Cell parameter extraction method for AC plasma display panels

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Abstract

This paper presents a cell parameter extraction method for three-electrode AC plasma display panels (PDPs). This method uses three different two-electrode AC discharges to extract the cell capacitances. The drive point capacitances of the cell with and without a two-electrode dark discharge were measured, and the cell capacitances were extracted from them. The extracted cell capacitances agree well with those obtained from a three-dimensional electromagnetic simulation. Electrical equivalent circuits of the plasma were constructed using Jung’s model [Y.K. Jung, J.W. Seo, Y.H. Kim, B.K. Kang, Circuit model for two-electrode AC discharge, IEEE Trans. Plasma Sci., 31(3), pp. 362–368, 2003.] and the measured firing voltages. A circuit model for the cell was constructed using the cell capacitances and the equivalent circuits for the plasma. The results of electrical simulation using this circuit model agree well with the measurements, indicating that the presented circuit model would be useful for simulating the electrical behaviors of a three-electrode AC PDP.

Keywords: AC discharge; Circuit model of plasma; Plasma display panel (PDP); Dark discharge; Firing voltage

1. Introduction

The typical cell structure of an AC plasma display panel (AC PDP) is shown in Fig. 1. It has three electrodes: the data (X), scan (Y), and common (Z) electrodes. The X electrode is located on the rear glass plate, and the Y and Z electrodes are located on the front glass plate. All electrodes are covered with either a dielectric/MgO or a dielectric/phosphor layer. The dielectric rib separates the front and rear glass plates and provides a discharge space. The Y and Z electrodes are orthogonal to the X electrode and form a matrix pattern; however, in Fig. 1(b), the front glass plate was rotated 90° from the actual direction to represent the cell structure easily. When there is no discharge in the discharge gap, the cell can be represented by a circuit consisting of nine capacitors, as shown in Fig. 1(b). The following notations have been adopted to represent different cell capacitances; the subscripts d, g, and w before the underline represent the dielectric rib or glass, the discharge gap, and the wall dielectric over electrodes, respectively; and the subscripts x, y, and z after the underline represent the corresponding electrodes. When there is a discharge between a pair of electrodes, the plasma shunts the corresponding gap capacitor, as represented by the current sources in Fig. 1(b). The number n represents the number of facing discharges in the cell. It is two if the cell has discharges between the X and both the Y and Z electrodes. Otherwise, it is one. Direct measurements of these capacitances and plasma properties are impossible because all electrodes are separated from the discharge gap by dielectrics.

Most AC PDPs are driven by a very complicated waveform to display a picture properly. For an electrical engineer designing a new drive circuit for an AC PDP, it would be very convenient to have an electrical equivalent circuit since numerous accurate circuit simulation tools would be available to estimate the consequences of changes on the drive waveform and cell structure on the picture quality. A few circuit models have been reported for the electrical simulation of AC PDPs [1–3]. Furutani et al. modeled a cell of a three-electrode AC PDP with 22 capacitors and 12 discharge paths [1]. The plasma on each discharge path was represented with a simple discharge model, and an electrical–physical hybrid simulation was used to calculate responses of the cell for various input waveforms. This method is quite accurate, but not applicable to general circuit simulation tools. Tamitu et al. modeled the cell with circuit elements, which are available in most circuit simulation tools [2]. They modeled the plasma with a variable resistor, and the time-dependent change of resistance was modeled with a first-order differential equation. The differential equation...
requires several physical constants, such as the growth and decay time constants for discharge, number of initial electrons, conductivity of adjacent cells, rate of change of conductivity, etc. Because of this, this model has limited application for the cell driven by a very complicated waveform. Jung et al. described an electrical equivalent circuit for a two-electrode AC discharge [3]. This model consisted of a series connection of an equivalent circuit for the plasma and two capacitors for the insulators. The equivalent circuit for the plasma was constructed using the measured electrical properties of a two-electrode discharge and standard circuit elements; thus it can be implemented easily on most circuit simulation tools. This circuit for the plasma could be used as a building block for constructing an electrical equivalent circuit for the three-electrode AC PDP.

