10.4L: Stability of Positive Resistance Discharges for AC PDPs

Vladimir Nagorny and Paul Drallos
Plasma Dynamics Corp., Hazel Park, MI, USA

Larry F. Weber
Plasmaco, Inc., Subsidiary of Matsushita Electric Industrial Co., Ltd., Highland, NY, USA

Abstract

We analyze a novel voltage-ramp procedure which has recently been used in the setup period prior to addressing for plasma displays. The ramping procedure allows lower voltages to be used in addressing, larger manufacturing tolerance and reduces light emission from the setup cycle, thus improving the dark room contrast

1. Introduction

Reliable addressing of a PDP cell requires a certain minimum level of ionization within the cell and a certain wall voltage condition on the cell's dielectric surfaces. For this reason a setup period is commonly used during each field or sub-field, during which every AC PDP cell experiences a bulk write-erase sequence of discharges [1]. This sequence guarantees that each cell will be in the off-state at the beginning of the selective write pulse, and that a priming particle density sufficient for reliable write firing will be present in the cell. However, because of the non-uniformities of the panel of the order of manufacturing tolerances, the firing conditions in every cell may differ. One should also recall that, unlike the well-defined on-state wall voltages, there is great uncertainty in the wall voltage of the off-state. Hence, in order to reliably address every cell, one must resort to voltages for the setup and selective write discharges high enough to energize the most stubborn of pixels, but still not too high for other more eager cells. Besides the price one has to pay for using high voltages in the selective write pulse, these setup pulses also produce significant light which has the effect of decreasing the display dark room contrast ratio. Recently L. F. Weber proposed a new driving scheme for the setup [2], which, instead of using a square wave write-erase sequence, suggests using a slowly rising and falling ramp voltage waveform.

The basic idea behind his suggestion is shown in Figure 1. When we slowly increase the voltage across a cell's gap from a low value, there is no discharge activity in the cell until the gap voltage reaches the breakdown voltage, V_b for that particular cell. As soon as we exceed V_b, the cell becomes active and the voltage across the gap stays constant, and equal to V_b. As the ramp voltage progresses, every cell will eventually discharge with their respective V_b values appropriate for each individual cell. If after a while, as shown in Figure 1 we start to ramp the voltage down, then discharge stops and starts again when the voltage across the gap reaches the value V_b, but in opposite direction. As it was during the ramping up, the voltage across the gap stays equal to V_b. If, as shown in the Fig.1 at $t = 1100\mu s$, we raise the applied voltage by, say $20V$, then every cell is left $20V$ below the breakdown voltage independently of the value of the breakdown voltage of that particular cell, and of the initial wall voltage at $t = 0$. Such exact setting of the wall voltage during the setup is very valuable, because it allows one to use relatively low voltages for the selective addressing operation since no excess voltage is needed to cover any possible uncertainty in wall voltages [3].

The essential idea then, is based on the ability of the cell to hold a voltage equal or very close to the breakdown voltage after the setup. In this report we investigate some of the factors that affect the stability of the voltage across the cell during the ramp.

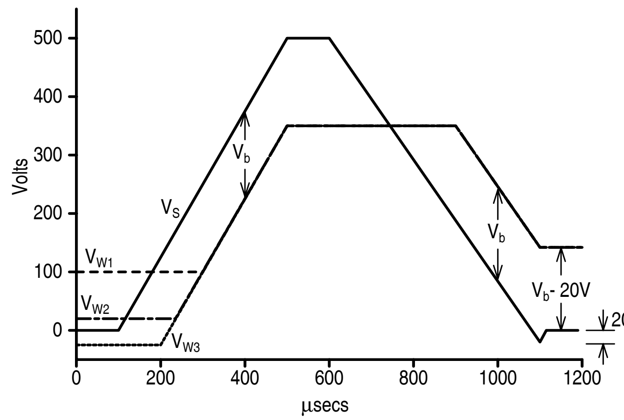

Figure 1. The applied voltage V_s and wall voltages V_w for three different initial wall voltages during the setup period. All end up with the same final wall voltage.

