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The microscopic physics of electronic paper revealed

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Abstract

For many years, it was thought that passive matrix addressing of electrophoretic image displays (EPIDs) was impossible due to the absence of a threshold. We proved that there are ways to bypass this [Proc. 22nd Int. Display Res. Conf. (2002) 251]. However, the physical basis was not fully understood. This article presents new insights in the physics of EPIDs. By applying the theory of dielectrophoresis (DEP), several discrepancies between theory and measurement, that occurred in explaining properties of EPIDs, are solved. We introduce a new terminology: DEPIDs. For the first time the theory of DEP is applied to model the movement of pigments in electronic paper.

Keyword : Electronic Paper Interface Device; Dielectrophoresis

1. Introduction

In the search for electronic paper, electrophoretic image displays (EPIDs) are a major contender. Colored pigments in a solvent move in response to an electric field, which is essential to their operation. Colloidal pigment solutions are prepared by dissolving pigments in a colored solvent and then squeezing the solution through a 125 mm-thick gap between two transparent electrodes. A voltage differential between the electrodes creates an electric field, which causes the pigments to migrate. The color of the pigment is reflected in the pixel when the field is applied in one direction. When an electric field is applied in the opposite direction, a colored solvent covers the ITO- electrode that is nearest to the viewer. If the solvent has a high enough light extinction coefficient, the pixel will take on the color of the solvent rather than the pigments on the adjacent electrode. It is possible to create a reflecting display that mimics the appearance of ink on paper by using pigments and solvent of contrasting colors. All the benefits of electronic paper may be enjoyed with these displays. After being drawn to an electrode, the pigments exhibit bistability. Because of this, a display's written picture may last for a long period without the need for constant voltage.

the electrodes, therefore it doesn't use any energy. They have better contrast in sunlight than other common display technologies (CRT, LCD). Since they are reflective displays giving off an ink-on-paper vibe, their screens retain their pristine picture quality even when placed in direct sunlight. Their compatibility with bendable substrates is promising. Nothing about the colloidal liquid, the sealing medium, or the ITO electrode coating prevents them from being made flexible. This not only makes EPIDs more durable, but also opens up possibilities for use in situations requiring flexible displays.

Passive matrix addressing of EPIDs has been regarded to be unachievable for a long time due to the lack of a threshold in the switching characteristics. When a non-zero electric field is supplied in the appropriate direction, the pigments within each pixel do really move. Since active matrix addressing in flexible big area applications is still in its infancy, this would make EPIDs less appealing for commercial deployment. When dealing with high-resolution screens, direct line addressing becomes too complicated. However, we demonstrated [2] that passive matrix addressing is achievable. A prototype screen costing £5 & $7 displayed the data.

The issue with the switching speed persisted. The ideal switching speed of each pixel was significantly reduced due to the characteristics of the switching method. Since there was also no way to see into the mechanics of EPIDs, a reasonable justification for the findings was not attainable. We designed a passive matrix addressing system that makes use of the display's other physical qualities despite the lack of a threshold in the switching properties. It was not clear where these characteristics came from. In this study, we examine a switching pixel's microscopic features and behavior. For the first time, a theoretical explanation is offered for hitherto mysterious characteristics.

1. Identifying the issue

1.1. There are differences between electrophoresis theory and the findings discovered from optical and electrical tests on screens.

2DisposalPhase

The amount of light that is reflected back to an observer decreases exponentially with increasing distance. I0 is the input intensity from the light source, an is the extinction coefficient of the medium, s is the scattering efficiency, and an is a geometrical factor that varies with the incidence angle of the light and the dielectric properties of the medium, so the formula is It14 NI se2aadvt. The accuracy of Hopper and Novotny's model relied on the inclusion of a removal time. After applying an electric field, the particles need some time to be swept away from the electrode. To represent the typical removal time distribution, they propose the following function, R t:! The observed lag between the introduction of an electric field and the onset of an optical response has no known explanation. screen's reaction [1,8]. As seen in Fig. 1, the optical response occurs after the external field has been applied. The optical response of a reflecting electrophoretic display was theoretically modeled by Hopper and Novotny [8]. For the pigment speed, they expect a normal distribution. The typical removal time for a particle is ta, and its standard deviation, ts: The expression for the intensity, and hence the optical response of a switching pixel, is obtained by replacing t in the formula n x; t by t 2 tremoval and combining this formula with those for I t and R t ;. amid the transition. The average velocity of the pigments is va, and the standard deviation is vs: This provides a typical distribution of pigment locations along This equation applies to colors that are advancing toward the viewer. Distance from the observer is calculated using the same formula.

