# Transient Current Properties in Electronic Paper

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## Summary

### 1. Problem definition

*Electronic paper is a very promising solution in the search for low-power, paper like reflective displays. While the technology is already mature, little is known about the internal physical properties. A lot can be learned from current measurements in order to better understand the charge transport inside electronic paper.*

*The transient current curve resembles this of LCDs very much. There is a transient part where charges inside the pixel are moved from one side to the other. There is a steady state part where a constant current level is maintained due to generation and recombination. In LCDs the shape of the current curve is defined by the presence of ions inside the pixels. These ions negatively influence the optical properties of LCDs and their presence inside LCD pixels is therefore avoided as much as possible. Electronic paper is based on the movement of charged pigments inside a solvent. By applying the right voltage, the observer side of the pixel can be coated with coloured pigment. The ions in electronic paper are a side-effect of the charging of the pigments. Normally pigments are neutral macromolecules; surfactant is added to charge the pigments, which makes it possible to manipulate them in an electric field. This surfactant also induces free charge in the solvent. These charges (charged pigments and free charge) define the current.*

*Under normal conditions the current response to a voltage step decays in time. After application of the external voltage, charge is moved to the electrodes. As less and less charge is in motion inside the pixel, the current becomes smaller. However, under some conditions the current increases before decaying to its steady state value. This is measured when applying sufficiently high voltage steps, but never on application of the first step after a long period of short-circuiting the pixel. This is shown in fig. 1. This has also been measured in LCDs [1], yet without a definitive explanation. It is also measured in electronic paper.*

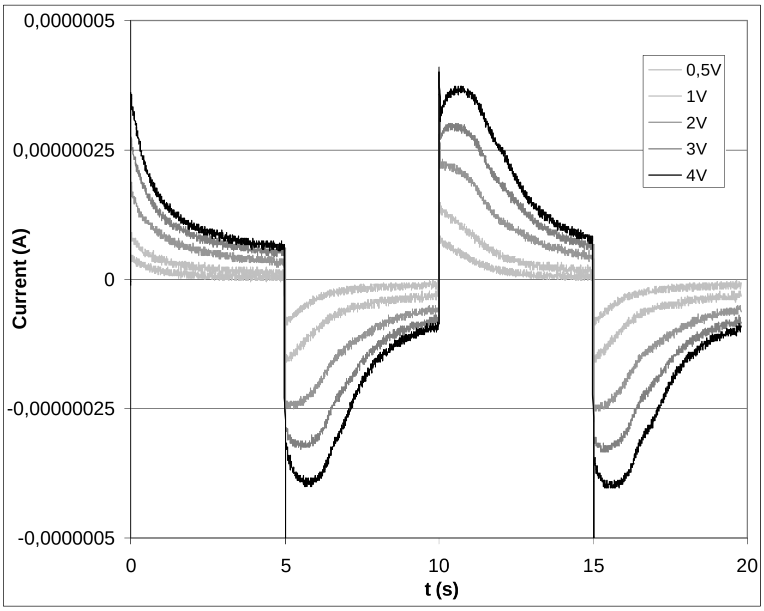


**Fig. 1.** Current response of electronic paper on application of a block wave, after short-circuiting the pixel for a long time.

*Its not clear why current bump occurs for high voltage or what its properties are, based on the applied voltage.*

*In this article we will give an explanation for the current bump, and explain its properties.*

## 2. Solution

*When a pixel is short-circuited for a long time, charges redistribute themselves uniformly inside the pixel due to Coulombic forces between them. When a voltage is applied, charges are accumulated near the electrodes and the current decays as more and more charges stop at the electrode. When the voltage sign is reversed, charges move to the other electrode: a current with an opposite sign flows. The surface under this current curve is an indication for the total amount of charge that is moved.*

*The charge movement can not easily be predicted from the amplitude of the applied voltage, since the charge itself also influences the internal field. The field induced by this charge is given by the Poisson equation:*

$$\nabla \mathrm{E} = \frac{r}{e}$$

*This is one of the reasons why contaminations by ions have to be minimized in LCDs: the optical properties become worse as the internal electric field is lowered by the field induced by the charges. The ions at the electrode shield the LC-molecules from the external field which negatively influences their polarizing properties. This shielding of the electric field will also help us understand why the current bump occurs.*

*When we start from a uniform charge distribution, the field shielding by the charge will not be very big, since the charge concentration is at the same low level throughout the pixel. All charges feel the same field –which is almost equal to the external field- and move with the same velocity towards the electrode: the current decays in time as more charges stop at the electrode.*

*However, when we start from a non-uniform situation where all charge is placed at one electrode (for example after application of a voltage step); the field-shielding can not be neglected. The charge concentration is very big at the electrode; this has a great influence on the field inside the pixel.*

*A bump in the current response means that there is a certain point when a maximum amount of charge is in motion inside the pixel. We now can see how this happens. After sufficiently long applying a high voltage, all charge is packed close together at the electrode: on application of an opposite external field, only a small force acts on the charges due to the field shielding. They slowly move away from the electrode and their distribution becomes bigger due to diffusion. This means that the field shielding becomes lower, the internal field becomes higher, charges move faster and the current increases. At a certain point, the first charges reach the opposite electrode and the current decreases to its steady state value. We have a maximum in the current curve.*

*This means that the occurrence of a current bump does not depend on the applied voltage, but on the charge distribution before application of this voltage. This means that the amplitude of the previous voltage determines the occurrence of a voltage bump: a high voltage packs the charges closely at the electrode, giving a high field shielding. A low voltage packs the charges more uniformly at the electrode, giving a small field shielding.*
*To check this, we measured the current response for different values of previously applied voltages. This is shown in fig.2.*

