Understanding the Physics of Plasma Display Addressing

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Abstract

This article discusses physical processes affecting the speed of addressing discharge, and ways to both significantly increase the speed, and lower the cost of addressing.

1. Introduction

With recent improvements of plasma displays, switching to a high-definition (HD) and 10-subfield addressing the addressing time has became a critical issue. Indeed, if it takes ~1.5μs to address a line, then for 10-subfield addressing scheme it will take ~7.5μs (1080 lines) for addressing the panel using dual-scan method. If one adds 3ms for the ramp reset time, then the time left for the actual sustaining will be only about 6ms. This creates a serious problem for the single scan method, which requires twice as fast addressing (~0.8 μs/line) or at least sub-microsecond per line. Currently this problem is being resolved by using interlacing, variable sustain frequency, complex algorithms instead of a true 10-subfield scheme, etc. In the result, new artifacts appear, and while new panels do not have distortions that older 8-subfield panels had, the quality of a static image of new HD and especially Full HD panels are often worse than those of older ones with lower number of subfields. Thus the addressing speed has become the bottleneck for high quality plasma panels, and to understand what limits its speed and how to overcome the speed problem is of utmost importance.

2. Discharge speed - the Background

Two things determine dynamics and speed of any discharge between two parallel electrodes - the priming (initial density and intensity of external sources of charged particles in the volume), and the voltage across the gap relatively to the breakdown voltage [1]. These two parameters still are the most critical for the discharge dynamics in a real three-electrode cell, though other factors like details of cell geometry or even its volume, configuration of electric field become important as well. Before addressing issues related to geometry of a cell and particular driving, we will analyze briefly general features of priming and applied voltage with respect to address discharge used in a PDP. Since reliable operation of a PDP can be based only on mechanisms of priming that are sustained by discharges during PDP operation, it is important to be clear about the sources of such priming.

A. Priming

Sustain period is the most important for the priming, since sustain discharges are responsible (directly or indirectly) for most of the priming of all discharges used in PDPs. During sustaining, the alternating voltage is applied to sustain electrodes and every time it changes its polarity, the net voltage (external voltage together with the wall voltage) applied to the gap of the cells addressed ON, almost doubles the breakdown voltage between sustain electrodes. Assuming that some priming particles are present in the gap, this voltage ignites a strong discharge, which results in creation of high density plasma and large number of excited atoms. Typical sustain discharge transfers about $\delta N \sim CV_S / e \sim 10^8$ electrons and ions between electrodes, which completely compensate the electric field in almost the whole cell volume and leaves about the same amount of charged and about $10^8 - 10^9$ excited particles in the volume. Here C is the capacitance of the dielectric near sustain electrode, V_S is a sustain voltage, and e is the electron charge. All these particles left in the volume and produced or left on the surface have capabilities of been utilized for priming, and at different stages of PDP operation some or the other (ions, electrons, metastables or electrons emitted from the surface) may become the major or even the only priming source for the discharge, however the only source of electrons in the cell that can work for a long time (much longer than

1*ms*) is electron exoemission [2-4] from MgO surface, excited by electrons, ions and photons during sustain period. Every two sustain pulses about 10^8 electrons and ions strike MgO surface just above sustain electrodes, filling the energy levels in the forbidden zone, and making holes in the valence band. As electrons and holes recombine in the process of MgO relaxation, the released energy may be absorbed by another electron trapped in the forbidden zone, which then may be ejected from the surface. In this presentation we will not make any quantitative estimates for exoemission rate for the reason that it depends on the number and distribution of energy levels in the forbidden zone, the number of electrons in the forbidden and conductive bands and holes in the valence band, temperature, presence of dopants, surface condition, etc., which should be a subject of a separate investigations both theoretical and experimental. We will simply use the fact that the exoemission rate depends on time much slower than those discussed previously and for a long time (seconds at least) this process can provide sufficient flux of electrons (a few tens per microsecond) from the activated by electrons and ions surface - just above sustain electrodes, where they were deposited.