2. Dynamics of the "Ramp"

Figure 1 shows the "ideal" response of the cell to the applied voltage, which demonstrates a zero differential resistance of the discharge in the vicinity of V_b: $R_{dif} = dV_{gap} / dI = 0$, and the current reaches value $j_{ideal} = C_\varepsilon dV_s / dt$, where C_ε is the capacitance of the dielectric layers, and V_s is the applied voltage, as soon as V_{gap} exceeds V_b. However, in the actual cell the voltage excess over V_b causes current growth, rather than instantaneous change of its value, so the actual response of the cell differs from the ideal one and actually has somewhat oscillatory behavior. If not properly controlled these oscillations can become unstable and cause highly undesirable addressing failures. This presentation is the first to discuss the oscillatory nature of the ramp current and we provide here some highlights of our 1D theory describing this phenomenon, and discuss the results of both numerical and physical experiments. A more detailed presentation of the theory does not meet the format of this meeting and we will leave it for a Journal publication.

Since the voltage across the gap during the ramp discharge is close to V_b we investigate here the effect of the time variation of the applied voltage and of the initial conditions on the discharge dynamics for a system near the breakdown threshold,

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when the applied voltage changes linearly with time. We first neglect the influence of metastables and assume that the discharge is weak - distortions of electric field due to a space charge are small. Later we'll discuss the influence of metastables and some other components. We assume that the electron density is very low initially, so that when the electric field reaches the breakdown value it has to grow higher before a change in the electric field due to a charge deposition on the electrodes compensate that change due to increasing applied voltage.

Under the described conditions one can use previously developed theory [4]. One should only take into account the change of the electric field across the gap due to the growth of the applied voltage (dV_s / dt). We direct a coordinate z along the electric field and place the anode in the beginning of the coordinate system $z = 0$, so that $z = L$ is the coordinate of the cathode. Then the system of equations for the electron current j_e and electric field E will take the following form:

$$\frac{\partial j_e(L,t)}{\partial t} = \kappa(E - E_{br}) j_e(L,t) \qquad (1)$$

$$\frac{\partial E}{\partial t} = -\chi j_e(L,t) + \lambda \qquad (2)$$

where L is the gap length, $E_{br} = V_{br} / L$ -is the breakdown electric field, χ, λ, and κ are constant coefficients that can be expressed in terms of first (α) and second (γ) Townsend coefficients, gap size and dielectric thickness d, dielectric constant ε, and the ramp rate dV_s / dt:

$$\lambda \approx \partial V_s / L\partial t\,, \qquad \chi \approx 8\pi d / \varepsilon L\gamma\,, \qquad (3)$$

and $\kappa = \kappa(\alpha, \gamma, v_i, L) \equiv \partial / \partial E(\partial \ln j_e / \partial t)|_{E=E_{br}}$ - can be taken from the paper [4]. The stationary solution of Eqs.(1)-(2) is

$$E = E_{br}\,, \qquad j_e(L,t) = \lambda / \chi = \gamma C_\varepsilon dV_s / dt\,, \qquad (4)$$

where $C_\varepsilon = \varepsilon / 8\pi d$ is the capacitance of the dielectrics. Eq.(4) means that the discharge current should charge the dielectric with the same rate as the voltage ramp rate. However, we need to know what happens when the initial conditions are different from (4).

