Monolayer Rotating Ball Electronic Paper Display

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Abstract

Optically anisotropic rotating balls were disposed in a monolayer, and controllably closely packed with respect to one another in the monolayer. The close packed monolayer configuration provided high brightness and improved contrast. The monolayer rotating ball display (MRB) electrically demonstrated a fast response time of approximately 40 msec at a voltage of 30 V. Measurements of the rotation as a function of voltage led to surface charge density for the balls in the range of 3-4 μC /m^2.

1. Introduction

'Electronic paper (EP)', which possesses many advantages of paper, is a name given to a novel class of display being thin, lightweight, flexible, and recordable with minimal power consumption. Among various types of EP, an electrically anisotropic rotating ball (RB) display is one promising candidate [1-2].

Fig. 1(a) illustrates a schematic of typical RB display. It is composed of balls with black and white hemispheres that are immersed in individual liquid-filled cavities. The balls rotate in response to the applied voltage on the electrodes, displaying either black or white with respect to the polarity of the voltage. Typical gyricon displays are 500-700 μm thick and have switching voltages ranging from 100 to 150 V. Switching times are 300-500 ms. Lower-voltage operation can be achieved for thinner devices, however, a reduction in thickness results in poorer contrast due to sparsely dispersed ball configuration. In comparison with the gyricon display, in Fig. 1(b), a schematic of monolayer rotating ball (MRB) display investigated for this study is shown. Of particular note is that the balls are controllably disposed in a monolayer. Since the distance between the top and bottom electrode for the MRB is apparently closer than that for the typical RB display, this MRB approach can allow to achieve relatively lower voltage and faster response times.

This study demonstrates the newly developed MRB display, and conducts characterizations of the MRB display for improvement of performance, with particular emphasis on the response time as a function of the electric field.

2. Experimental

A substrate with a bottom electrode formed was patterned prior to allocating the balls onto the substrate. Prior to patterning the substrate, a commercially available Novolac type epoxy-based resin (GX-13, Ajinomoto) was laminated on the substrate and thermally cured for hardening. The resin was 100 μm thick and had an inorganic filler of SiO_2. The filler provided additional mechanical strength, and the filler content in the resin was approximately 38 wt.%. The glass transition temperature (T_g) of the resin was 156 °C. The patterned structure was achieved by irradiating the laminated resin with a short pulse (tens of nano second) of Nd:YAG laser (with a wavelength of 1024 nm).

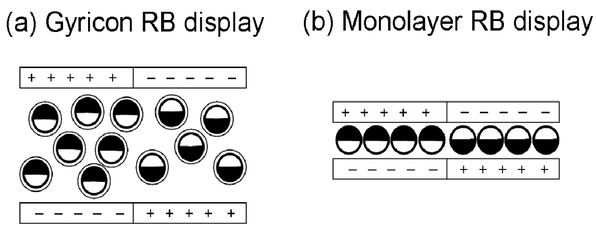

Fig. 1. Schematics of gyricon rotating ball display versus monolayer rotating ball

Either a glass plate with a thin layer of sputtered Ta or a Cu metal plate was used as a bottom electrode. A thin indium tin oxide (ITO) on a glass substrate was used as a transparent top electrode. The balls were confined between the two wide horizontal electrodes. The balls were put into patterned arrays before the plates were in contact. A dielectric liquid (silicon oil with a viscosity of approximately 2 mPa.s) was filled between the electrodes. Rotation behavior of the balls was then measured as an electric field was applied across the plates. Angular rotation speed can be computed from time taken as rotating from start to a 180 degree turn using the recorded video images.

3. Results and discussion

In Fig. 2, plan-views of the RB display are shown. The bichromal balls were approximately 100 μm in diameter. Carbon black and titanium oxide dispersed in two hemispheres have different charge quantities, providing an asymmetric surface charge distribution. Other details in fabricating the balls are described elsewhere [3]. In Fig. 2(a), the balls are periodically disposed in a controllable manner. A distance between two adjacent balls is approximately 30 μm. The inset of Fig. 2(a) displays a case where the balls are randomly located. Note that the balls tend to attract one another due to electrostatic interaction. In Fig. 2(b), the balls are nearly contiguous.