The sum of all particles in the system is denoted by N.

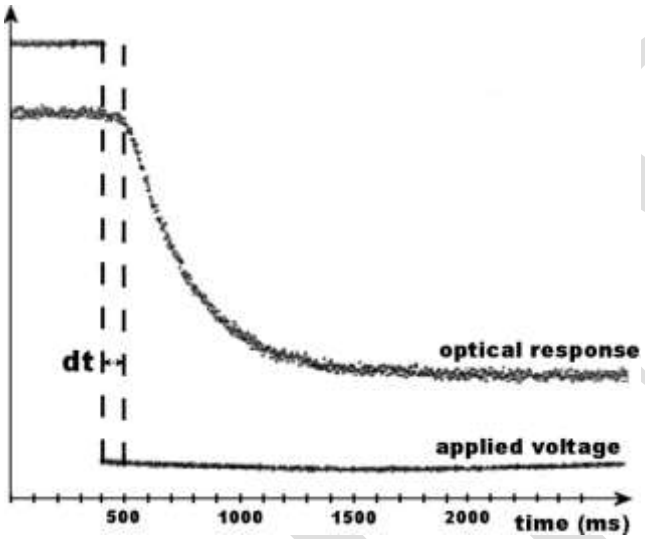


Fig. 1. Delay time between optical response and application of externalelectrical field.

This formula agrees with the findings of Ref. [1] and is more precise than the one established by Hopper and Novotny.

The physical basis for the removal time R t is beyond the comprehension of Hopper and Novotny. They think a shift in the image force is due to a reorganization of charge on the particle's surface. There is no definite justification provided.

No such lag period is expected according to electrophoresis theory. When an electric field is applied, colloidal particles—like the pigments in a pixel—that move according to the rules of electrophoresis react instantly. That's the first inconsistency between theory and application.

Inaccurate physics, section 1.2

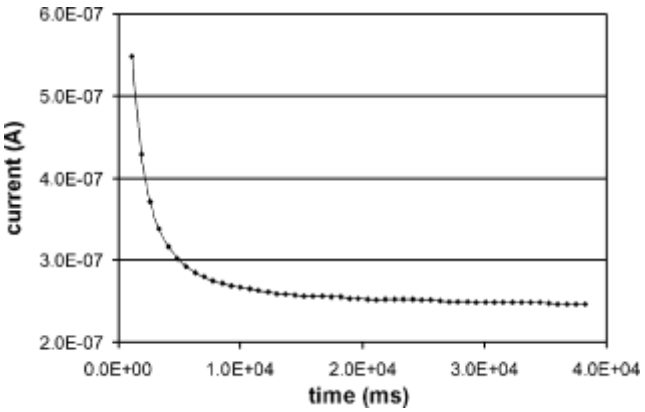
It requires unrealistic values for physical attributes to get a good fit between measurements and theory. Zeta-potential values over 1 V and charge on each pixel values above normal values are obtained by fitting the recorded speed and force to the rules of electrophoresis [6]. We employ the equations developed by Comiskey et al.

The formula for the Reynolds number is: rvr Re ¼ hDensity of the internal fluid, particle radius, viscosity of the internal fluid, and particle velocity are all denoted as r, r, h, and v, respectively. Our system uses the following values: r = 0.804 g/cm3, v = 100 mm/s, r = 0.4 mm, and h = 0.003875 kg/m/s. Density and viscosity numbers were taken straight from the product info sheet: For Isopar P. We were able to determine the fluid velocity by comparing the predictions of the Hopper and Novotny model [8] with the data from Ref. [1]. With a Reynolds number of 1.04E-5, we may confidently assume a laminar flow condition. flow.

