Discharge current reduction in plasma displays for high Xe gas composition

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Abstract: Plasma displays with high brightness require high Xe percentage in the gas composition. The increase in Xe percentage in Ne-Xe gas mixture increases the sustain voltage as well as the discharge current. High power consumption is one of the main drawbacks of plasma displays. The challenge is to limit the power consumption without affecting the brightness. In present investigation the different constituents of discharge current have been studied and a new driving waveform has been proposed for suppression of Xe ion current.

1. Introduction: Low Luminous efficacy is main drawback of plasma displays. Luminous efficacy (LE) is a property of light sources, which indicates what portion of the emitted electromagnetic radiation is usable for human vision. For plasma displays, if V is operating voltage and I is the sustain current then maximum radiated power would be equal to product of voltage and current i.e. V x I, whereas brightness (B) measures the radiated power usable for human vision. Thus

\[ LE \propto \frac{B}{V \times I} \]  \hspace{1cm} (1)

Luminous efficacy is directly proportional to brightness and inversely proportional to applied voltage and discharge current [1]. In present global scenario high-energy efficiency is the first criterion for any device and for a display device i.e. LE must be high. But the plasma displays are less energy efficient than Liquid Crystal Display devices (2.2 Lumen/Watt for PDP and 5.0 Lumen/Watt for LCD).

An ideal plasma display with high luminous efficacy must have:
1. High average brightness
2. Low discharge current
3. Low sustain voltage

Considering only discharge parameters i.e. ignoring optical losses and VUV to visible photon conversion losses; the desired ideal condition could be achieved by well known solutions:
1. High brightness: high Xe %;
2. Low discharge current: Low frequency ultra short pulses;
3. Low sustain voltage: alternative material with high secondary electron emission than MgO;

But implementation of aforementioned solutions has not been possible till date since increase in Xe% in gas composition results in increase of discharge current as well as the operating voltage.

In this paper, basics of Ne-Xe discharge have been revisited and a driving method, which reduces discharge current for high Xe% has been proposed.

2. Fundamental of Ne-Xe Discharge

In plasma displays the Ne-Xe discharge produces VUV photons. In commercially available plasma displays Xe% is less than 10% in the gas composition. The characteristic emissions of Xe at 147 nm and 172 nm are utilized for excitation of phosphors for display visual effects. The high brightness requirement demands production of more number of VUV photons which could be only achieved if Xe% in gas mixture is increased. But this increment in Xe content also increases current and operating voltage. The first question is why sustaining voltage increases with Xe% and second question is why discharge current too increases?

As we know that Ne provides secondary electron for sustaining the discharge and Xe provides VUV photons. Let us consider an ideal case in which Xe percentage in gas composition is 0, i.e. a Ne discharge where voltage V1 is sufficient sustaining the discharge.

Let’s consider 10 electrons are released from cathode surface and accelerate through the gap between electrodes, and before getting collected at anode each electron ionizes one Ne atom. These 10 newly born Ne\(^+\) ions accelerate towards cathode. The condition for sustaining demands that the loss of 10 electrons at anode must be compensated by emission of 10 electrons at cathode. These required electrons are generated by bombardment of Ne\(^+\) ions. When a Ne\(^+\) ion with potential energy 21.55 eV strikes the MgO surface (say) emits two electrons, one goes for neutralization of the ion while other accelerates towards anode, sustaining the discharge.

Consider another case with gaseous mixture contain 90%Ne-10%Xe. For this case; 10 electrons emitted from the cathode would ionize 9 Ne atoms and 1 Xe atom for getting collected at anode. On reaching cathode, nine Ne\(^+\) would generate 9 secondary electrons from cathode surface but the tenth ion i.e. Xe\(^+\) ion with 12.12 eV could not generate secondary electron. Thus, we begin with 10 electrons and remained with only 9 electrons for 10% Xe case and hence discharge would extinguish. [Note: the secondary emission coefficient of Xenon is very low \((x_{e}=0.02-0.05)\) in comparison to Neon \((x_{e}=0.3-0.5)\) for MgO surface.