All of these circuits require accurate values of cell capacitances for simulation. This paper presents a method of measuring the cell parameters of a three-electrode AC PDP. Because all electrodes of the AC PDP are separated from the discharge gap by dielectrics, the cell parameters were measured indirectly using the properties of an AC discharge between a pair of electrodes. The structure of the experimental three-electrode AC PDP is given in Section 2. A circuit model for cell capacitance extraction is described in Section 3.

An electrical equivalent circuit of the experimental device and the results of electrical simulation are given in Section 4. A conclusion is given in Section 5.

2. Test device

The test device was a three-electrode AC PDP with a diagonal size of 7-in. It had 360 (horizontal) × 68 (vertical) cells. The cell structure of the test device is shown in Fig. 1(b). The horizontal and vertical cell pitches were 420 and 1260 μm. A glass plate with a thickness and relative permittivity of 2.8 mm and 7.2 was used for the front and rear glass plates. The dielectric rib had a well structure and its cross sectional shape was a trapezoid with a height, bottom width, and top width of 125, 100, and 70 μm, respectively. The relative permittivity of the rib was ~10. The discharge gas was a 96% Ne-4% Xe gas mixture at a pressure of 500 Torr. The width and thickness of the ITO electrodes for the Y and Z electrodes were 380 and 0.15 μm. A bus electrode made of Cr/Cu/Cr was formed on each ITO electrode. The width and thickness of the bus electrode were 7×4 and 2 μm. The thickness and relative permittivity of the dielectric on the Y and Z electrodes were ~38 μm and ~12. An MgO layer with a thickness of 0.7 μm covered the
dielectric. The X electrode was made of 2 μm-thick Ag with a width of 170 μm. The dielectric on the X electrode was ~21 μm thick and the phosphor was ~18 μm thick. The relative permittivity of the dielectric and phosphor layers was ~10.

3. Circuit model for cell capacitance extraction of three-electrode AC discharge

3.1. Properties of AC discharge between a pair of electrodes

The circuit shown in Fig. 2 is a basic circuit for measuring the cell capacitances of a three-electrode AC PDP. This circuit consists of a series connection of a voltage source $V_A$, an external capacitor $C_{\text{ext}}$, and a two-electrode AC discharge. The two-electrode AC discharge represents the discharge between any pair of electrodes of a cell in the three-electrode AC PDP. It was modeled with four capacitors and one current source $I_p$ for the plasma. The capacitance $C_{i,j}$ represents the capacitance between the $i$ and $j$ electrodes either through the glass substrate or through the dielectric rib. The discharge gap between the electrodes was modeled with the capacitor $C_{d,i}$. The dielectric walls over the electrodes were represented by the capacitors $C_{w,i}$ and $C_{w,j}$.

When the gap voltage $V_g$ is lower than the firing voltage $V_f$ for a Townsend (dark) discharge, the plasma current $I_p = 0$ and the driving point capacitance $C_{i,j}^{d,i}$ between the $i$ and $j$ electrodes is given by:

$$C_{i,j}^{d,i} = C_d + (C_{i}^{w,i} \oplus C_{j}^{w,j}).$$

Here $C_{i}^{w,i} = C_{w,i} \oplus C_{w,j}$, where the symbol $\oplus$ stands for a series connection of two capacitors, as it does throughout the text. Then, the total charging current $I$ to the cell is given by

$$I = I_1 + I_2 = (C_{i,j}^{d,i} \oplus C_{\text{ext}}) \frac{dV_A}{dr} = C_{\text{ext}} \frac{dV_{\text{ext}}}{dr}$$

and we have

$$\frac{dV_{\text{ext}}}{dr} = \frac{C_{d,i}^{\oplus} \oplus C_{\text{ext}}}{C_{\text{ext}}} \frac{dV_A}{dr} = \frac{1}{k_{i,j}^{d,i}} \frac{dV_A}{dr}. \quad (2)$$

The constant $k_{i,j}^{d,i}$ can be determined if we measure the ratio of $dV_A/dr$ to $dV_{\text{ext}}/dr$ when the cell has no discharge.

