharge efficiency increases. In the meantime, the minimum sustaining voltage increases as w_1 decreases or l_1 increases. There exists a trade-off between the discharge efficiency and the operating voltage in electrode-shaping configurations.

From the results above, one sees that among all the considered non-standard configurations that can achieve higher discharge efficiency, the D-shape cells have relatively low sustaining voltages. The Δ-shape cells need higher operating voltages and, the discharge currents are low due to the small areas of electrodes. The U-shape cells also need higher sustaining voltages, and the larger distance between the coplanar

electrodes in the centre where the data electrode is located makes it more difficult to address the cell. The W-shape design may overcome this shortcoming. Thus the D- and W-shapes indicate a possible design of PDP cells to keep both higher discharge efficiency and lower operating voltage.

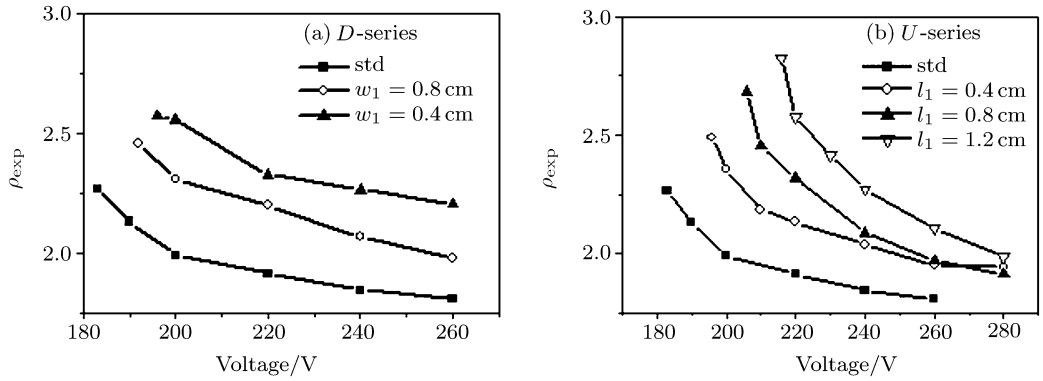


Fig.5. Effects of design parameters on the discharge efficiency and the operating voltage, (a) D-series; (b) U-series.

4. Conclusions

The 3D fluid model and the macroscopic cell are very useful and efficient for understanding the 3D features of the discharge and the electrode optimization of PDP cells. Four non-standard PDP designs (i.e. D-, Δ-, W- and U-shape electrodes) have been investigated experimentally in macro-cell together with 3D modelling. The results show that the design parameters have considerable effects on the discharge efficiency and the operating voltage. The breakdown voltage and the sustaining voltage increase slightly in the non-standard geometries. The discharge current rises more slowly in the non-standard cells and has a larger FWHM than in the standard case. The discharge efficiency of the electrode-shaping configurations is about 10%–30% higher than that of the standard one. There exists a trade-off between improving the discharge efficiency and decreasing the operating voltage of PDP cells by electrode shaping. Among the considered non-standard configurations, the D- and W-shape designs can improve the PDP discharge efficiency without increasing the sustaining voltage significantly.

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