# Modeling, Characterization and Simulation of Dielectric Absorption in Capacitors in Image Sensors

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**High density capacitors are widely used in pixels to extend the dynamic range or to provide global shutter functionality. These high-density capacitors often suffer from dielectric absorption.**
**This paper presents a simulation model for a capacitor with dielectric absorption, fits it on measurement data and applies it to a number of use cases.**

### Motivation

Many recent pixel designs include large capacitors either to increase the dynamic range [6, 7, 8, 9] or to provide (voltage domain) global shutter functionality [10, 11, 12]. The combination of increasing capacitance value and shrinking pixel pitch is enabled by the development of high density capacitors. The high-k dielectrics used in these capacitors often suffer from dielectric absorption and the subsequent relaxation which causes lag. Evaluating the impact of the dielectric absorption on the sensor performance requires a simulation model. This paper presents an RC based model and its application.

### Capacitor model

A very basic representation for a capacitor with dielectric absorption is shown in figure 1 where the absorption is represented by a single RC branch (R and $C_0$ - $C_\infty$) [1]. When the capacitor is fully charged to $V_0$ and then briefly discharged, only the $C_\infty$ fraction is discharged. When left floating the remaining charge on C0 - C∞ will redistribute between the two capacitors and a voltage will re-appear at the terminals as shown in figure 2. This effect is internal to the dielectric of capacitor. It is not related to the wiring to the capacitor.

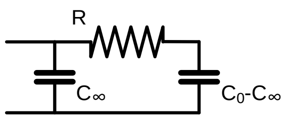



*Figure 1: Basic capacitor schematic showing the concept of dielectric absorption/relaxation lag [1]. The schematic shows an example with a single time constant, which is not representative for the real behaviour.*

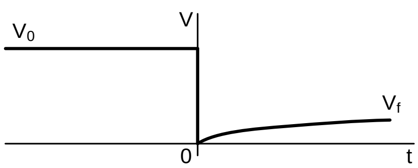
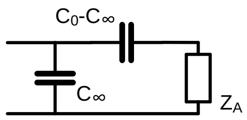



*Figure 2: Output voltage as a function of time for the schematic of figure 1 stressed to $V_0$, discharged and left floating.*

Lag due to absorption/relaxation of the dielectric does not have a single time constant. It rather has a "distributed time constant" which has small contributions at any time constant. This can be modelled by the Cole-Cole model [1,2]. This model shown in figure 3 needs only four parameters to describe the frequency behaviour of the capacitor. The impedance $Z_A$ can be approximated by the RC ladder network shown in figure 4




$$Z_A(s) = \frac{\tau_0}{(C_0 - C_\infty)(s\tau_0)^\alpha}$$

*Figure 3: Schematic of the Cole-Cole model. The impedance $Z_A(s)$ is defined by 4 parameters*

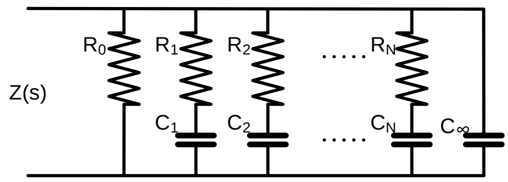



*Figure 4: The impedance $Z_A(s)$ of the Cole-Cole model can be approximated in a chosen frequency range by an RC ladder network. The network can be generated by the fracpole tool [1].*

### Capacitor characterization and model fitting

The four parameter model is fit on measurement data obtained from a capacitor used in an overflow pixel. Other structures could be used, but when the capacitor has a switchable reference voltage, an overflow pixel is well suited to characterize the lag with a voltage recovery method similar to [3, 4 and 5].

Figure 5 shows the schematic of the pixel and figure 7 shows the timing diagram for the lag measurement. The measurement consist of three phases: stressing the capacitor by applying a voltage, discharging it and finally letting it float. The charge that is absorbed during the stress phase will (partially) release again during the float phase. At the end of the float phase the released charge is read from the sensor.

The model is fit on the lag measurements for sweeps of the stress, discharge and float times. The model parameters are optimized such that for the same stimuli as in the measurement the simulation output fits the measurement data.

In each optimization step the RC network is re-generated based on the four updated parameters using the fracpole tool [1]. The lag response based on this RC network is simulated using Eldo and the cost function based on the difference between the simulation output and the measurement data is calculated in Matlab. The four model parameters are optimized by the Matlab "fminsearch" function to minimize this cost function.

Figure 6 shows an overlay of the measured data and the simulated data from the fitted model. The fit is remarkably good taking into account the model only has four parameters and the time scale for stress and float times are three orders of magnitude higher than the time scale for the discharge time. Table 1 shows the model parameters for the device that is used for the examples in this paper.