Closer analysis of the set of Eqs.(1)-(2) shows that it is equivalent to the equations of motion of the particle with mass κ^{-1}, and momentum $E - E_{br}$ in the potential $V(q) = -\lambda q + \chi j_0 e^q$, where $q = \ln(j_e / j_0) \equiv \ln(j_e \chi / \lambda)$ and has the integral of "motion", equivalent to the particle energy integral

$$\mathcal{E} = \kappa \frac{(E - E_{br})^2}{2} + (-\lambda q + \chi e^q) = const\,. \qquad (5)$$

It is useful to plot the function $V(q)$ and phase trajectory of the "particle", corresponding to some energy $\mathcal{E}$. As it is seen from the Fig.2 the "particle" with energy $\mathcal{E}$ oscillates in this potential between points $q_1(\mathcal{E})$, and $q_2(\mathcal{E})$, which means that the current oscillates around the stationary value (4). The turning points correspond to a largest and lowest currents. In these points $E - E_{br} \propto dj / dt = 0$, so the electric field is equal to a breakdown field.

One can see from this figure that the closer the applied voltage is to the breakdown voltage at the beginning of the ramp, the smaller are current peaks we observe, and their frequency is higher. When the amplitude of oscillations are small they become harmonic and their frequency does not depend on the amplitude. The sign of $E - E_{br}$ determines the direction of the "motion", which is clearly seen from the phase trajectories. If at the beginning $E < E_{br}$, then the current first decreases, and will reach the peak later; in the case $E > E_{br}$, current increases right away. What is interesting, is that in the absence of metastables the peak current does not depend on the initial sign of $E - E_{br}$, but only of its magnitude. This is because there is no limit to how small the current can be.

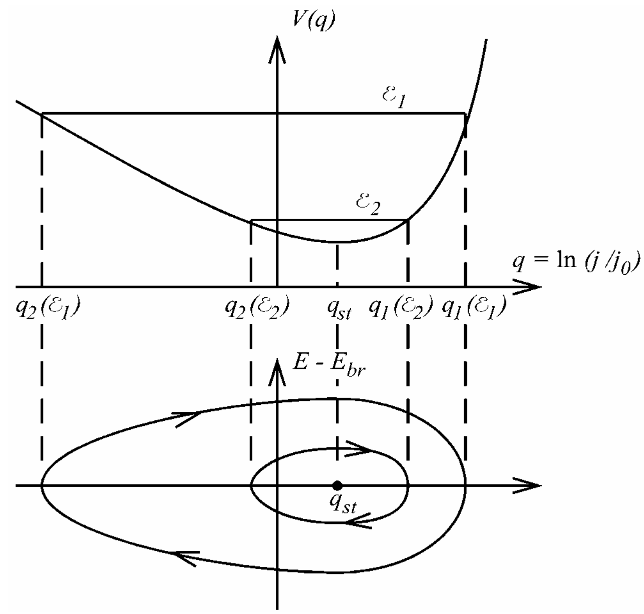

Figure 2. Function $V(q)$ for some value of initial current j_0 $(q = 0)$. Two horizontal lines show two different values of the energy $\mathcal{E}=\mathcal{E}_1$, $\mathcal{E}=\mathcal{E}_2$, $\mathcal{E}_1>\mathcal{E}_2$. The larger value of a peak current [turning point $q_1(\mathcal{E})$] corresponds to the larger energy.

From (5) we obtain for $j_{\max}$:

$$j_{\max} = j_0 + \frac{\kappa}{\chi}\frac{(E - E_{br})^2}{2} + \frac{\lambda}{\chi} q_{\max}\,. \qquad (6)$$

One can neglect the value of j_0 in the r.h.s. of Eq. (6), since $j_{\max} >>> j_0$. Then, for any chosen $(E - E_{br})^2$ the larger peak current corresponds to a larger $q_{\max}$. The values of $q_{\max}$ are determined by the function $V(q)$, and $\mathcal{E}$. Detailed analysis of $V(q)$ shows that larger initial current (better priming) and smaller ramp rate have smaller value of $q_{\max}$, and, thus, related to a smaller peak current. Of course, we assume that $j_{\max} >> j_0$.

