

# Neutral nanoparticle-based display

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## Abstract

We present a novel display based on the manipulation of neutral nanoparticles dispersed in an insulating liquid. The operative mechanism is based on dielectric forces and electric field-induced dipolar interactions between neutral nanoparticles, leading to compact aggregates that change the optical characteristics. Such displays can operate either in a diffusive scattering mode or in a written mode, both based on the capacity to have a compact particle storage mode. Owing to the hysteretic behaviour, low-power operation is obtained.

## 1. Introduction

The search for a low-cost electronic, passive, paper look-alike display has been ongoing for more than 30 years. Most efforts in this direction have been devoted to electrophoretic (EP-) effect-based displays, in which charged particles manipulated through electrostatic force can lead to locally altered reflectivity on a transparent sheet, behind which reflecting or absorbing materials can act as the back-plane [1–3]. It has been demonstrated that such displays can be fabricated as a paper-like sheet on flexible polymer substrates [2]. In this paper, we introduce a novel display concept which relies on the use of neutral nanoparticles in either a compact storage display mode or a diffusive scattering mode, with hysteretic effect stabilizing either mode in the absence of applied electrical power. The displacement and aggregation of the particles are based on dielectrophoretic (DEP) forces [4] and induced dipolar interactions, of the same nature as those usually leading to the electrorheological (ER) effect [5–7]. We thus denote such displays as ER displays (ERDPs).

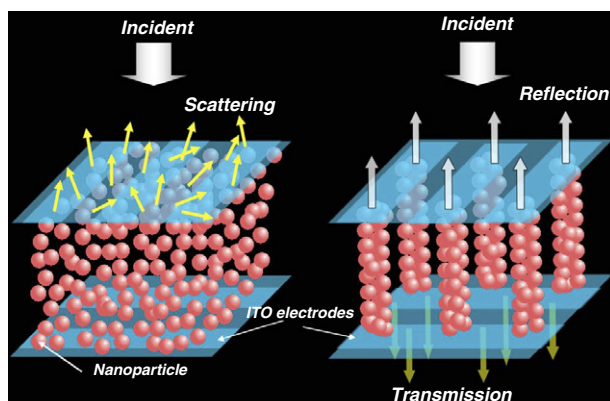
Figure 1 illustrates the mechanism of ERDPs. In the absence of an external electric field, figure 1(a) shows schematically a suspension of nanoparticles sandwiched between crossed top–bottom stripe-shaped ITO electrodes with 0.1 mm gap. The particles are dispersed randomly in the liquid, and no contrast stems from the display panel due to the random, diffusive backscattering of light. This is the diffusive scattering mode. When an electric field is applied between the crossed top–bottom electrodes, figure 1(b) shows the formation of

compact structures at the crossing locations. While the aligned columnar structures between the top and bottom electrodes block the light so that only reflection occurs, other locations are mostly transparent, allowing light transmission. Contrast can thus be generated between regions with electric field and without electric field. Due to the fact that the particles are ‘stored’ in the columnar structures which display the written information, this mode is denoted the storage mode display.

The underlying physical mechanism of columnar structure formation is the particle–particle interaction under an external electric field, in which the dielectric particles suspended in the liquid acquire induced dipole moments, leading to dipole–dipole interaction force  $f_{d-d}$  between two particles separated by a distance  $r$  expressible as

$$f_{d-d} = \frac{6p^2}{4\pi\epsilon_0\epsilon_f r^4}, \quad (1)$$

where  $p = 4\pi\epsilon_0 a^3 \epsilon_f \beta E$  denotes the induced dipole moment,  $E$  is the external field strength,  $\epsilon$  denotes the dielectric constant,  $a$  the particle radius, and  $\beta = (\epsilon_p - \epsilon_f)/(\epsilon_p + 2\epsilon_f)$  represents the mismatch factor of permittivity between solid and liquid phases, where the subscripts p and f indicate the particle and fluid, respectively. The particles would tend towards the lowest energy configuration, i.e., would first form chains and then the columns when the field strength increases. This structure formation process has been confirmed both experimentally and theoretically during the past decades [8–10]. The imposition of an external field would thus change a homogenous suspension to an inhomogeneous system with



**Figure 1.** Schematic illustration of the mechanism for the storage mode display: left and right panels show the cases without and with applied electric field, respectively.