When the input voltage increases slowly, a dark discharge is induced in the discharge gap for $V_g \geq V_f$. The charged particles generated by the discharge are attracted to the electrodes and charge up the dielectric wall. The charges accumulated on the surface of the dielectric wall (wall charges) screen the external electric field and keep the gap voltage $V_g$ at $V_f$ [6,7]. In this case, the total current $I_1$ through the discharge gap is given by

$$I_1(t) = C_{w}^{d,i} (V_A - V_{\text{ext}} - V_g) / dr = C_{d}^{w} (V_A - V_{\text{ext}}) / dr,$$

and the current ratio $I_2/I_1$ is $C_{d}^{i,j} / C_{w}^{i,j}$. Then, the charging current $I$ is given by

$$I = \left( 1 + \frac{C_{d}^{i,j}}{C_{w}^{i,j}} \right) I_1 = (C_{d}^{i,j} + C_{w}^{i,j}) \left( \frac{dV_A}{dr} - \frac{dV_{\text{ext}}}{dr} \right).$$

In the above equation, the term

$$C_{d}^{i,j} + C_{w}^{i,j} \equiv C_{i,j}^{d}$$

is the driving point capacitance between the $i$ and $j$ electrodes when there is a dark discharge in the discharge gap. Because the above charging current to the cell should flow through the external capacitor $C_{\text{ext}}$ and satisfy $I(t) = C_{\text{ext}} dV_{\text{ext}}/dr$, we have the following equation

$$\frac{dV_{\text{ext}}}{dr} = \frac{C_d^{i,j} + C_{w}^{i,j}}{C_{\text{ext}} + C_d^{i,j} + C_{w}^{i,j}} \frac{dV_A}{dr} = \frac{C_d^{i,j} \oplus C_{\text{ext}}}{C_{\text{ext}}} \equiv \frac{1}{k_{i,j}^{d}} \frac{dV_A}{dr}.$$  \quad (4)

This equation is the same as (2) except for the driving point capacitance. The constant $k_{i,j}^{d}$ can be determined if we measure the ratio of $dV_A/dr$ to $dV_{\text{ext}}/dr$ while the cell is subject to a dark discharge.

The waveform $V_A$ shown in Fig. 3 has been used to measure the constants $k_{0,j}^{d}$ and $k_{i,j}^{d}$. Before the start of measurement at $t = t_0$, the cell was initialized by the preceding positive and negative voltage ramps. The input voltage $V_A$ increases at $t = t_0$ from 0 V and it begins to induce a dark discharge in the discharge gap at $t = t_1$ when $V_g$ exceeds $V_f$. Accordingly, there is no dark discharge in the discharge gap for $t_0 < t < t_1$ and we measure $V_{\text{ext}}$ to determine the constant $k_{0,j}^{d}$. After $t = t_1$, the dark discharge is maintained in the discharge gap until the input voltage $V_A$ returns to 0 V at $t = t_2$. The gap voltage $V_g$ for $t_1 < t < t_2$ is close to the firing voltage $V_f$ and we measure $V_{\text{ext}}$ to determine the constant $k_{i,j}^{d}$. The measured $V_{\text{ext}}$ for a two-electrode AC discharge is also shown Fig. 3. The cell was subject to a dark discharge only for $t_1 < t < t_2$, as was confirmed from the measured optical emission, and the slope of $V_{\text{ext}}$ for $t_0 < t < t_1$ is different from that for $t_1 < t < t_2$. The slopes of $V_{\text{ext}}$ divided by the measured slopes of $V_{\text{ext}}$ for $t_0 < t < t_1$ and $t_1 < t < t_2$ gave the constants $k_{0,j}^{d}$ and $k_{i,j}^{d}$, respectively, and the
driving point capacitances $C_{\text{Ci}}^j$ and $C_{\text{Ci}}^n$ for the cell with and without a dark discharge were obtained.