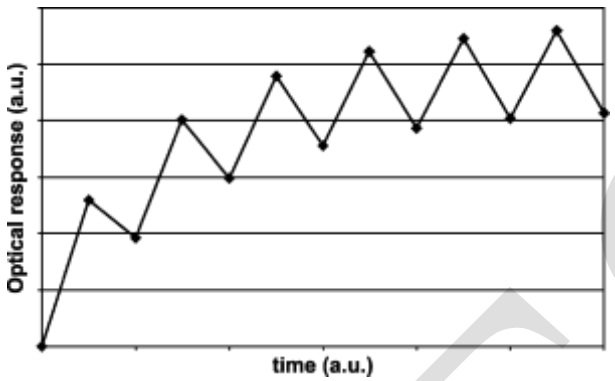
The formula for particle velocity in a laminar flow (in regime) is:

Fig. 3. Electric current in a pixel during switching.

proportional to the applied field. When the direction of the



To AC Fields, a Reaction of 1.2



It seems that applying a pure alternating current (AC) field causes an optical reaction, leading to a net force on the pigments that is not zero. Figure 2 displays the results of this measurement from Ref. Insufficiently low frequencies prevent this from happening. Since each cycle of the field exerts an absolutely opposing force on the pigments, an electrophoresis application would predict no net movement of the pigments. The theory of electrophoresis predicts zero net force when a square wave with zero DC value is delivered, even at higher frequencies (we tested up to around 20 Hz). A particle feels the force of an electric field instantly and with great intensity.

Fig. 2. Optical response when a pure AC voltage is applied.

likewise reverses course, but with the same amplitude as before. The particle may be returned to its original place by applying an opposing force for the same amount of time as the first half period. Therefore, applying a block wave with a zero DC value cannot result in a net movement of a particle, as postulated by the theory of electrophor- esis.

This final inconsistency proves that electrophoresis alone cannot account for the observed phenomena.

RC-model

During switching, we monitored the current and voltage between the electrodes of a £3 display. Figure 3 displays the obtained outcomes. The electrical response may be modeled by fitting a macroscopic RC-network to the measured data. The network shown in Fig. 4 performs well. Matching the model's parameters with the data results in a variation of less than 1% for the time-constant, steady-state current, and start-current. Comparing this to the mechanics of electrophoresis, one finds no explanation for the macroscopic model's capacitive component. No delay in electrophoresis can be attributed to any tiny physical component.

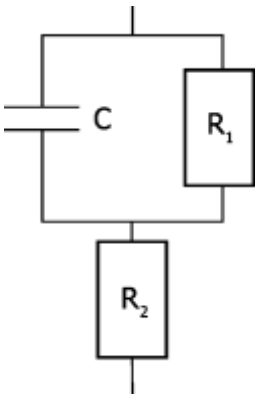


Fig. 4. Equivalent RC-network to fit the current measurements.

time as a capacitor stores energy. A particle's reaction to a field, as discussed above, occurs instantly. For a given capacitor load, the model predicts an exponential behavior where some property tends to an asymptotic end value over a finite amount of time. Hopper and Novotny [8] claim that ionization of charge control agent in the solution regulates the steady-state current. This likely explains why the steady-state current isn't zero, but it doesn't account for the capacitive behavior. If the ionization current behaved exponentially, the current would increase exponentially (instead of decreasing exponentially, as seen in Fig. 3), and the time constants would have different values. The time it takes for molecules to be ionized by an electric field is on the order of nanoseconds, which is almost a million times quicker than