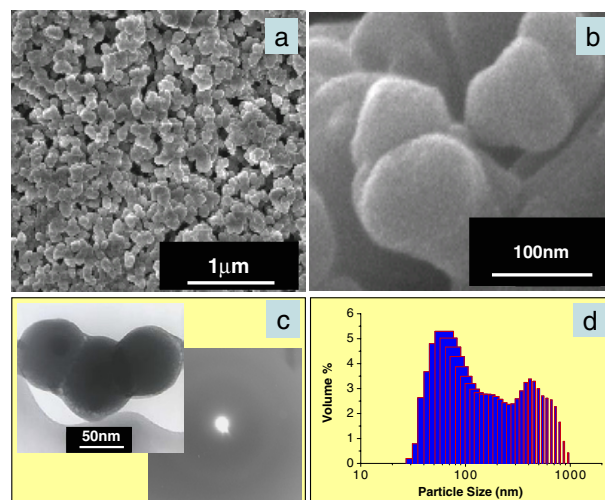
aligned columns, in which the particles are removed from the path of light in a given region of space and stored in another, thus achieving optical contrast. Long retention time of at least a few hours in the storage mode was observed after turning off the electric fields, implying a high degree of stability. Hence these types of displays have the potential for ultralow power consumption.

A potential drawback of the ER displays is the required high voltages for their operation. However, the recent discovery of coated nanoparticles with the giant ER effect has overcome this difficulty by allowing for efficient operation under low voltages [11]. Below we give a brief description of this crucial material aspect of the display.

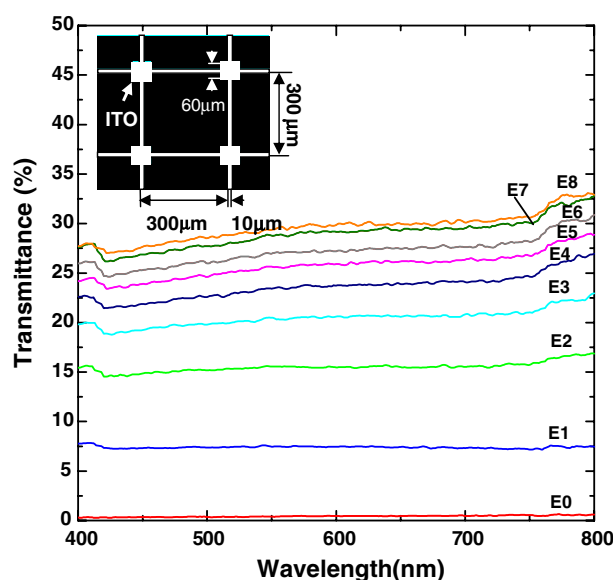
## 2. Nanoparticle fabrications

The nanoparticles used in our experiment have a core/shell structure with a hard core coated with a relatively soft shell, wherein the hard core is made of inorganic materials of  $\text{BaTiO}(\text{C}_2\text{O}_4)_2$  and the shell is made of organic materials such as urea [11]. The nanoparticles were fabricated by first dissolving barium chloride in distilled water at 50–70 °C. Separately, oxalic acid was dissolved in water at 65 °C in an ultrasonic tank, with titanium tetrachloride slowly added. The two solutions were mixed in an ultrasonic bath at 65–80 °C. Nanosized barium titanium oxalato particles were formed after drying. Figure 2(a) shows SEM images of clusters of nanoparticles, and enlarged images for individual nanoparticles can be seen in figure 2(b), where we can observe that the average size of nanoparticles is about 50 nm which was also confirmed by both TEM images and particle size analyser (Coulter LS230), seen in figures 2(c) and (d). A TEM image showed (see figure 2(c)) the barium titanium oxalato nanoparticles to have amorphous structures, consistent with the results obtained by XRD experiments.