### 3.2. Configurations for cell capacitance extraction of three-electrode AC PDP

For the three-electrode AC PDP shown in Fig. 1, the Y and Z electrodes have the same geometrical structure and are located symmetrically along the horizontal center of each cell. There exist three different ways of exciting the cell using two electrodes. Possible ways of a two-electrode excitation of the cell are shown schematically in Fig. 4; the X, Y, and Z electrodes in Fig. 4(a) are floated, biased with $V_A$, and connected to $C_{\text{ext}}$, respectively, and those in Fig. 4(b) are connected to $C_{\text{ext}}$ biased with $V_A$, and floated. In Fig. 4(c), Y and Z are biased with $V_A$ and X is connected to $C_{\text{ext}}$. If we use these three configurations and measure the driving point capacitances $C_{\text{Ci}}^j$ and $C_{\text{Ci}}^n$, we can obtain three sets of $k_{ij}^j$ and $k_{ij}^n$ which can be used to determine all cell capacitances for the equivalent circuit shown in Fig. 1.

For the configuration shown in Fig. 4(a), the measured constants $k_{y,z}^0$ and $k_{y,z}^1$ determine the driving point capacitances $C_{\text{Ci}}^y$ and $C_{\text{Ci}}^z$ between Y and Z. To find the relationship between the cell capacitances shown in Fig. 1 and the measured driving point capacitances $C_{\text{Ci}}^y$ and $C_{\text{Ci}}^z$, we calculated the driving point capacitances using the circuit shown in Fig. 5, which is an equivalent circuit of the cell. In this circuit, the voltage $V_C$ of Y with respect to Z was defined as $V_C = V_A - V_{\text{ext}}$. Because each cell of the PDP shown in Fig. 1 has a symmetry plane along the horizontal center, it satisfies $C_{w,y} = C_{w,z}$, $C_{d,yx} = C_{d,zx}$, and $C_{g,yx} = C_{g,zx}$. With the symmetry, the voltages of the nodes A, B, and C are the same as that of floating X, and the circuit can be divided into...
two identical sections along the symmetry plane. Also, the voltage of Y with respect to X is \( V_{c}/2 \) and the voltage of Z with respect to X is \(-V_{c}/2\), resulting in the circuit configuration in Fig. 5. The constant voltage source \( V_{f} \) shunts \( C_{g,yz} \) when there is a dark discharge (Y–Z discharge) in the discharge gap between Y and Z, while it is disconnected otherwise.

The capacitance \( C_{Cn}^{y,z} \) between Y and Z is one half of the capacitance \( C_{y} \) between Y and X, and we have

\[
C_{Cn}^{y,z} = \frac{C_{y}}{2} = \frac{C_{d,y} + C_{w,y}}{2} + \frac{C_{g,y} + C_{g,yz}}{2} \tag{5}
\]

when the case that the cell has no dark discharge. The following relationships are obtained by comparing (5) with (1):

\[
\begin{align*}
C_{d}^{y,z} &= C_{d,y} + C_{y}^{z}/2 \quad C_{w}^{y,z} = C_{w,y}/2 \\
C_{g}^{y,z} &= C_{g,y} + C_{g,yz}/2
\end{align*} \tag{6}
\]

If the cell has the Y–Z discharge, the constant voltage source \( V_{f} \) shunts \( C_{g,yz} \) and we obtain the driving point capacitance

\[
C_{Cf}^{y,z} = (C_{d,y} + C_{y}^{z}/2) + C_{w,y}/2, \tag{7}
\]

which becomes (3) with the identities in (6). This result confirms that we can use (5) and (7) to extract the cell capacitances from the measured driving point capacitances \( C_{Cn}^{y,z} \) and \( C_{Cf}^{y,z} \).