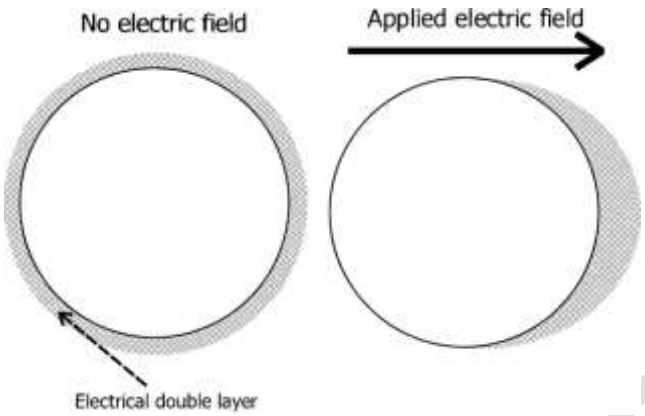


Fig. 5. Model of the polarization of a pigment and its counter ions in anelectrical field.

ddressing matrices passively (1.2)

lectrophoresis alone cannot account for the remarkable success of the tried-and-true passive matrix addressing approach [2]. No threshold was ever observed, and electrophoresis did not predict one, thus for a long time it was believed that passive matrix addressing was impossible. We demonstrated the viability of passive matrix addressing by distinguishing between the optical response to a voltage step and the response to an AC-signal with the same DC-value as the voltage step [2]. We discovered that the response time of a pigment was shorter for a DC-step than for a DC-signal with a non-zero DC-value. Using this idea, a passive matrix driving system was created by applying block waves to both the rows and columns. The proof of concept was shown using a £5/$7 prototype.

When pigments are dissolved in a medium with a permittivity of 1m, their radius, R, the real component of the Clausius-Mossotti factor, Re fCM, and the electric field gradient, E2, are all given in the formula. The existence of additional particles inside a pixel creates a gradient in the local field. Dielectrophoretic force between two adjacent particles due to electric field-induced dipole-dipole interactions was calculated by Wang et al. [12]. Our setup results in a homogeneous electric field between the electrodes. The field is locally non-uniform due to the existence of additional particles and the induced dipole moment in these particles. The gradient in E2 necessary to generate a dielectrophoretic force is supplied by this induced non-uniformity in the electric field. According to Wang et al., the force exerted on a pigment at location x; z by an electric field E in the z-direction due to the induced dipole of a particle at position (0,0) is:

$$\bar{F} \frac{1}{4} 2p1_m R^3 E^2 \eth 0{:}5 Re \eth f_{CM} \flat |f_{CM}|^2 7 \eth P^2 \flat Q^2 \flat 2 |f_{CM}|^2 7 P \flat$$

The Answers and the Outcomes

Dielectrophoresis (DEP) theory may explain all the inconsistencies between experimental data and electrophoretic theory.

An explanation of dielectrophoresis

1.2. Dielectrophoresis results from the interaction between the electric field and the induced dipole and describes the mobility of polarizable particles in a spatially non-uniform field [5]. In Fig. 5 [7], we see a model of the induced dipole that occurs when an external field acts upon a particle that is symmetrically surrounded by counter ions.

1.3. consist of spatial features.

1.4. Clausius-Mossotti (fCM) factor, R = pigment radius, 1m = permittivity of medium in which pigments are dissolved. When the electric field is measured in units of E, the force exerted is proportional to E2.

1.5. Modeled in Fig. 6 is the breakdown of an otherwise uniform external field into a locally irregular one.

True to life physics, version

All physical parameters may be accurately estimated by comparing dielectrophoretic theory with observations [9,12]. Using the

values obtained from the measurements

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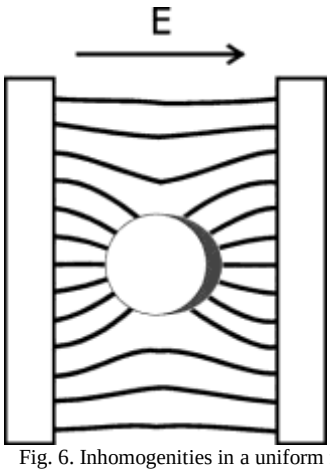


Fig. 6. Inhomogenities in a uniform field due to the presence of a pigment.