B. Applied Voltage, VT-curves

The second factor affecting any discharge speed is the voltage applied to the gap. As one knows from one-dimensional theory [1], when the voltage across the gap is close to the breakdown,

$$\Delta \equiv \gamma(e^{\alpha L} - 1) - 1 << 1,$$

where α and γ are first and second Townsend coefficients and L is the gap length, the discharge grows/decays with an average characteristic time about $\tau_i/\Delta \sim L/\mu_i(E - E_{br}) \sim L^2/\mu_i(V - V_{br})$, where E, E_{br} and V and V_{br} are electric field in the gap, the breakdown field and appropriate voltages across the gap, μ_i is ion mobility, and $\tau_i \sim L/\mu_i E$ is the ion transit time. If the voltage significantly exceeds the breakdown voltage ($\Delta \sim \gamma e^{\alpha L} >> 1$, then this time is much shorter: in the beginning, until the ion density distorts the electric field (linear mode/phase), the discharge growth rate is about $\Delta/\tau_i \sim \alpha\mu_i V/L$ and then it grows much faster (nonlinear mode) [5]. Since the linear phase is the slowest of two, it is this phase that determines the formative delay of the discharge. After the peak of the discharge a high density plasma, capable of depositing large charges on electrodes fills the discharge gap, so one can control the memory charge by choosing appropriate electrode potentials after the peak of the address discharge. Sometimes discharge may reach a nonlinear mode having initially small Δ or even $\Delta = 0$, if one injects large number of electrons in the gap, and the gap is long enough. The important difference between discharges operating only in linear mode and developing the nonlinear mode is that the voltage transfer achieved in a linear discharge is much smaller than in the latter one, while the voltages initiated them can be very close. That is why it is very important to achieve the nonlinear mode in the address discharge.

Since the amplitude of the address voltage affects the cost of a panel, it is important to know the breakdown parameters of a cell, and "place" a cell correctly before addressing with respect to the breakdown so that a relatively low address voltage would initiate the strong address discharge. The appropriate method of the preparation a cell for addressing using ramp reset [6] and correct reset waveform [7] in a two-electrode cell were discussed in details earlier. The important *for addressing* feature of the ramp setup is that one can control the wall charges and set a cell into a specific state chosen for the purpose of addressing. For analysis of the breakdown conditions and predicting wall charges in a three electrode cell Sakita et al. [8], and Kim et al. [9] suggested a model of three capacitors (one capacitor for every pair of electrodes X-Y, X-A, Y-A, where X and Y designate sustain bus and scan electrodes, and A - data electrode) and introduced a Vt-close curve (Fig.1) for such analysis. The Vt-curve is essentially a 3-electrode analog of the breakdown voltage between two parallel electrodes, as it shows in the coordinates of voltages between two of the electrodes and the third one the boundary between regions where discharge decays (inside) and grows (outside).

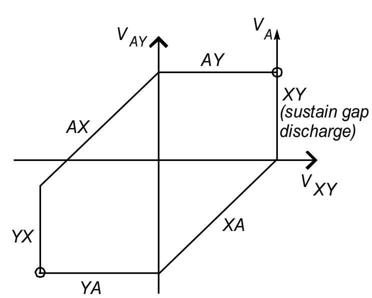


Fig.1. Vt-curve for three-capacitors model [8, 9].

There are, however, significant differences between the Vt-curve for a three-capacitor model and the Vt-curve of a real 3-electrode cell. Real Vt-curve depends on the wall charge surface *distribution*, which is not uniform and depends on parameters of a cell, discharge "history", trajectory ($V_{XY}(t)$, $V_{AY}(t)$) rather than final V_{XY}, V_{AY}, so Vt-curve transforms during the discharge (Fig.2) and has to be measured in every "critical" operation-wise point (after sustain period, before and after ramps UP and Down, AFTER address discharge) otherwise actions one takes may have undesirable results.