For the configuration shown in Fig. 4(b), the constant voltage source \( V_{f} \) shunts \( C_{g,yz} \) when there is a dark discharge (Y–X discharge) in the discharge gap between Y and X, while it is disconnected otherwise. In this case, the circuit does not have any symmetry and \( n=1 \) because Z is floated. The equivalent circuit of the cell shown in Fig. 6 was obtained using the delta–wye transformations successively. The capacitors \( C_{1}, C_{2}, C_{3}, \) and \( C_{4} \) in Fig. 6 are given by

\[
\begin{align*}
C_{1} &= C_{g,y}C_{g,y}C_{A}^{-1}, \quad C_{2} = C_{C}C_{A}(C_{1} + C_{j} + C_{k})^{-1}, \\
C_{3} &= C_{j}C_{j}(C_{1} + C_{j} + C_{k})^{-1}, \quad C_{4} = C_{j}C_{k}(C_{1} + C_{j} + C_{k})^{-1}
\end{align*}
\]

where

\[
\begin{align*}
C_{A} &= C_{w,y} + C_{g,yz} + C_{g,y} \\
C_{i} &= \left\{ \frac{C_{w,y} + C_{d,y}C_{A} + C_{g,yz}}{C_{g,yz}} \right\} \\
&\oplus \left\{ \frac{C_{w,x} + C_{d,y}C_{g,yz} + C_{A}C_{w,x}}{C_{g,yz}} \right\} \\
C_{j} &= \left\{ \frac{C_{w,y}(C_{g,yz} + C_{d,y})}{C_{A}} \right\} \\
&\oplus \left\{ \frac{C_{w,x}C_{g,yz}(C_{w,x} + C_{d,y})}{C_{A}C_{w,x}} \right\} \\
C_{k} &= \frac{C_{A}C_{d,y} + C_{g,yz}(C_{d,y} + C_{w,y})}{C_{A}} \\
&\oplus \left\{ \frac{C_{d,y}C_{g,yz}(C_{w,x} + C_{d,y})}{C_{A}C_{w,x}} \right\}
\end{align*}
\]

The driving point capacitances \( C_{Cn}^{y,z} \) and \( C_{Cf}^{y,z} \) between X and Y are

\[
\begin{align*}
C_{Cn}^{y,z} &= C_{d,y} + C_{4} + C_{j} \oplus (C_{g,yz} + C_{1} + C_{2}) \tag{8} \\
C_{Cf}^{y,z} &= C_{d,y} + C_{4} + C_{3} \tag{9}
\end{align*}
\]

By comparing (8) with (1), the following relationships are obtained:

\[
\begin{align*}
C_{d}^{y,z} &= C_{d,y} + C_{4} \quad C_{w}^{y,z} = C_{3} \tag{10} \\
C_{g}^{y,z} &= C_{g,y} + C_{1} + C_{2}
\end{align*}
\]

The configuration shown in Fig. 4(c), in which Y and Z are biased at \( V_{A} \) and X is connected to \( C_{ext} \), is the same as the one shown in Fig. 4(a) except for the bias points. Because both Y and Z are biased at \( V_{A} \), no current flows through the symmetry plane and \( n=2 \). So, we can disconnect the circuit along the symmetry plane after dividing \( nC_{w,x} \) into two parallel-connected \( C_{w,x} \). When there is a dark discharge in the discharge gap, both \( C_{g,yz} \) and \( C_{g,gy} \) are shunted by a constant voltage source \( V_{f} \). Then, the driving capacitances \( C_{Cn}^{y,z} \) and \( C_{Cf}^{y,z} \) between the X and Y–Z combined electrodes are given by

\[
\begin{align*}
C_{Cn}^{y,z} &= 2C_{d,y} + 2(C_{g,y}C_{w,x}C_{w,y}) \tag{11} \\
C_{Cf}^{y,z} &= C_{d,y} + 2(C_{w,x} + C_{w,y}) \tag{12}
\end{align*}
\]