The nanoparticle-based suspension was made by mixing the solid powder with silicone oil to form a milk-like colloid with viscosity around 10 mP s at zero electric field. The suspension was injected into a display cell formed with two top and bottom ITO stripe electrodes cross-aligned, seen in the inset to figure 3. The optical transmittance at different field strengths was determined by a UV-vis (ultraviolet-visible)



**Figure 2.** Nanoparticles and their characterization. A SEM picture of nanoparticle clusters is shown in (a), and an enlarged image showing individual nanoparticles is shown in (b). (c) is a TEM image showing the amorphous structure of the nanoparticles, and the nanoparticle size distribution is shown in (d). Most nanoparticles are in the range of 50–70 nm.

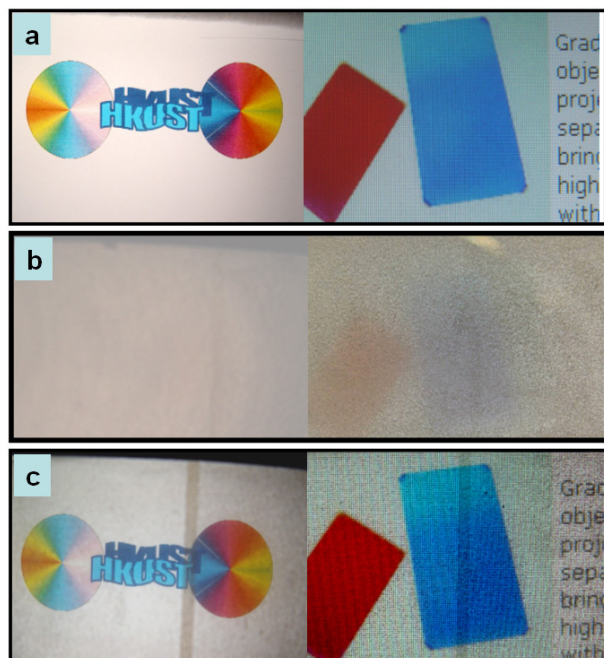


**Figure 3.** Measured optical transmittances of the display panel plotted as a function of wavelength under different applied electric fields. Here E0, E1, E2 etc denote 25, 50, 75, 100, 125, 150, 175 and 200  $\text{V cm}^{-1}$ , respectively.

spectrophotometer (Shimadzu) with a wavelength range of 200–900 nm.

## 3. Experiments and results

The results can be seen in figure 3, where we observe that at zero field no transmission of visible light could be detected. With increasing electric field, the optical transmittance increases accordingly and eventually saturates at ~30% (normalized with the free path). Such electric-field-induced transmittance is clearly observable, as seen in figure 4; where figure 4(a) are the original images, without the

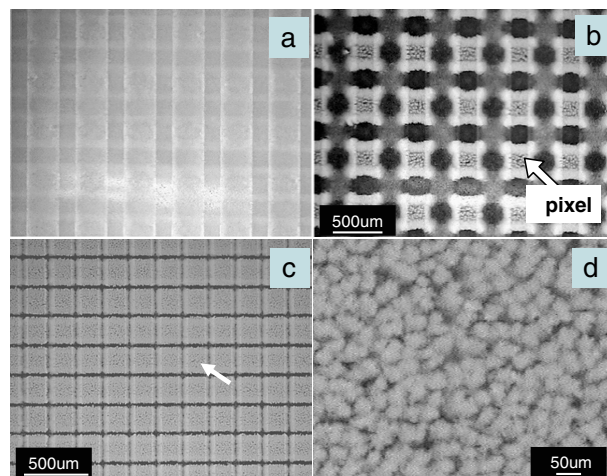


**Figure 4.** Images viewed through the display panel. The original pictures are shown in (a). When viewed through the display panel, (b) and (c) show the images taken without and with electric field applied to the display panel, respectively.