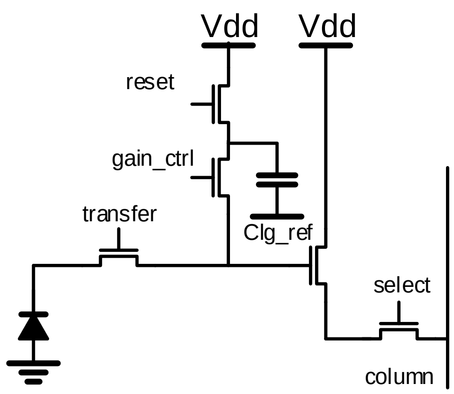



*Figure 5: Schematic of the overflow pixel used for the characterization of the dielectric absorption in the capacitor*

| | |
|---|---|
| $C_\infty$ | 100.0 fF |
| $C_0$ | 104.0 fF |
| $\tau_0$ | 16.5 µs |
| $\alpha$ | 0.84 |

*Table 1: Model parameters of the example capacitor normalized to 100 fF high frequency capacitance.*

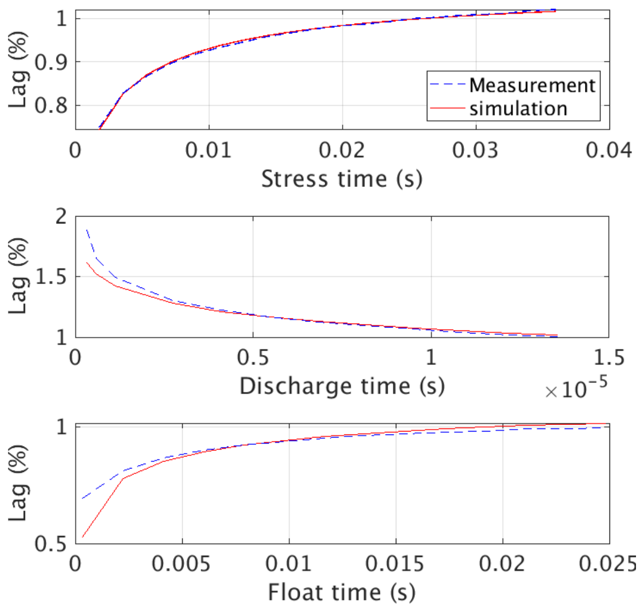



*Figure 6: Measured and simulated lag relative to the stress signal as a function of stress time, discharge time and float time with the two other parameters kept at their respective maximum value.*

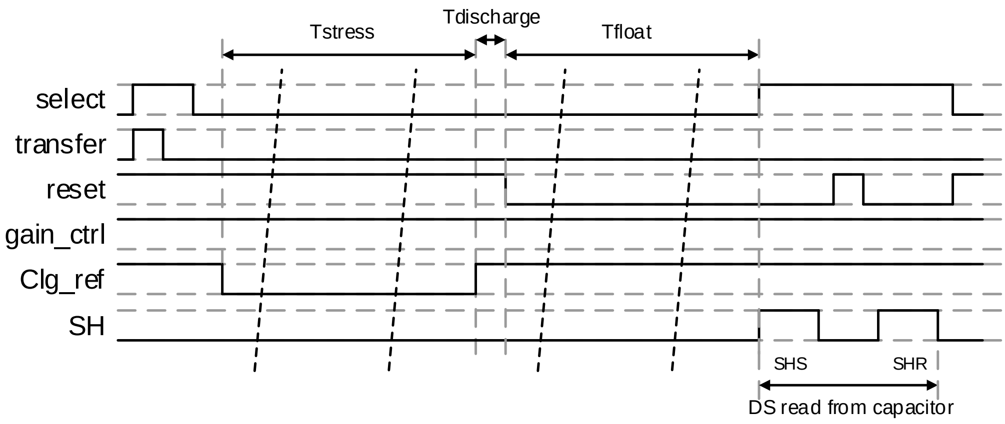



*Figure 7: Timing for characterizing dielectric absorption in the capacitor of an overflow pixel. During $T_{stress}$ voltage stress is applied to the capacitor and charge will be absorbed in the dielectric, during $T_{discharge}$ the capacitor is discharged and during $T_{float}$ the capacitor is left floating and signal will re-appear due to relaxation of the dielectric. Finally the signal is read from the capacitor in a double sampling read. The phases of the characterization timing can be mapped on the operation of an image sensor. E.g. $T_{stress}$ is the integration time of a first frame, $T_{discharge}$ is the non-integrating time between frames and $T_{float}$ is the integration time of a second frame.*

**Use cases**

This model allows simulating both transient and steady state effects. A typical transient effect is frame to frame lag where a bright area in one frame leaves a residue in a subsequent dark frame. An example of a steady state effect, hence an effect on a static scene, is gain variation with integration time. The lag simulations use the reduced schematic of the overflow pixel shown in figure 8.