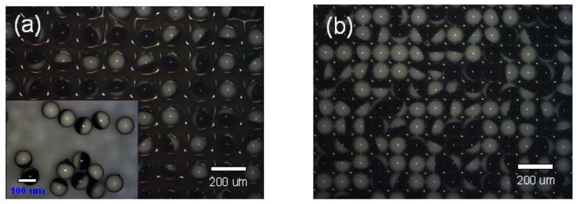

Fig. 2. Rotating balls disposed in a monolayer. The balls are approximately 100 μm in diameter. The ball-to-ball spacing is (a) 30 μm and (b) nearly zero. The inset of Fig. 2(a) is a case where balls

The ball motion is composed of both rotation and translation. As a voltage is applied, the ball begins to rotate. There is a short pause before the ball separates from the lower electrode, however, eventually it rotates from start to a 180 degree turn and simultaneously translates toward the upper electrode, implying it has both dipole and monopole moments. The angular speed of the ball in an electric field is given as [4]:

$$\varpi = \frac{\sigma E}{3\pi S}\sin\theta \cong \frac{\sigma E}{6\pi S} \qquad (1)$$

where σ is the difference in the surface electric charge densities of the hemispheres of the ball, E is the external electric field, S is the viscosity resistance of the dielectric liquid, and θ is the angle of the boundary between hemispheres off the perpendicular to the electric field. Since the rotation rate is not uniform and θ dependent, although it is a rough estimation, the above equation assumes the average angular speed would be half of the maximum angular speed. The measurement of angular motion can be carried out by observing individual balls as they are actuated with applied voltage.

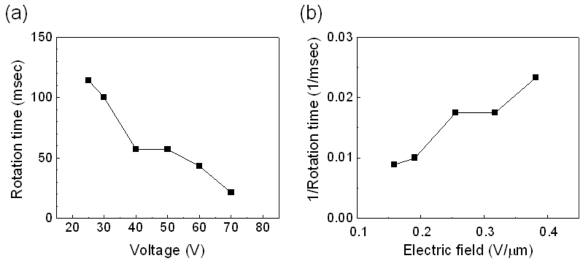

Fig. 3. (a) Rotation time as a function of applied voltage and (b) 1/Rotation time as a function of applied electric field.

In Fig. 3, electrical actuation of the RB display was performed. The time was measured in msec as a function of applied voltage. See Fig. 3(a). The rotation time improved down to 20 msec in voltage going from 20 to 70 V. The rotation time was 110 msec at 20 V. In Fig. 3(b), 1/(rotation time was replotted as a function of electric field. Using Eq. (1), surface charge density (σ) was computed, which was in the range of 3-4 $\mu C/cm^2$.

A programmed pattern of a voltage was applied to switch colors (black and white). In Fig. 4, with a peak amplitude of 80V, a high-contrast image was shown. Even a peak writing signal of 50V, an notable contrast was obtained. The insets which are the magnified images of the corresponding figures indicate 180 degree turn are mostly achieved during electrical actuation.

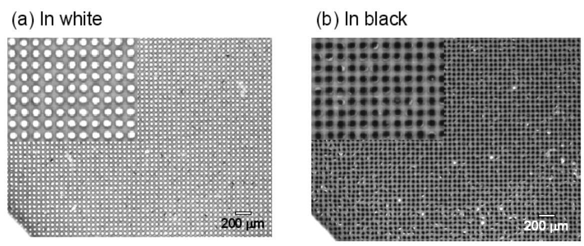

Fig. 4. Electrical actuation of the MRB display. A voltage of 80V was applied between the top and bottom electrode. (a) Switched in white and (b) in black. The insets in (a) and (b) are the magnified

In Fig. 5, a photograph of an image created on a prototype MRB display is shown. The size of the display was 7 cm ×7 cm. The contrast for this sample was approximately 4.5, and the viewing angle of the MRB display appeared to be quite wide and approached 180 degrees.

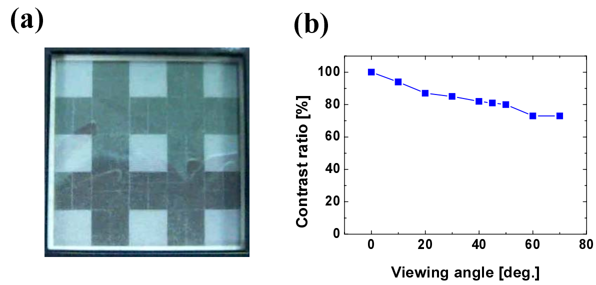

Fig. 5. (a) An image created on the MRB display. The sample size was 7 cm ×7 cm. (b) Contrast ratio as a function of viewing angle for the sample.

4. Summary

We have successfully demonstrated the MRB display. In the MRB, optically anisotropic balls were disposed in a monolayer and controllably densely packed in the monolayer. The optical and electrical characterization was performed to better quantify the MRB display. This novel approach enables us to achieve superior reflecting characteristics with a relatively faster response time and a lower driving voltage in comparison with the typical RB display.

5. References

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