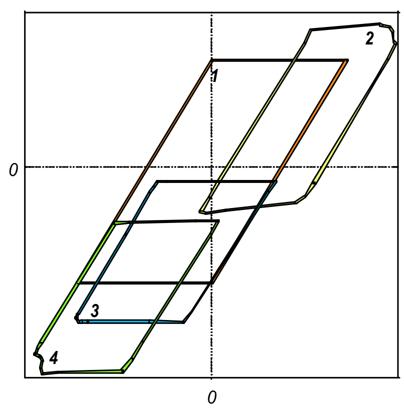


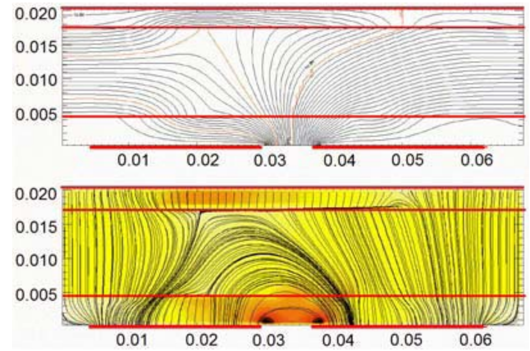
Fig.2. Vt-curve for 3-electrode cell and its evolution (1→4) after series of two sequential ramps (1→2, 2→3→4) involving both X and Y electrodes.

As in 1-dimensional (1D) case the breakdown voltage provides only the reference point for comparison with voltage across the gap, the Vt-curve shows where the balance between production of charged particles and their losses is and thus serves only as a reference line for 3 electrode system, but does not provide any information about the dynamics and the speed of the discharge if one applies a vector ΔV which takes the cell off the balance. Another significant difference between three-capacitor model and three-electrode cell is a nonlinear response to the applied voltage. Beside a usual nonlinear response of the discharge to the magnitude of the applied voltage, the applied voltage (ΔV_{XY}, ΔV_{AY}) may so much change the *structure* of the electric field in the gap, as shown in Figs. 3*a*-3*b*, that discharge will develop in completely different way compared to the 3-capacitor model.

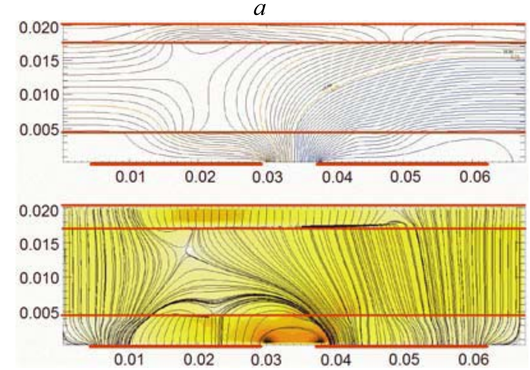
1. Addressing Discharge. Statistical and Formative Delays

1. Statistical delay

Statistical delay is usually associated only with



a



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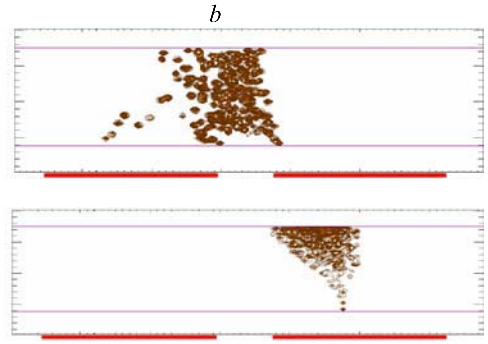

c

Fig. 3. Lines of equal potential and lines indicating the direction of electric field immediately after the ramp (*a*), and when the address voltage (80*V*) is applied to the data electrode (*b*). Lower two figures (*c*) show the ions produced in an avalanche initiated by electrons started from the inner edge and from the central part of the cathode. The latter produced 4.5 times more ions and started the discharge.

the occasional appearance of the priming electron in the gap, which follows from a 1D theory, if $\Delta >> 1$ commonly assumed for the addressing discharge.