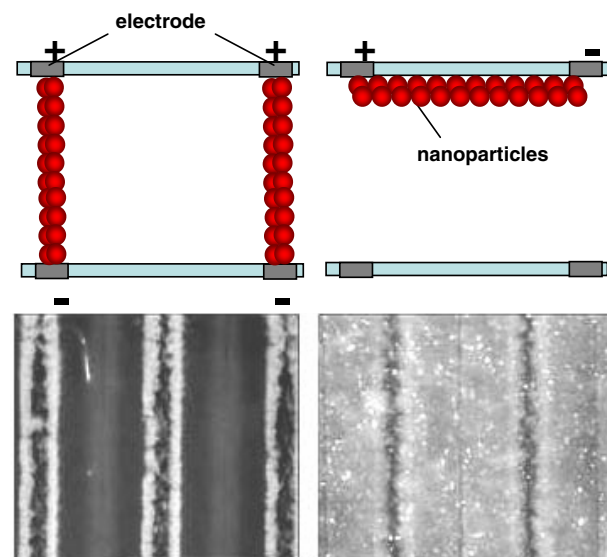
display panel, while figure 4(b) shows the images observed through the display panel when there is no electric field applied (nanoparticles are randomly dispersed). When the electric field was applied, the panel changed from opaque to transparent and the images became clearly visible as shown in figure 4(c).

Figure 5 shows fine-resolution pictures of the nanoparticle-based panel display. In the absence of electric field, the nanoparticles were randomly dispersed in the liquid, as shown in figure 5(a). When 5 V was applied (across the 0.1 mm gap, so the electric field is  $\sim 500 \text{ V cm}^{-1}$ ), the particles were observed to aggregate and to form fibrous structures between the two electrodes. The chain-like structures would merge to form columns if the applied voltage was further increased to 50 V, leading to visible pixels (white regions) as seen in figure 5(b). Physically, the optical contrast is attributed to random light scattering by the aggregated nanoparticles in the regions where there is electric field in the crossing 'points' of the top and bottom electrodes, leading to increased reflection, while in the surrounding areas where there are few particles the cell is nearly transparent and would thus appear dark due to the reduced reflection. Thus our display is based on a different physical mechanism than that for twist LCDs, which relies on optical birefringence of the LC molecules. Figure 5(c) shows a different design of the display screen where the pixels are spaced much more closely. A closer examination of the region indicated by an arrow in 5(c) is shown in figure 5(d), where we note that the ends of the aligned columns formed from aggregated particles are clearly visible through the ITO electrodes. Optical contrast may be improved through further optimization of particle properties and concentrations.

Figure 6 illustrates another way of displaying information, denoted the written mode display. The top panels show schematically the two ways of organizing the particles: one



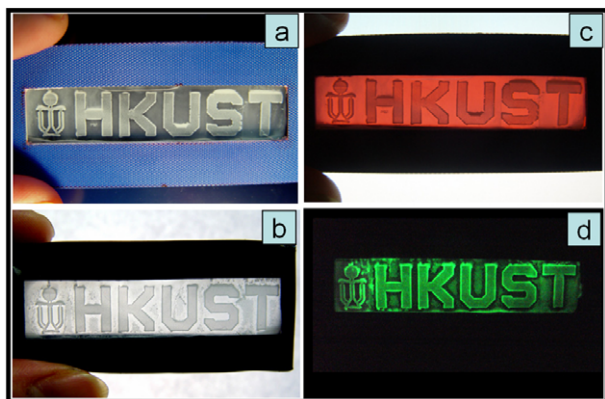
**Figure 5.** Fine-resolution pictures of the display panel. In (a), no electric field is applied, and the ITO crossed grid pattern is dimly visible. In (b), electric field is applied across the top and bottom electrodes. The bright spots (pixels) are the crossing 'points' of top and bottom electrodes where the applied electric field induces the formation of columnar structures, leading to enhanced reflection. A different ITO grid pattern is shown in (c), where the separation between the pixels is reduced from that shown in (b). An enlarged picture of a pixel, pointed to by an arrow in (c), is shown in (d), wherein the ends of the columnar structures are clearly visible.