By comparing (11) with (1), the following relationships are obtained:

\[
\begin{align*}
C_{d}^{y,z} &= 2C_{d,y} & C_{w}^{y,z} &= 2(C_{w,x} + C_{w,y}) \tag{13} \\
C_{g}^{y,z} &= 2C_{g,yz}
\end{align*}
\]

3.3. Cell capacitance extraction of test device

The cell parameters of the test device were measured using the circuit configurations shown in Fig. 4. The test signal \( V_{A} \)
was an alternating voltage ramp with a slope and amplitude of ±142.85 V/ms and 350 V, respectively. The capacitance of $C_{\text{ext}}$ was 10 nF. The driving point capacitors were calculated from three measured sets of $k_{ij}^y$ and $k_{ij}^z$ using Eqs. (2) and (4), and all circuit capacitances for the circuit shown in Fig. 1 were obtained by solving Eqs. (5)–(13) numerically. The values of measured $k_{ij}^y$ and $k_{ij}^z$ were $k_{0}^{x,y} = 8.83$, $k_{1}^{x,y} = 3.89$, $k_{0}^{y,z} = 6.77$, $k_{1}^{y,z} = 3.55$, $k_{0}^{y,x} = 7.27$, and $k_{1}^{y,x} = 2.62$, resulting in the driving point capacitances of $C_{\text{d}}^{y,x} = 141.3$, $C_{\text{d}}^{y,z} = 70.8$, $C_{\text{d}}^{z,x} = 160.5$, $C_{\text{d}}^{z,y} = 65.1$, and $C_{\text{d}}^{z,y} = 251.6$ fF.

The cell capacitances of the test device extracted using the above values are given in Fig. 7. For comparison, the cell parameters calculated using the Maxwell 3D electromagnetic solver from Ansoft Co. are also given in Fig. 7 in the parentheses. The extracted cell capacitances agree well with the calculated ones, demonstrating that the proposed method is a good experimental method for extracting the cell parameters of the three-electrode AC PDP. Some differences between the measured and calculated values originate from differences in the dielectric properties. Exact measurements of the relative permittivities of the rib, phosphor, and dielectric layer materials, were impossible after the fabrication of the PDP.

Typically, the three-electrode AC PDP uses two types of two-electrode discharge: one between X and Y for addressing picture data and the other between Y and Z for displaying and erasing the picture. The external voltage $V_A$ required for igniting a discharge between the electrodes $i$ and $j$ increases with a decrease of the voltage ratio $V_i/V_A = C_{w}^{ij}/(C_{w}^{ij} + C_{d}^{ij})$. The test device had $C_{w}^{y,x} = 104.0$, $C_{d}^{y,x} = 17.4$, $C_{w}^{y,z} = 100.7$, and $C_{d}^{y,z} = 12.2$ fF, resulting in $V_i/V_A = 0.86$ and 0.89 for the discharges between X and Y and between Y and Z, respectively. The capacitances of the dielectric rib or glass substrate increase the displacement current injected to the cell, which reduces the power efficiency of the PDP. The test device had $C_{d}^{y,z} = 37.27$ and $C_{w}^{y,z} = 59.89$ fF, which are much larger than the gap capacitances and indicate that a significant portion of the input current does not contribute to the discharge current.

4. Circuit model for three-electrode AC PDP and simulation of test device

4.1. Plasma model and equivalent circuit

An equivalent circuit for the plasma between each pair of electrodes is required to complete the circuit shown in Fig. 1(b). Jung et al. reported an equivalent circuit for a two-electrode AC discharge [3], which is used here as a building block in constructing an electrical equivalent circuit for the three-electrode AC PDP. To use Jung’s circuit, the DC voltage–current $(V-I)$ characteristic curves of the plasma should be given. However, for a three-electrode AC PDP, it is impossible to measure the curves directly because the insulating walls surround the discharge gap. Therefore, we measured the break $(V, I)$ points and approximated the curve between them with straight lines.