Since exoemission is the only source of priming for address discharge, the only way to shorten this delay seems to come from the increase of the exoemission rate. This conclusion instigated attempts to increase this rate by any means. One should remember though that exoemission is only a "visible" part of the relaxation process, which may be inefficient or efficient, depending, for example, on the quality of the MgO film and the way it is being prepared [10], because it effects how deep under the surface most electron-hole recombination events occur. If exoemission increased mainly by increasing the recombination rate, rather than improving the efficiency of the exoemission, then this rate being high in the beginning, will decay faster. But independently of the exoemission rate, there are other ways to improve addressing. Contrary to 1D theory, there are many other factors in a PDP cell strongly affecting statistical delay. Manipulating with some of them can often solve the problem more efficiently and without extra cost.

In 1D case electron diffusion perpendicular to the electric field has no effect on the number of ions produced in the avalanche, the position of initial electron on the cathode also does not play any role. Electric field (voltage) does effect the number of ions produced in the avalanche, but as long as $\Delta \gg 1$, this number is so large that they produce large number of secondary electrons, and discharge will grow, as soon as the first electron is emitted, so the only statistical element relates to the source of that first electron. None of this is true in a real PDP cell.

In a PDP cell, when the address voltage is applied, the electric field is very nonuniform and its structure is very complicated. It has different zones, where field connects to different electrodes (Fig.3*b*), the parameter Δ strongly depends on the electric field line - for some lines $\Delta >> 1$, for others $\Delta \sim 1$, or $\Delta < 1$. Electron can emerge from the part of the cathode, where $\Delta < 1$, or connected (by the field) to the other sustain electrode. Due to diffusion many electrons end up on the sidewalls or diffuse to a "wrong" zone, so that they do not start the discharge, or it may take very long time and "luck" to start it. The probability of *not starting* the discharge is much higher for those electrons that appear close to the walls, or close to the zone connecting sustain electrodes, or in the area of the cathode for which $\Delta \sim 1$ (or <1). Figures 3 show the result of 3D Monte-Carlo simulation where exoelectrons were emitted from the inner edge of the sustain electrode and from the central region, connected to the address electrode by strong electric field. Just one electron emitted in the central region was enough to start the discharge, while it took many electrons and much longer time to finally start the discharge from the edge. Obviously increasing the efficiency of utilizing exoelectrons can significantly shorten the statistical delay. One can achieve it by modifying geometry of a cell (reduce plate gap to sustain gap ratio) and driving voltages in a way that increase the favorable (effective) area of the cathode surface, and by increasing the electric field between scan and address electrode. In a strong enough field the ionization becomes so intense that even with losses to the wall or the neighboring regions, what left of the avalanche may be enough to start the discharge (see extreme case of discharge propagation [11]. Stronger field between scan and address electrodes also improves the structure of the field in the volume, the favorable area of the cathode, and shortens both delays. Of course, the question is how to increase the electric field in the gap without increasing the voltage of address drivers. Later we will discuss the author's solution of this problem [12], [13].

2. Formative delay

The formative delay is associated with a hydrodynamic phase of the discharge, when the number of participating particles is large enough to ignore small fluctuations of the current. Basic features of this phase in a PDP cell are similar to those of a 1D discharge (larger field, shorter gap lead to a faster discharge growth), but it is much more complicated than a 1D discharge. First, there are three electrodes rather than two and there is more than one way for discharge to develop. Second, due to a non-uniformity of the electric field, electron diffusion leads to their losses from the region of the highest growth rate to the neighboring areas, averaging somewhat the Δ over larger area. This results in the lower discharge growth rate compared to a 1D case. Third, although discharge finally undergoes a fast nonlinear phase between two sustain electrodes, this phase can be initiated in different ways, which also affects the timing of the transition to the final phase, and thus the delay. During the nonlinear phase a highly conductive plasma region created at the anode side focuses the electron flux from a wider area of the cathode, further accelerating the discharge.