In order to increase the ionization probability of Ne atoms i.e. to get 10 Ne\(^+\) ions for 90%Ne-10Xe in gas mixture voltage between electrodes must be increased, for same surface material. The challenge is; how to get 10 electrons from cathode surface without increasing voltage? My opinion neither Ne\(^+\) based secondary electron emitter surface nor the electrode gap reduction is a solution to this problem. The solution is hidden in electron emission property of material i.e. it should be based on quantum of charged state, rather than energy state of incident ion, i.e. if 10 ions with unit charged state, strike the surface, 10 electrons should be emitted should be emitted from the surface irrespective of potential energy of ions.
The reason for increase of discharge current with Xe% is following. In addition to sustain voltage the discharge current also increases voltage with Xe percentage. The rise of discharge current is attributed to high collision cross-section for ionization of Xenon atom, which is ten times larger than ionization cross-section of Neon for PDP operational conditions \((\text{Xe} = 10 \text{ Ne})\) \(^2\). In other words, due to low ionization energy (12.12 eV) and larger size, ionization of Xe is much higher than Ne, under same condition. Thus, improvement of brightness by using high Xe ion partial pressure is almost nullified by sharp rise in current and operating voltage. Though, enormous effort has been made to reduce the operating voltage and improve brightness to achieve high luminous efficacy of AC PDP, no significant effort has been made to limit the current.

The current has following components:

A. Discharge current: has two components
   a. Electron current
   b. Ion current: has further two components: i) Ne\(^+\) ion current, ii) Xe\(^+\) ion current

B. Displacement Current

The discharge current is composed of different subcomponents and their dominance during a pulsed discharge is shown in figure 1.

2.1. Electron Current: In order to understand the contribution of electron current, let’s recall the fundamentals of Dielectric-barrier discharges (DBD’s): Their defining feature is the presence of dielectric layers that make it impossible for charges generated in the gas to reach the conducting electrode surfaces. With each half-cycle of the driving oscillation, the voltage applied across the gas exceeds that required for breakdown, and the formation of narrow discharge filaments initiates the conduction of electrons toward the more positive electrode. As charge accumulates on the dielectric layers at the ends of each filament, the voltage drop across the filament is reduced until it falls below the discharge-sustaining level, whereupon the discharge is extinguished. The low charge mobility on the dielectric not only contributes to this self-arresting of filaments but also limits the lateral region over which the gap voltage is diminished, thereby allowing parallel filaments to form in close proximity to one another. Thus, the entire gas-filled space between electrodes can become, on
average, uniformly covered by transient discharge filaments, each roughly 0.1 mm in diameter and lasting only about 10 ns [3]

Thus, filamentary mode of discharge lasts only for few hundreds nano-seconds (~ 500 ns). Since, motilities of massive ions are hundreds of times less than for light electrons, in each filament of discharge, current is mainly due to fast electrons. As much as number as well as energy of electrons is higher the probability of excitation of Xe ion, for desired emission, would also be higher. Thus, high electron current is desired. Since, conductivity of weakly ionized gas is determined by degree of ionization and the ionization cross-section of Xe is 10 times larger than Ne, electron current increases with Xe composition upto 20%. For Xe percentage more than 20% in gas composition (for 500 total pressures) degree of ionization begins to reduce [4]. Note that, contribution of electron current dominates during initial ~ 500 ns of the applied pulse.