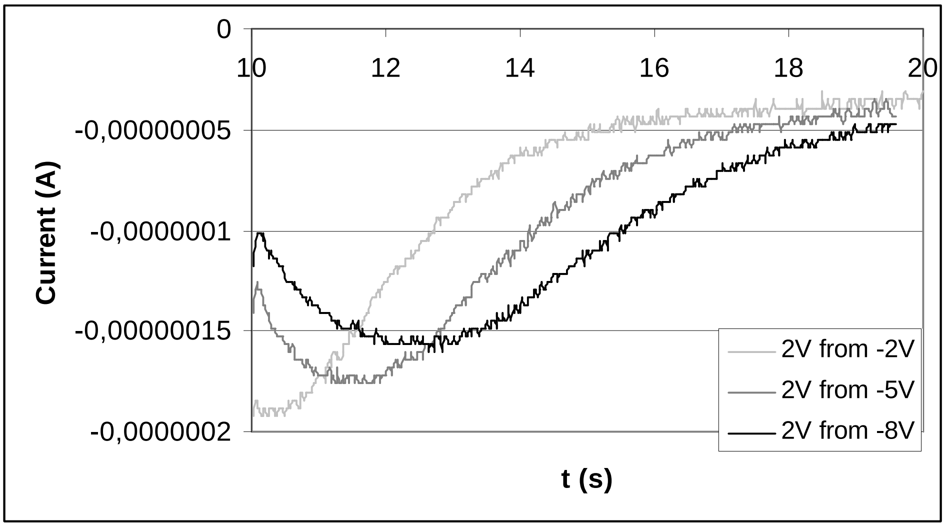


**Fig. 2.** Dependence of the current response (on application of a voltage step of 2V during 10s) on the voltage applied in the previous period.

*We see that for a transition from -2V to 2V no current bump occurs. However this current bump becomes visible as we increase the amplitude of the voltage in the previous step. We see that the higher the previously applied voltage is, the later the current bump is, the lower it is and the broader it is. This can all be explained by the theory of field shielding.*
*The higher the previously applied voltage is, the higher the field shielding is. Therefore, for higher voltages in the previous step, the charges come loose more slowly from the electrode: the peak of the current bump comes later and its value lies lower. The distribution due to diffusion is higher for more closely packed charges, therefore the current bump becomes broader as the configuration in the beginning is more closely packed.*
*The trend for the position of the current peak versus the applied voltage in the previous step is shown in fig.3.*

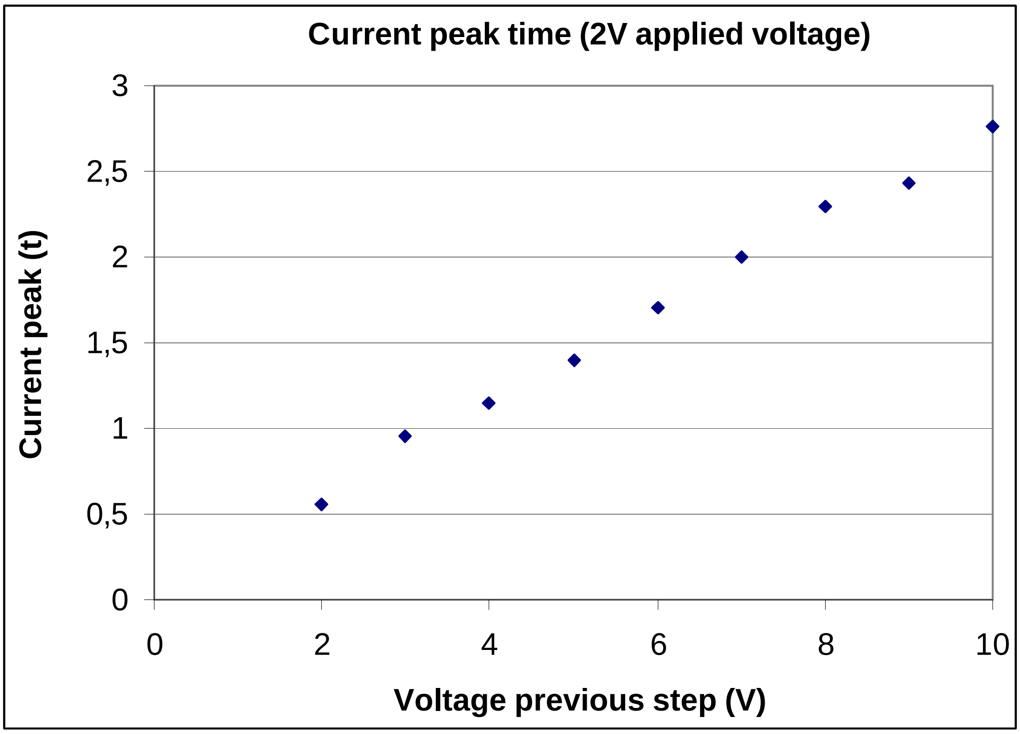


**Fig. 3.** Dependence of the current peak time (on application of a voltage step of 2V during 10s) on the voltage applied in the previous period.

*We see a lineair dependence of the position of the peak to the previously applied voltage*

## 3. Conclusion

*We managed to explain the occurrence of a bump in the current response of LCDs and electronic ink. The presence of this bump is not dependent on the value of the applied voltage, but on the voltage that was applied in the previous step.*
*We are currently incorporating this into a simulation program which will make it possible to predict the charge transport.*

## References

[1] C. Colpaert, Geleidingsprocessen in nematische vloeibare kristallen., Ph.D. Thesis, Ghent University, 1997.