In order to lower the address voltage all addressing schemes using the ramp setup waveform place a cell before addressing to a corner of the Vt-curve (Fig.1), so that both V_{AY}, and V_{XY} voltages are equal to appropriate breakdown ones (assuming that geometry allows it). Due to "communication" between regions (because of electron diffusion), one may be a little above and the other a little below the breakdown, and discharge in one of the areas supports the discharge in the other one. When the address voltage is applied, this communication slows down the growth of the plate gap (PG) discharge between scan and address electrodes, but provides priming for the "driven" sustain gap (SG) discharge between sustain electrodes. As the main discharge grows, so does the driven one. At some moment the ion density in the SG discharge may grow to a point, that it significantly affects the electric field in the gap and the discharge transforms from being driven and slightly under-breakdown to a strong nonlinear main discharge. The stronger connection between regions the longer it takes to reach this stage. The much faster scenario can be realized if the "communication" between regions is week. The PG discharge quickly grows and becomes nonlinear leading to restructuring of the potential distribution in the gap. This results in bifurcation and switching to a strong SG discharge (X-Y). After the bifurcation the conductive (plasma) channel connects two sustain electrodes, and the address electrode potential loses its importance. One can change the address voltage to zero, but it will have no effect on the discharge. As with statistical phase of the discharge, the stronger the electric field between address and scan electrodes, the faster the discharge.

4. Fast Addressing

Let us summarize the results of previous sections.

1. Priming of address discharge is provided by exo-emission;
2. Fast growing PG discharge provides electrons for all discharge regions. Both statistical and formative delays can be reduced by increasing the PG voltage. Formative delay strongly depends on the PG size (~L^2).
3. Strong SG discharge can start before or *in the result* of a strong PG discharge, depending on how strong is the electron diffusion from PG to SG between regions. Mitigation of such communication can accelerate the appearance of a strong SG discharge (shorten delay).
4. SG discharge is responsible for the memory charge; it produces high-density plasma, which decays mostly due to recombination. Removing the scan voltage before plasma decayed may erase this charge.
5. The discharge dynamics strongly depends on the applied voltage. Small voltage difference may be the only reason for initiating a weak or strong discharge. The first one transfers very little voltage, the latter one results in address discharge.

Using this summary as guidance, we have designed two addressing schemes for significantly different cell parameters (different Vt-curves). Both schemes use high PG voltage combined of selective address voltage controlled by address drivers and nonselective voltage V_{OFF} between all sustain and data electrodes, but geometry dictates additional measures. For the cell with small SG and large PG the additional major obstacle is a communication between regions, for large SG and small PG the problem is a spread of the discharge to SG region.

First, let us notice that a small voltage applied to address electrodes does not produce address discharges, and thus it can be applied to all address electrodes (or the opposite voltage to both sustain electrodes). Then only additional voltage that makes a difference between address discharge and weak discharge has to be controlled by address drivers. To maximize V_{OFF} one needs to suppress communication between regions (or eliminate it), and make sure that a weak PG discharge initiated in all OFF cells by V_{OFF} will not initiate a strong SG discharge. For this reason we apply additional voltage V_{Xlock} *reducing* the voltage between sustain electrodes, as in Figs.4,5. This way only strong PG discharge will initiate necessary for addressing SG discharge.

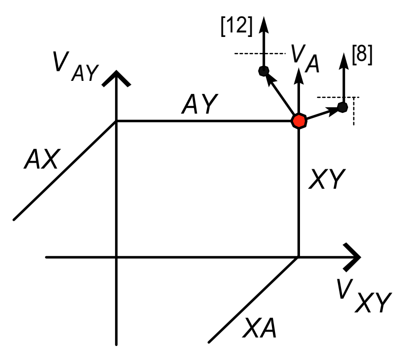

Fig. 4. Part of the Vt-curve with different addressing vectors, related to a standard (vertical vector V_A), “sequential priming” [8], and “dual” [12] addressing schemes, all using the same amplitude of address voltage. Dashed lines show the boundaries between weak and strong discharges. The “dual” scheme allows achieving significantly larger PG field in the gap than the others.