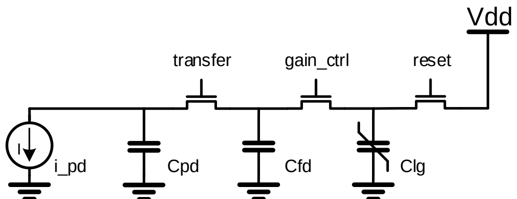



*Figure 8: Reduced schematic used for the lag simulations on an overflow pixel*

**Simulation of transient effects**

As an example of a transient effect figure 9 shows the simulated lag on the first frame after a single illuminated frame in a series of dark frames. The lag is low at short integration times where the reset time between frames is long, but it increases significantly when the integration time approaches the frame time. The same figure also shows measured data. The measurement is done by moving a pulsed LED in the field of view and comparing the measured lag level to the saturation level in the previous frame. An example image of this measurement is shown in figure 14 at the end of the paper. The LED strongly oversaturates the pixel so that maximum signal on the capacitor is reached almost instantaneous at the beginning of the integration time. This is the worst case condition. The fit between the simulation and the measurement is very good.

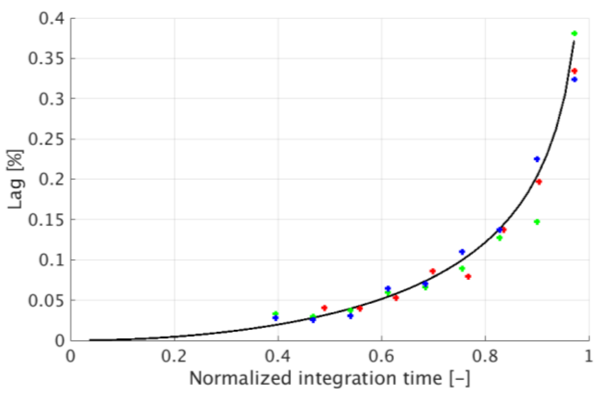



*Figure 9: Simulated (black curve) and measured lag as a function of integration time normalized to the frame time. The different marker colors represent data sets captured with different LED pulse times.*

For an overflow pixel the final HDR signal is a combination of the high gain photo diode read and the low gain overflow read [7]. Only the overflow read suffers from lag. Hence, the lag will only be present in the medium to high light signals. In practice this can be acceptable since the small lag signal will be superimposed on a much larger signal.

**Simulation of steady state effects**

Steady state effects are effects observed on a static scene. Figure 10 shows how each frame is influenced by the previous frames and influences the next frames. The balance between charge that is absorbed during the integration time and charge that is released during the reset time in between the integration times causes an integration time dependent gain variation.

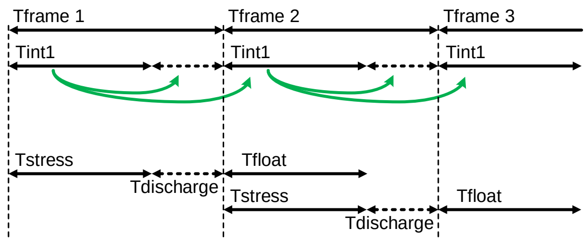



*Figure 10: Timing diagram showing the concept of a steady state effect. Each integration time is both a stress time for the next integration time and a float time accumulating lag due to the signal in the previous integration time.*

Figure 11 shows the simulated gain of an overflow read relative to the gain of low gain photo diode read (which is typically not used but serves as a reference here). At low integration times, there is little time for the charge to get absorbed in the dielectric and hence the gain is the highest. At medium integration time more charge is absorbed, but there is still plenty of time for the charge to get released in the reset time before the next integration time, hence the gain is lower. Finally, when the integration time approaches the frame time there is no time any more for the charge to get released between the frames and the gain increases again. The gain of the overflow read has to be known accurately to combine the reads correctly in the HDR signal. Even small gain errors will result in color artefacts.

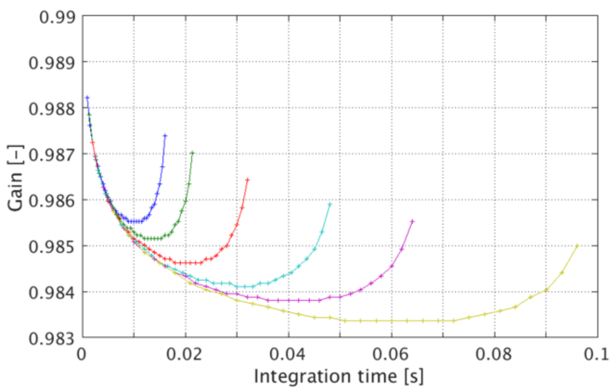



*Figure 11: Gain of the low gain overflow read relative to a low gain photo diode read as function of integration time with frame time as a parameter.*

### Application to Global shutter pixels

The example use cases shown above are for overflow rolling shutter pixels. The results are however also applicable to voltage domain global shutter pixels. In these pixels, the signal is read from the photo diode and stored on the capacitor at the end of the integration time. The signal remains on the capacitor until it is read out.