Apparently if the current and voltage oscillations would not decay, the idea of the ramp did not work. There are however some factors that cause these oscillations to decay. As such a factor we investigate here the role of metastables. When two metastables collide they produce an electron-ion pair. This production results in a certain background current that decays slower than the current of the discharge, caused by direct ionization process. This limits the value of the minimum current in the discharge ($q_2(\mathcal{E})$) which has strong effect on the value of peak current. Metastables also effect (slightly) the dynamics of the discharge at other phases of a discharge. To comply with the format of the current presentation we give here only the qualitative description of the effect of the metastables, leaving the quantitative analysis for the follow-up paper.

For qualitative analysis we assume that the only role of metastable is setting up the minimum of the electron current. We model this in the following way: when the solution of equations (1)-(2) gives $j_e > j_{\min}$, where $j_{\min}$ is the minimum electron current due to metastables, j_e obeys the equations (1)-(2), while when $j_e < j_{\min}$, we set $j_e = j_{\min}$. The electric field though obeys equation (2) with $j_e = j_{\min}$.

It is convenient to trace the solution of such a system using phase trajectories for the system without metastables. Let's assume the starting point is below the line $E - E_{br} = 0$ as it is shown in Figure 3. Then, if the limiting current, $j_{\min 0}$, is very low then the "particle" moves along the trajectory as if no current limitation exists. After the first current peak occurs, the value of the limiting current changes to a higher value $j_{\min 1}$, since some of the metastables had been produced. After that the trajectory of the particle stays on the previous curve only until it reaches the value $j_{\min 1}$, then it stays constant until the electric field surpasses the value of the breakdown field ($E > E_{br}$), and at the point $E = E_{br}$ it changes the trajectory once again to the one, described by Eqs. (1)-(2), which has in it the point $(E = E_{br},\ j_{\min} = j_{\min 1})$, as in Figure 3. As it is seen from this figure the peak current related to this trajectory is smaller than the first one, and as the density of metastables will grow from peak to peak, the transformation of the trajectories will happen again and again and the current oscillations around stationary values (4) will, thus, decrease. This will go on and on until the metastable density reaches a certain high value.

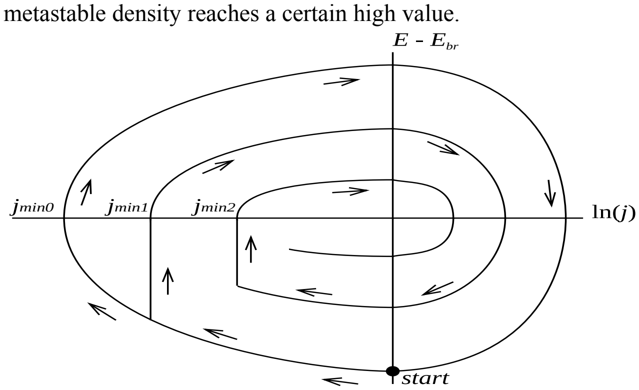

Figure 3. Phase trajectory of the voltage-current "particle" with the account of metastables.

3. Numerical Simulation and Discussion

Figure 4 shows a one dimensional computer simulation of the positive resistance discharge that demonstrates the oscillatory behavior. Figure 4a shows a rising applied sustain voltage ramp V_s and the resulting wall voltage V_w. Except for the oscillations, this is very similar to the ideal response shown from $100\mu s$ to $500\mu s$ in Figure 1. Figure 4b clearly shows the oscillations in the current from $100\mu s$ to $250\mu s$. After $250\mu s$ the current has apparently stabilized at a final stable breakdown current I_b. Figure 4c shows the same discharge current as in Figure 4b on a log scale. Figure 4d shows the voltage across the gas cell V_c, $V_c = V_s - V_w$. V_c rises until the breakdown voltage V_b of 140V is reached at $t = 100\mu s$. The oscillations are clearly seen until $t = 250\mu s$ where V_c stabilizes to the value of V_b.