On the other hand, if electrodes are narrow, widely separated and the plate gap is relatively short (tetragonal Vt-curve), communication between regions is absent, a weak PG discharge cannot possibly initiate the SG discharge, then after choosing a proper nonselective voltage, we apply additional voltage V_{acc} *increasing* the voltage between sustain electrodes, as in Fig. 6, to assist in propagating the discharge when and only when the strong PG discharge occurred. Otherwise V_{acc} does not play any role.

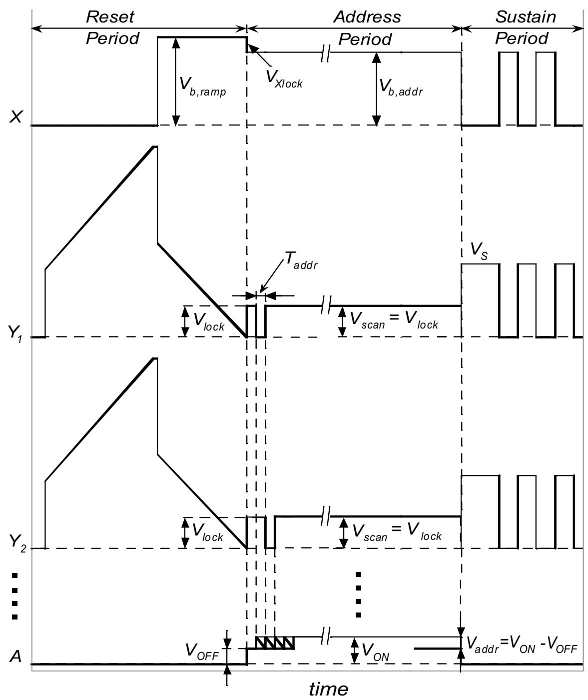

Fig.5 Version of the driving scheme, realizing "dual" addressing shown in Fig. 4.

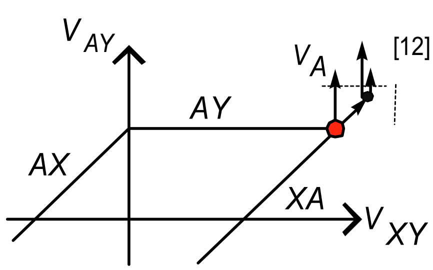

Fig. 6. Addressing the cell with large SG and short PG. In this case the field structure with regard to PG discharge phases -both statistical and hydrodynamic- is almost ideal (the whole area of the Y electrode is connected to the address one, diffusive losses from the region are small, Δ near its maximum, and τ_i is small), so the PG part of the discharge can easily be made fast, and the main concern is the speed of channeling discharge to SG region. The PG discharge here is so fast that one can design a scheme, where addressing of different lines overlaps in time, significantly reducing addressing time per line [12,13].

Using 3D PIC/Monte-Carlo simulations of a PDP cell we have tested the dual addressing scheme and shown that for moderately wide SG, when we could completely suppress communications between regions, and with only 40-50V used for the V_{OFF} one can achieve addressing time of about 600-700ns with exoemission rate of only 20 electrons per microsecond from the cathode area, which is quite low.

5. Summary

In this presentation we discussed physical mechanisms causing significant delays – statistical and formative of the address discharge and simple ways to overcome the problem. This of course does not mean that these are the only ways to a fast discharge – increase of the exoemission rate will also shorten addressing. One has to be careful though, because it could mean faster decay of exoemission, and/or loosing the memory charge, since this current is multiplied many times by ionization in the volume. This presentation is by no means complete. Due to size limitation we could only choose a small amount of available material.

6. References

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