2.2. Ion Current: Generally in PDP Ne-Xe gas mixture is used hence ion current constitute of Ne$^+$ ion current and Xe$^+$ current. These ions accelerate inside cathode sheath and gain translational energy. Though, each Xe$^+$ ion gain lower from applied potential due higher mass (131.29 a.m.u.) than Ne$^+$ (20.17 a.m.u.), the number density of Xe$^+$ ions much larger than Ne$^+$ ions, due to high ionization cross-section of Xe atom. On reaching the cathode surface they dump their translational energy. Ne$^+$ ion emits secondary electron due to its high potential energy. The translational energy of ions is loss of power without any gain. It was estimated that at least 70% of total power lost in ion heating [5]. As Xe % in gas composition is increased ion heating also increases due high number density of Xe$^+$ ions. The question is how can we suppress Xe$^+$ ion current? Further, contribution of ions to discharge current dominates after ~ 300 ns as the ion response time is much larger than electron response time [4]. Ions keep gaining energy from applied field till end of the pulse accumulate positive charge on cathode. Thus, ion current and electron current dominate at different period of the applied pulse. The excitation of Xe atom for desired emission is very insignificant during the period in which ion current dominates. It provides a very simple and know technique to reduce ion heating loss i.e. apply the potential only for short duration in which electron current dominates. In other words, ion current could be limited by keeping the ON time of the applied pulse “very short” i.e., 100 ns – 500 ns, so that electron current remain unaffected. In such a short period ions would not gain translation energy significantly and hence the ion heating loss could be limited. But, this technique would be successful at higher frequency, where role of wall charges is least. Wall charges due to electrons plays important role in extinguishing the discharge. While wall charges due to ions plays important role in initiating the discharge in next half cycle of the applied pulse till sustain frequency up to 500 kHz. For higher frequency displacement current is a very high resulting in high capacitive losses. It raises another question that, can we limit ion current without increasing frequency? In this paper we have propose a possible answer to this question.

2.3. Displacement Current: The displacement current of simplest dielectric material (ignoring polarization) can be expressed in terms of electric flux:

\[ I_d = \varepsilon_0 \frac{d\Phi_e}{dt} \quad (2) \]

Where \( \varepsilon = \varepsilon_0 \varepsilon_r \). The permittivity (\( \varepsilon \)) of material is defined in terms of relative permittivity (\( \varepsilon_r \)) and electric constant respectively. For low displacement current either permittivity of material should be low (nano structured SiC have possibility of achieving its dielectric constant < 2) or least change in electric flux with respect to time is required. Thus, for a high voltage pulse the rise time should be sufficiently large. This contradicts the requirement of short rise-time for effective VUV excitation [6]. Question again arises, how to apply a voltage pulse such that displacement current is low and VUV excitation is higher?
3. Contribution of Xe ion current

A one-dimensional, time-independent (since applied sustain pulse \( \sim 2500 \) ns, while electron plasma frequency \( 1.1 \) ps) model has been developed to estimate ion energy velocity distribution at cathode [7]. An ion starts from plasma-sheath edge (i.e. from \( x=S \)) accelerate towards the cathode. It undergoes momentum exchange collision with background atoms, which was at rest.

In the formulae below, the \( x \) and \( x_0 \) both were running variable. Using power law potential profile inside sheath velocity distribution was estimated. The equation of motion for an ion starting from rest at \( x = x_0 \) after a collision expressed as

\[
\frac{du}{dt} = \frac{eE}{m_i} - beV_{e,0}^s (s-x)^b
\]  

(3)

Where, \( u \) is the ion velocity. Integration of Eq. (1) yields,

\[
u^2 = \frac{u_i^2}{S} \left[ (S - x)^b - (S - x_0)^b \right]
\]

(4)

\[
u_u = \left( \frac{2eV_{e,0}^s}{m_i} \right)^{\frac{1}{2}}
\]

(5)

\( \nu_u \) is the maximum velocity at the cathode. The normal ion velocity distribution at any position \( x \) can be expressed

\[
f_i(u, x) = \left( \frac{1}{\lambda} \right) \exp \left[ \frac{-(x_0 - x)}{\lambda} \right] dx_0
\]

(6)

Differentiating Eq. (4) and substituting it in Eq. (6) yields Eq. (7)

\[
f_i(u, z) = 2 \frac{(u^b)}{\lambda b u_i^b z^{b-1} \left( 1 - \frac{u^b i S}{u_i^b z^b} \right)^{b-1}} \times \exp \left[ \frac{-(z)}{\lambda} \left( 1 - \frac{u^b i S}{u_i^b z^b} \right)^{b} \right]
\]

(7)

where \( z = S - x \). Using Eq. 5 the velocity distribution of ions can be obtained for known value of sheath thickness and the value of the exponent \( b \). The value of sheath thickness and value of exponent was obtained using collisional sheath model [6].