The formulae developed by Wang et al. [12] agree well with those found in Ref. [1]. Particle speed at location x; y in the non-uniform field created by a particle in (0,0) is seen in Fig. 7. The figures on the graph represent the velocity in microns per second on a log10 scale. Because of the spatial functions P x; z and Q x; z in the formulations from Wang et al., the velocity decreases rapidly as the distance between the particles increases. However, the velocities still have enough values to match the observations out to distances several times the particle's radius.

When it comes to practical values for physical attributes, DEP more closely matches theory than electrophoresis does. The correct numbers for force and, by extension, the velocity of the pigments, may be obtained by plugging in the physical parameters of our display material into the formulae for dielectrophoretic force.

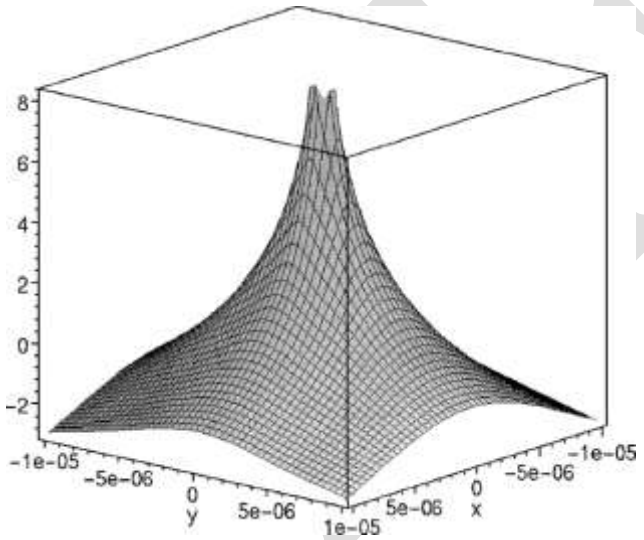


Fig. 7. Velocity of pigment in position ðx; yÞ due to non-uniformity in the electric field induced by a pigment in (0,0). The plotted values are $\log_{10}$ ofthe velocity in micron per second.

1.6 Time Lag Explanation

1.6. DEP explains why there is a lag in the switching characteristics. The time constant required to create a dipole from a stationary particle is given by Schwarz's formula [9,10].

1.7. In other words, R2e t = 2mkT

1.8. Surface mobility of counter ions is a function of temperature (T), Boltzman constant (k), and pigment radius (R). In an electric field, a particle's polarization and, by extension, its dipole moment, increase exponentially to an asymptotic value, as determined by Hu and Chen's derivation in Ref. [9]. Schwarz's formula determines the time constant for this change. We can only make an educated guess based on the recorded values of the time constant as to the surface mobility of the counter ions surrounding the pigments. This achieves results that are commensurate with surface mobilities in other systems, which is to say, satisfactorily.

1.9. The delay seen in the switching characteristics may be explained by the fact that inducing the dipoles takes a limited amount

of time. Without an external electric field, the counter ions around each pigment are evenly dispersed. Particles do not immediately move in response to an applied electric field because it takes some time for the dipoles responsible for inducing electric field non-uniformity to develop. Schwarz's formula specifies a time constant t during which the pigments undergo polarization. With the same time-constant, the dielectrophoretic force approaches its steady-state value. Because of this, the optical response to an applied electric field must be modeled using a removal time, as Hopper and Novotny accomplished in Ref. [8]. They reasoned that the elapsed time was due to a change in the distribution of charge on the particle's surface. Particle polarization is a redistribution of the surface charge, hence they were correct. However, the removal time is based not on the mirror charge of this redistributed charge but on the limited time required to redistribute this charge and create a dipole. This dipole can only move after it is generated, since the other dipoles induce a non-uniform field.

1.10. Once again, DEP theory is put to good use, this time to shed light on the phenomena of the delay time.

1.11 **Changes in the AC field's net motion**

1.11. When DEP is applied to EPIDs, we can see why there is a net pigment-movement at high frequencies, even when a pure AC signal is used. Fig. 2 depicts this in a model form. It seems that the dipole is not induced if the duration of the applied field is less than the delay time required to do so.