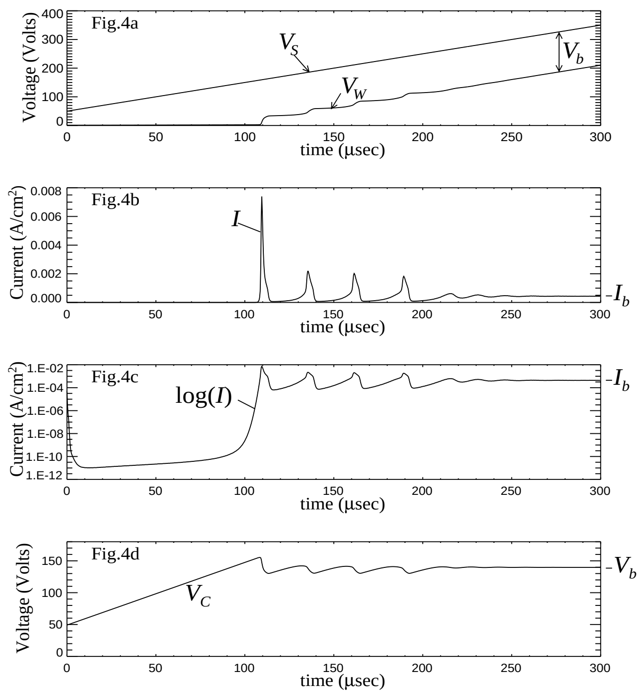

Figure 4. The voltages and currents that show the oscillations of the ramp discharge.

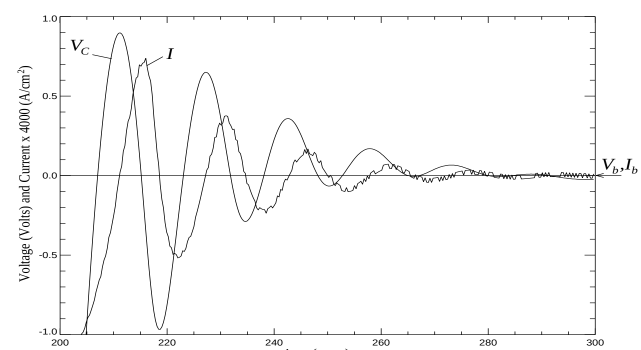

Figure 5. Expanded view of the voltage V_c and the current I of figure 4. These are expanded around V_b and I_b.

Here is worthwhile to give an explanation of these oscillations in different terms. Let us examine the period of Fig. 4 between $200\mu s$ and $300\mu s$, when the changes in voltage and current are small enough so that the oscillations are nearly linear. The plot of $V_c - V_b$, and $I - I_b$ during this period is shown in Fig. 5.

From this figure (see also Eq.(1)) it is clear that the current

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phase is delayed by nearly 90 degrees from the voltage phase. The discharge appears to act similar to an inductor in series with a positive resistance. The inductive reactance dominates the resistance since the voltage is nearly proportional to the time rate of change of the current. This inductive behavior is due to the well known phenomenon of the gas discharge current growing when the cell gap voltage V_c is above the breakdown voltage and similarly, the discharge current decays when the cell gap voltage is below the breakdown voltage.

An additional 90 degrees of phase delay occurs since the voltage across the dielectric capacitor is determined by integrating the discharge current. This accumulated dielectric capacitor voltage is negatively fed back to the discharge to determine the voltage across the gas V_c.

Thus, the discharge, behaving like an inductor, coupled with the capacitance of the dielectric, forms a circuit that behaves very much like a simple LRC circuit. The discharge inductive behavior should not be confused with the plasma panel stray inductance. PDP stray inductance is not a factor here because the currents and their rate of change are very low.

When the amplitude of the oscillations increases, they become nonlinear, but as long as the gap voltage V_c is very near the breakdown voltage V_b the response will result in a damping oscillations seen in Figs. 3-5. Oscillations are nonlinear for $t \cong (100-220)\mu s$ and linear for $t \cong (220-300)\mu s$. If V_c is significantly different than V_b, then the non-linear characteristics of the discharge will distort the current and voltage response.