Figure 12 shows how for a global shutter pixel the storage time and the reset time vary with the y-location in the array. The lines that are read first have almost an entire frame of reset time until the next signal is stored. Those will have very little lag. The lines that are read last have far less reset time and may have a substantial amount of lag. So, lag is a strong function of y-location.

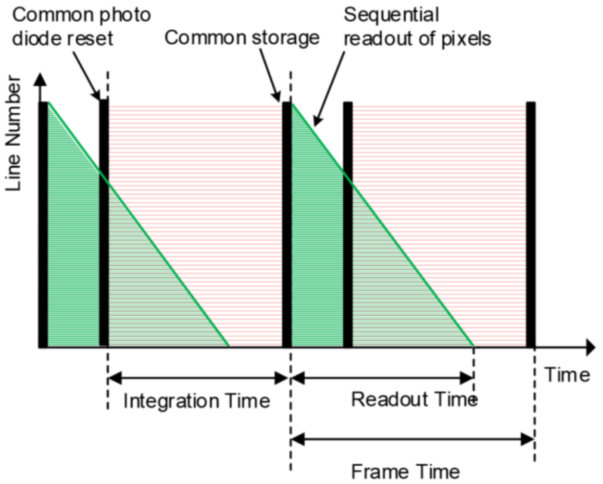



*Figure 12: Timing diagram for pipelined global shutter operation. The vertical axis indicates the y-location in the array. The green triangular region shows that the storage time for a pixel depends on its y-location*

One way to improve the lag performance of a voltage domain global shutter pixel is increasing its readout speed. When the readout is done in a fraction of the frame time then the storage capacitors of all pixels can be kept in reset for the remaining time. Figure 13 shows the lag for different readout speeds. These curves are stretching the curve of figure 9 in horizontal direction.

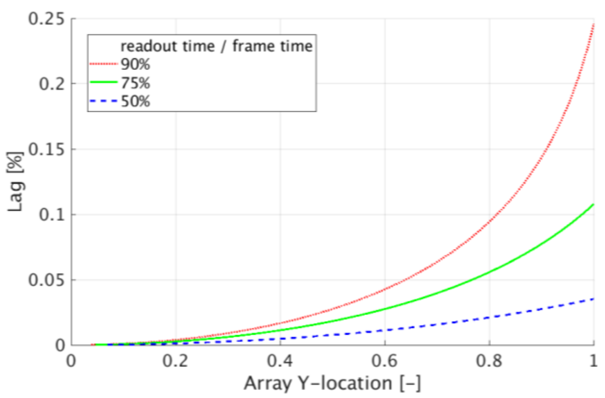



*Figure 13: Lag as a function of array y-location with the readout time normalized to the frame time as a parameter.*

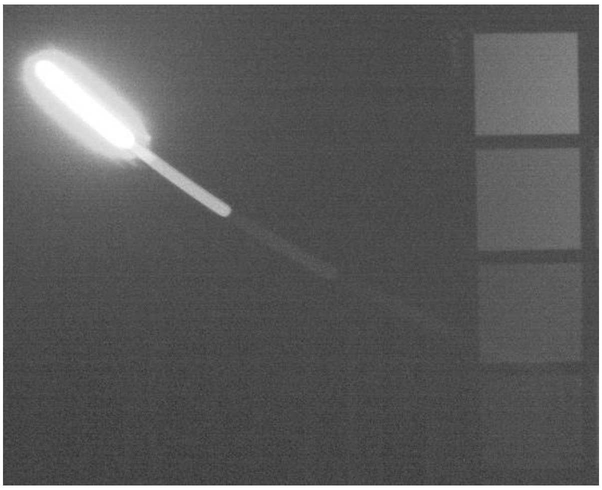


*Figure 14: Highly gained up image of a moving LED. It is taken in the worst case conditions without reset time between the frames. The tail is caused by is lag.*

### Conclusion

Dielectric absorption and relaxation are unfortunately a part of reality when using high density capacitors. This paper presents an approach to modelling, meassuring and simulating the effect. This is essential for understanding and mitigating it. This is one more tool to add to the designer's toolbox.

### Acknowledgment

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