1.12. fails to 'follow' the playing field. The time constant required to create a dipole around a pigment in an electric field is given by Schwarz's formula. This time constant provides a rough estimate of how long a field must be applied to produce a dipole in a certain direction. A net dipole-moment and, thus, a net force in one direction will arise if the switching speed of the external field is faster than the maximal switching speed of the dipole. The following is what happens to a stationary pigment when an electric field is applied (let's assume at t 0) with a period T=2 less than the time-constant from Schwarz's formula: During time T=2, the dipole will not have progressed to its asymptotic value prior to the reversal of the field. The dipole creation in the opposite direction of the field is initiated. Instead of a symmetrical rest phase (as at t = 0), a partly generated dipole in the opposite direction is the starting point this time around. Therefore, the dipole will not only be partly created when the field reverses direction at time t T, but the dipole moment will also be less than it was at time t T=2: This is because the initial state at time zero is symmetrical, and the state at time T=2 is induced in the other way. The dipole moment will have a net value other than zero after being subjected to such a block wave for several times. In light of this, a

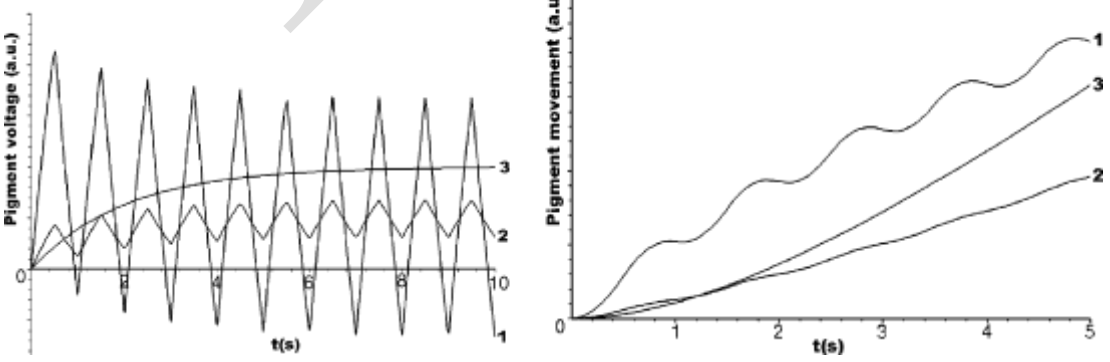
1.13. 1.1. RC-model

The microscopic dielectrophoretic theory may be reconciled with a macroscopic RC-model. Creating a dipole by polarizing the pigment has the same effects as loading a capacitor [4,11]. The present observations in Fig. 3 can be reproduced using a basic RC-network. The polarization of the pigments is compared by Ramos et al. [11] to the charging of a capacitor. It is also physically clear that the exponential development of a polarized pigment to its asymptotic end state is analogous to the exponential charging of a capacitor with a non-zero resistance. The distribution of charges in both scenarios tends to flatten out dramatically. Figure 4 depicts the macroscopic RC-model used to suit the present-day observations.

In this case, we treat the pigment as a capacitor and the solvent around it as a combination of series and parallel resistors. In reality, one must join a huge number of these RC-networks in series and parallel in order to simulate one whole pixel. Since this has no effect on the basic switching shape, this basic model is enough. The model can only be true if the amount of current flowing through this network corresponds to the amount of current read from the screen. Current across the network changes as seen in Fig. 4 when a voltage step V is applied. net motion, despite the fact that the average applied field strength is zero.

1.14 **Passive addressing matrices**

The most crucial outcome is that dielectrophoretic theory can now be used to justify the efficiency of the passive matrix addressing technique. Think about the RC-model on a huge scale once again. The force exerted on a pigment and its resulting velocity may be approximated by calculating the voltage across the capacitor when a voltage is applied across the whole network. Applying a voltage step of V



over the whole

network yields the voltage across the capacitor as shown below..

Each pigment's force is proportional to the voltage it experiences in the macroscopic model. For simplicity, let's assume that the frictional force exerted on a moving pigment is directly proportional to the pigment's speed. As a result, not only can force but also velocity be modeled using the aforementioned RC-network. A pigment's motion along the applied field's axis may be calculated by integrating this velocity over time.