**Figure 6.** Schematics of a different 'writing' mode of the display panel, the 'written' mode display, formed by different configurations of the electric fields. Left panels show the schematic and actual picture of the 'storage' mode formed by a vertical electric field and their induced columnar structures. Right panels show the schematic and actual picture of the 'write' mode formed by a planar electric field and their induced columnar structures parallel to the electrode surface.

with the columnar particle structures perpendicular to the electrodes, and another with the columnar structures parallel to the surface, in between the parallel top electrodes. Details of this writing mode depend on electrodes' positions and shapes (which affect the vertical and/or in-plane electric fields), the field strength and their relative signs, plus the particle properties and concentration. With this horizontal writing





**Figure 7.** Display panels formed with different backgrounds are shown in (a)–(c). In (d), the display was formed with the addition of luminous powder to the suspension. The picture was taken in a dark room.

mode, we have also observed that, once written, patterns remained stable for at least several hours after the supply voltage was turned off.

Figure 7 presents some images using a nanoparticle-based colloid. Figure 7(a) shows the reflection mode display, wherein the background is dark so that the reflection enhancement of columns between the two electrodes delineates the letters ‘HKUST’. The width of the thinnest line in the logo is  $30\ \mu\text{m}$ , clearly visible. In figures 7(b) and (c), the backgrounds are white and red light, respectively. We have also tried displays with luminescent property, tested in a dark room by mixing some luminous powder with nanoparticles. We see that the ‘HKUST’ pattern is clearly visible (figure 7(d)) when the light is switched off. In this case, the sustaining time of the image varied depending on the concentration of luminous powder in the suspension.

The major issue in such neutral particle based displays is the classic tendency of particles to agglomerate together irreversibly, i.e. the flocculation effect. This can lead to unwanted irreversibility of writing, the only way to refresh the display once it is in the display storage mode requiring the use of either ultrasound or micromechanical pumping. To obtain multiple writing and erasing sequences by voltage manipulations only, one requires to treat the particles with the usual anti-flocculation recipes [12], such as coating agents like stearic acid DEDMS. Particles can then be driven away from their metastable positions by applying the right voltage sequences between electrodes: it is thus possible to switch

back and forth between the two modes shown in figure 6 in a fraction of a second.

A specific advantage of ERDP relies on the variation of the sign of the dielectrophoretic [4] forces with particle dielectric constants and driving electric field frequency. Using particles with different dielectric constants and colours, one can manipulate particles separately, and thus operate a multiple-colour-per-pixel display.

#### 4. Conclusion

In conclusion, we present a novel storage mode display using a neutral nanoparticle suspension. The physical mechanism is based on particle aggregation due to induced dipole–dipole interaction under an external electric field. By using such a technique we have made the first step towards the realization of a cheap and easy-to-fabricate bistable display. By further optimization of the particles, we should be able to operate such displays at low voltages, have better optical aspects and also have colour capacity.

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#### References

- [1] Comiskey B, Albert J D, Yoshizawa H and Jacobson J 1998 *Nature* **394** 253–5
- [2] Rogers J *et al* 2001 *Proc. Natl Acad. Sci.* **48** 48357
- [3] Terry A 2001 *Library Hi Tech* vol 19 (England: Emerald Group Publishing Ltd) p 376
- [4] Green N G and Morgan H 1998 *J. Phys. D: Appl. Phys.* **31** L25
- [5] Davis L C 1992 *Appl. Phys. Lett.* **60** 319
- [6] Wen W, Wang N, Ma H, Lin Z, Tam W Y, Chan C T and Sheng P 1999 *Phys. Rev. Lett.* **82** 4248
- [7] Dassanayake U, Fraden S and van Blaaderen A 2000 *J. Chem. Phys.* **112** 3851
- [8] Chen Y, Sprecher A F and Conrad H 1992 *J. Appl. Phys.* **70** 6796
- [9] Klingenberg D J, Zukoski C F and Hill J C 1993 *J. Appl. Phys.* **73** 4644
- [10] Gulley G L and Tao R 1997 *Phys. Rev. E* **56** 4328
- [11] Wen W, Huang X, Yang S, Lu K and Sheng P 2003 *Nat. Mater.* **2** 727
- [12] See e.g. Morrison I D and Ross S 2002 *Colloidal Dispersions: Suspensions, Emulsions and Foams* (New York: Wiley)