Three important break points of the $V-I$ characteristic curve are the firing voltage $V_f$ at which a dark discharge begins, the transition voltage $V_T$ at which a transition from dark to glow discharge occurs, and the minimum voltage $V_{g\text{min}}$ to sustain the glow discharge. These break points were measured using the voltage waveform shown in Fig. 8(a), which consists of alternating voltage ramps, test pulse 1, alternating priming pulses, and test pulse 2. The voltage ramps and test pulse 1 were used to measure $V_f$ and $V_T$, and the priming pulses and test pulse 2 were used to measure $V_{g\text{min}}$. The amplitude of the voltage ramp was decreased gradually to erase wall charges and to reduce the wall voltage. The amplitude was decreased until no dark discharge was induced by the voltage ramp, as shown by the optical emission signal in Fig. 8(b). The gap voltage at the peak of this voltage ramp is close to $V_f$ and the wall voltage is reduced to ∼0 V by previous voltage ramps. Thus, from the measured amplitude of the voltage ramp, the firing voltage $V_f$ can be calculated using the circuit shown in Fig. 7. The $V_{g\text{min}}$ for the test device were 141.9 and 195.8 V for the X–Y and Y–Z discharges, respectively.

The transition voltage $V_T$ was measured using test pulse 1, which follows the voltage ramps. A gap voltage higher than $V_T$ induces a glow discharge in the discharge gap, as shown in Fig. 8(c). If we measure the voltage $V_{\text{test}1}$ of test pulse 1 at which it begins to induce a glow discharge, we can obtain $V_T$ from the circuit shown in Fig. 7 because the voltage ramps reset the wall voltage to 0 V. The $V_{\text{test}1}$ for the test device were 185.6 and 233.5 V for the X–Y and Y–Z discharges, respectively.

The minimum voltage $V_{g\text{min}}$ to sustain the glow discharge was measured using the alternating priming pulses and test pulse 2. The priming pulses produce priming particles and test pulse 2 measures $V_{g\text{min}}$. The period and width of the priming pulses were 10 and 3 μs. The amplitudes of priming pulses were 186 V for the Y–X discharge and 236 V for the Y–Z discharge, respectively. The number of priming pulses was 100 and the width of test pulse 2 was 3 μs. The test pulse followed the priming pulse after a time delay of $\Delta t$, and its amplitude $V_{\text{test}2}$ was varied. For a very short $\Delta t$, the cell has many priming particles and the required voltage $V_{\text{test}2}$ for inducing a glow discharge is low. An increase of $\Delta t$ decreases the priming effect.
Fig. 8. Waveform for measuring the break points on the V–I characteristic curve of a two-electrode discharge: (a) overall waveform, (b) voltage ramps for $V_f$ measurement and optical emissions from dark discharge, and (c) test pulse 1 for $V_T$ measurement and an optical emission from glow discharge.

Fig. 9. The $V_{test2}$ required to induce a glow discharge versus the time delay $\Delta t$. 
and increases the required $V_{\text{test}}$. After measuring the minimum voltage $V_{\text{min}}$ and the maximum voltage $V_{\text{max}}$ required to induce a glow discharge, we can calculate the corresponding gap voltages using the circuit shown in Fig. 7. The difference in the gap voltages gives $V_T - V_{\text{gmin}}$. The measured $V_{\text{test}}$ versus $\Delta t$ curves for the test device with the Y–X and Y–Z discharges are shown in Fig. 9. The voltage differences $\Delta V_x^{\text{test}}$ and $\Delta V_z^{\text{test}}$ between $V_{\text{min}}$ and $V_{\text{max}}$ for the Y–X and Y–Z discharges were 30.4 and 66.6 V, respectively. These values resulted in $V_{\text{gmin}}$ of 159.5 V for the X–Y discharge and 174.3 V for the Y–Z discharge.