The conclusions from the preceding paragraph are confirmed when the voltages from the passive matrix addressing technique are applied to the macroscopic RC-model. The data in Fig.

pressures exerted on a pigment when subjected to a 20 V/218 V AC square wave voltage (curve 1), 4 V/22 V AC square wave voltage (curve 2), and a voltage step of 2 V. The result of applying these fields (integration of Fig. 9a) is shown in Fig. 9b. The square wave's period was set to be less than the RC-model's time constant t. This verifies the findings of Ref. [2]: Both DC values of the square waves are the identical, yet the responses they elicit are distinct. The magnitude of the AC component is also a factor. Since the effects upon which the addressing system is built only occur at sufficiently high frequencies, namely those above the one specified by 1=t, frequency also plays a role.

1.**14 Relaxation of the Optical Response**

After a pixel has been switched on and the applied voltage withdrawn, the optical response decreases somewhat. Once the voltage is removed, the optical response relaxes even if it was provided long enough to ensure that all pigments were deposited on the electrode surface. This is supported by dielectrophoretic theory. When an external field is applied, it induces dipoles that are in phase with one another and hence attract one another. Attractive forces are experienced along the dipole's axis, while repulsive forces are experienced perpendicular to the axis. As a result, the dipoles form an orderly configuration.

close together in rows or columns along the direction of the force. When this field is no longer there, the polarization of the pigments and the force that draws them together vanish as well. Because each pigment is surrounded by an electrical double layer, the pigments rearrange themselves into a symmetrical configuration. As a result, the packing density at the electrode surface relaxes as the distance between the pigments grows. This reduces the optical response, as predicted by Hopper and Novotny's hypothesis [8].

1.14. **Results**

1.15. Figure 10 is a snapshot of a prototype display from the £5/7 project taken while it was switching. Passive matrix addressing, as described in Ref. [2], was used to address the screen.

1.15. Each pixel was around 1 square centimeter in area. Since voltages as high as 28 V were needed, a high voltage driver was used to address the seven rows and five columns. The 127 mm thick spacer was used to separate the two ITO-coated glass slabs.

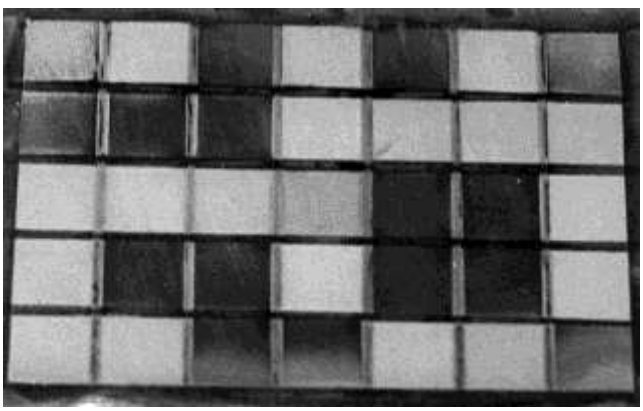


Fig. 10. Photograph of a 5 £ 7 display during passive matrix switching.

There is noticeable visual deterioration on the display's edges. The issue stems from faulty display sealing.

Discussion

Of course, a better insight in the microscopic physics does not solve all problems. The switching speed, which is an important parameter for successful passive matrix addressing remains a drawback. Moving images on an

electronic paper will not be seen in the near future. One can attempt to solve it as an electronical problem, by creating new addressing methods which use new wave forms or higher voltages. Alternatively, we can try handling it as aphysical problem by using smaller spacer to reduce thepigment travel distance. Specially shaped areas in which the pigments are placed, can help to improve properties. Dealing with the problem as purely a chemical one bycreating fast and stable pigments and solutions might help.

2. Conclusion

In this study, we share recent discoveries on the physics on the inside of EPIDs. Several gaps between theory and practice may be bridged by using DEP theory. The theory and characteristics of DEP are being applied to electronic paper for the first time. Dielectrophoretic image displays (DEPIDs) have been brought up as a topic that needs to be discussed.

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