The strongest discharge occurs in a pulse form at $t = 110\mu s$. The logarithm of the current shown in Figure 4c indicates more than 8 orders of magnitude difference between the initial priming current at $t = 10\mu s$ and at the $t = 110\mu s$ discharge peak that clearly illustrates the lack of priming. As the V_s ramp rises the low priming allows the V_c voltage to go to a value considerably higher than V_b. Once the discharge current builds up, the very large over voltage value of $V_c - V_b$ allows a strong discharge before V_c is reduced below V_b. The three discharges after the first large one have considerably less peak amplitude because they are sufficiently primed by the previous discharges. It is very common to experimentally observe a stronger peaked discharge at the beginning of the positive resistance discharge due to this lack of strong priming.

Figure 6 shows that an undesirably strong discharge can occur if the ramp rate is too high or there is insufficient priming. Figure 6a shows that the wall voltage rises abruptly at $t = 17.5\mu s$ and there is a very strong discharge current peak at the same time in figure 6b. In this case the $V_c - V_b$ over voltage was very large by the time that the discharge finally developed because the ramp rate was much larger than that of Figures 4 and 5.

Strong discharges are not desirable during the setup because the large light produced by them will degrade the picture dark room contrast. Instead, it is desirable for the setup discharge to produce as little light as possible. In addition a negative resistance discharge during a ramp leaves a highly uncertain output wall voltage which depends strongly on the somewhat variable level of priming.

It is interesting that for Figure 6 between 30 and 40 μs, there is a very stable positive resistance discharge. This clearly shows the critical role of priming on the stability of the discharge. For the discharge at $t = 17.5\mu s$ there is very little priming and so there is a very strong negative resistance discharge. This discharge created a large number of priming particles so that the positive resistance discharge from 30 to $40\mu s$ is very stable. Remarkably, these two strikingly dissimilar discharges were stimulated from the same steadily rising applied V_s voltage ramp.

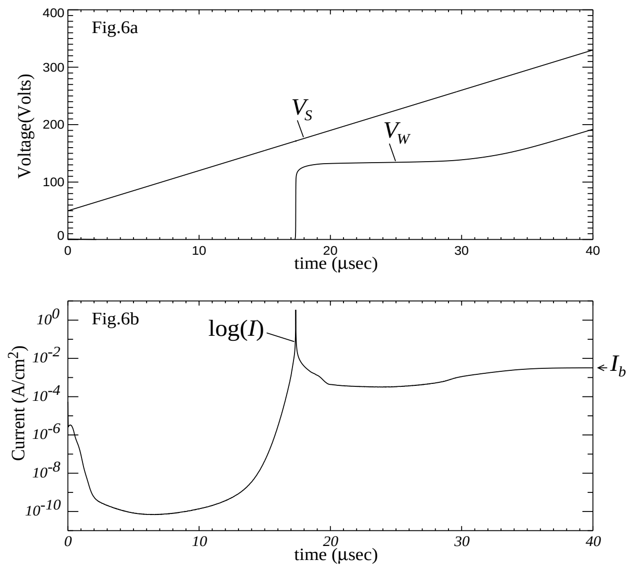

Figure 6. The voltages and current of a strong unstable discharge due to a too fast ramp rate, and insufficient priming.

Our analysis enables one to choose the ramp parameters more judiciously and obtain more stable and darker setup discharges as illustrated, for example, in Fig.4. Note that the ramp voltage illustrated in Fig.6 resulted in a discharge current reaching a peak value of nearly $3A/cm^2$, while the ramp in Fig.4 led to a maximum current of only $0.01A/cm^2$, nearly 300 times weaker and about ten times longer-lived.

The positive resistance discharge is now being used in the Panasonic 37 and 42-inch diagonal color AC PDP products. It is also used in the recently demonstrated 60-inch diagonal PDP prototype developed by Plasmaco for HDTV [5].

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