After obtaining all break points, we made the piecewise linear $V$–$I$ curves for the X–Y and Y–Z discharges shown in Fig. 10. The equivalent circuits for the plasma, as shown in Fig. 11(a) for the Y–Z discharge, were obtained from these curves following the procedures described in [3]. Each equivalent circuit for plasma shunts the corresponding gap.
capacitor and we have the electrical equivalent circuit of the three-electrode AC PDP, as shown in Fig. 11(b).

4.2. Simulation of test device

The input waveform shown in Fig. 12(a) was used for simulation of the test device. This waveform is the twin reset (TR) waveform [8], which uses two similar reset pulses for the Y and Z electrodes. The electrical behavior of the test device was simulated using the equivalent circuit shown in Fig. 11, and the results are shown in Fig. 12(b)–(d). During the setup period, a dark discharge is induced when the gap voltages \( V_{yg} \) and \( V_{zx} \) exceed \( V_f = 141.9 \) V. The dark discharge keeps \( V_{yg}^{\text{set-up}} \) and \( V_{zx}^{\text{set-up}} \) close to \( V_f \) and the wall voltages \( V_{w,y} \), \( V_{w,y}^{\text{set-up}} \), and \( V_{w,z} \) across the dielectric layer on the X, Y, and Z electrodes increase steeply, as shown in Fig. 12(b) and (c). During the set-down period, the gap voltage \( V_{yg}^{\text{set-down}} \) exceeds \( V_f \) while \( V_{zx}^{\text{set-down}} \) stays below \( V_f \). A dark discharge between the Y and X electrodes is induced by a \( V_{yg}^{\text{set-down}} \) slightly less than \( V_f \) because of the priming effect. The gap voltage \( V_{yg}^{\text{set-down}} \) increases slightly after the dark discharge, but it stays below \( V_f \). During the address period, the polarity of \( V_{w,x} \) and \( V_{w,y}^{\text{address}} \) is reversed by each sustain discharge, while that of \( V_{w,x}^{\text{address}} \) remains positive.

To compare the simulated results with experiment, we applied the same waveform to the test device and the optical emissions were measured. The measured results are shown in Fig. 13. Because the optical emission from dark discharge is much weaker than that from glow discharge, the rescaled optical emission for the reset period is shown in Fig. 13(b). The measured optical emission shows that the time points at which the cell has discharges agree fairly well with the simulation results shown in Fig. 12, demonstrating that the equivalent circuit is useful for simulation of a three-electrode AC PDP which is driven by a complex driving waveform.

For electrical simulation of other PDPs, the circuit parameters of the cell should be measured first using the methods described in Sections 3.1 and 4.1. Once one has an equivalent circuit, he can use any existing circuit simulation tools to understand important electrical behaviors of the cell, such as the changes of gap voltages and wall voltage of each electrode, the effects of parasitic circuit elements, the effects of waveform ringing on the discharge, etc. which cannot be observed easily by other means. Also, the effects of structural changes of the panel can be simulated easily by changing the corresponding circuit parameters of the equivalent circuit. A circuit simulation with a proper equivalent circuit for PDP
enables one to estimate the consequences of changes on the drive waveform and cell structure to the picture quality in advance, and will facilitate the design processes.

5. Conclusion

An experimental method for extracting the cell parameters of a three-electrode AC PDP is investigated. This method uses three two-electrode AC discharges to extract the cell capacitances of three-electrode AC PDP. The driving point capacitance of the two-electrode AC discharge, which changes when there is a dark discharge in the discharge gap, was measured by observing the voltage across an external capacitor, which was connected in series with the panel. The cell capacitances were extracted from the measured driving point capacitances. The extracted cell capacitances were compared with the results of a threedimensional electromagnetic calculation, which agreed well with the extracted values. Equivalent circuits for the plasma were constructed using Jung’s model as a building block, and the firing voltages required for the circuit were measured indirectly by observing optical emissions and by measuring the input voltage required for the onset of a discharge. An electrical simulation described the measured behavior of the cell quite accurately, demonstrating that the equivalent circuit is useful for simulation of a three-electrode AC PDP driven by a complex waveform.
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References