![Graph showing ion current distribution](image.png)
The electron temperature and plasma density used for estimation were taken from experimental results reported in Ref. [8, 9]. The comparison of Ne$^+$ and Xe$^+$ ion velocity distribution at 5%Xe-95%Ne is shown in Fig. 2. Velocity distribution for Xe peaked at lower velocity. In Fig. 3 the contribution of Xe$^+$ and Ne$^+$ to energy transport for different Xe-Ne composition is shown. It was concluded that Xe$^+$ ion current contribute 1.5-5.5 times larger than Ne$^+$ ion for 5%Xe to 30% Xe in gas composition respectively.

Fig. 2: Velocity distribution of Ne$^+$ and Xe$^+$ show the effect of inertia for 5%Xe-95%Ne composition. Velocity distribution for Xe peaked at lower velocity.

Fig. 3: Shows the contribution of Xe$^+$ and Ne$^+$ to energy transport for different Xe-Ne composition. (a) It was estimated that Xe$^+$ ion current contribute 1.5-5.5 times larger than Ne$^+$ ion for 5%Xe to 30% Xe in gas composition respectively. (b) Average kinetic energy of Ne and Xe for different gas composition.

Summarizing main points of the above discussion we reached on an obvious conclusion that for high brightness, high Xe% (25~35%) in gas composition is an essential requirement. But it accompanied with high break down voltage and high discharge current. For voltage reduction, in my opinion, alternative concepts based on charged state of ions should be explored rather than energy state of ions for ion induced secondary electron emission. It will be eliminating/reducing burden on Ne$^+$ ion for secondary electron emission. Second problem with high Xe% is high Xe$^+$ ion current due to high ionization cross-section of Xe atom. Actually, high ionization rate is required for achieving high electron density for efficient VUV excitation. Moreover, the excitation of Xe atoms is done by electron current, thus limitation of electron current is not required. However ion current only contributes to the power losses. So the question is how Xe$^+$ ion current could be distinguished first from electron current and Ne$^+$ ion current?

The answer is very simple. Selection of different constituent of currents could be made on basis of masses of the carrier. The mass of electron $m_e=9.1x10^{-31}$ Kg, mass of Ne atom = 1. 345 x10$^{-25}$ Kg and mass of Xe atom $m_{xe}= 8.757x10^{-25}$ Kg. The Xe$^+$ ion is ~6.5 times massive Ne$^+$ ion and ~1x10$^6$ times massive than electron. Fig.1 shows schematic of dominance of different constituents of current during application of a pulse in a PDP discharge cell. Thus, Xe$^+$ ion would be latest to respond to the applied pulse.

4. New sustain waveform for reduced ion current
The driving method of AC-PDP is quite complex and voltages in appropriate temporal sequence is applied on electrode on scan, sustain and address electrodes in order to display information electrode on AC PDP.
Fig. 4: Conventional sustain waveform. Positive pulses are applied alternatively on sustain electrodes.

Fig. 5: New bipolar sustain waveform with predetermined temporal sequence for suppression of Xe ion current for high Xe% in gas composition.

One frame of image information is divided into a number of subfields and each subfield has reset period, address period and sustain period. The sustain period emits light for visual effects by conversion of VUV photons into visible photons generated during sustain discharge according to display information i.e. video signal. The sustain discharge causes current to flow through sustain electrodes and resulting in power consumption equal to product of applied voltage and discharge current. The conventional sustain waveform applied on sustain electrodes shown in FIG.4.

For 30% Xe in gas composition, sustain voltage of 190V having 3 microsecond pulse width, is applied alternatively on sustain electrodes [1]. The sustain voltage is increased to 240V for 50% Xe. According to the proposed new bipolar sustain waveform shown in FIG. 5, the minimum voltage required for sustaining the discharge could be applied alternatively i.e., 190V one first electrode and 50 V on other sustain electrode in opposite polarity with predetermined temporal sequence in such a way that ions experience only 190V and hence reducing the Xe ion current [9].
5. **Conclusion:** High Xe % percentage in gas composition is an essential requirement for achieving high luminous efficacy of the plasma displays. With increase in Xe percentage, the sustain voltage and Xe ion current increases rapidly. The increase in discharge current is result of high ionization cross-section of Xe atom. The contribution of Xenon ion current could be limited by application of asymmetric bipolar sustain waveform in predetermined temporal sequence. Because of its high atomic mass Xenon ion current could be suppressed selectively by appropriate waveform, with pulse width in range of 100-500 ns

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