Power consumption of a Quick-Response Liquid Powder Display (QR-LPD®)

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Abstract

Quick-Response Liquid Powder Display (QR-LPD®) is a promising device for ultra-low-power applications. Several driving methods for this display were investigated in terms of image quality and power consumption. The power consumed both in a panel and in the output circuits of driver LSIs was evaluated by analog circuit simulation and discussed.

1. Introduction

QR-LPD® has very unique properties such as a quick response time of less than 0.2 msec, a high reflectance of more than 41%, a high contrast ratio of more than 10, good bistability of more than several days, zero power consumption during the non-updating period, a paper-white appearance, perfect ideal diffuse reflectance and high addressability with passive-matrix driving [1]. A plastic substrate can also be easily applied since a high temperature process is not required to fabricate the panel. This allows the resulting display to be ultra thin and flexible [2]. The advantages highlighted above make this technology one of the most promising candidates for electric paper. Figure 1 shows one example of QR-LPD®.

The bistability of QR-LPD® is outstanding and an image can be retained for a minimum of several days if no electrical shocks are applied. Images have been tested and found to have been retained perfectly after more than a year of storage. Physical shocks of normal strength do not affect the images at all. Like paper, QR-LPD® requires no power after an image is updated. These features offer the potential for a wide variety of application fields such as price cards, POP (point of purchase), and smart cards.

Even during updating periods, the power consumed is expected to be almost the same level as that required for LCD. Since the cells of both QR-LPD® and LCD are equivalent to a capacitor, their power consumption is basically related to that of a cell capacitance and an applied voltage to the cell. At present QR-LPD® still requires a higher applied voltage compared to LCD, but the capacitance is smaller than that of LCD. Thus, the power consumed to update a single image is almost the same for QR-LPD® and LCD. However, since the refresh rate of QR-LPD® can be set much less than that of LCD, the average power consumed for QR-LPD® is extremely less than that of LCD.

Fig.1. One example of a QR-LPD® product

In this work, we have analyzed the power consumption of QR-LPD® according to the driving method and simulated it by means of analog circuit simulation. The simulation includes the contribution of the output circuits of column and row drivers. For simulation purposes, we assumed that the QR-LPD® cell is a pure capacitor although this assumption is not entirely valid since charged particles are mobile within the cell. This assumption, however, does not give rise to such a large error since the charge accumulated by the applied voltage to the capacitor is estimated to be in the same range as the charge originated by the charged particles. The driver circuit was carefully designed and optimized by our laboratory to achieve the lowest power dissipation allowable. The output circuit of the driver consists of a level shifter and high voltage transistors that can provide output at three levels, HV (high voltage), MV (medium voltage) and GND (ground). As a result, we found that the power consumed in the driver circuit is almost equivalent to that in panel. Therefore, the designing of the driver LSI for QR-LPD® is the most important part to reduce the power consumption.

2. Operation principle

The fundamental principle of operation is shown in Fig.2. Two types of powders exist between the electrodes. One is charged negatively and colored white, while the other is charged positively and colored black. The individual particles in the powder do not require external friction to obtain their charge. The charge possessed is intrinsic to the particle itself, which is made possible by a well-controlled fabrication process. When no electric field exists between the electrodes, particles charged negatively and positively are attracted to each other by an attractive force, F_a, which consists of several forces, such as the Coulomb force, F_q, and the Van der Waals force, F_V. At the electrode surface, the forces that exist are almost the same with the addition of the image charge force due to the polarization of the conducting electrode by the charged particle. The attractive and repulsive forces between the particles and the electrodes are an origin of the bistability feature. When an electric field, E, is applied in the gap, the force generated by the field acts as a repulsive force to the pair of oppositely charged particles. If the field is strong enough, the pair of particles will separate and each particle will travel in the gap towards the electrode that is oppositely charged with respect to the particle. This principle can also be applied to the particles on the electrode surface although the Van der Waals force would be stronger than the force between the particles due to the apparently large contact area.

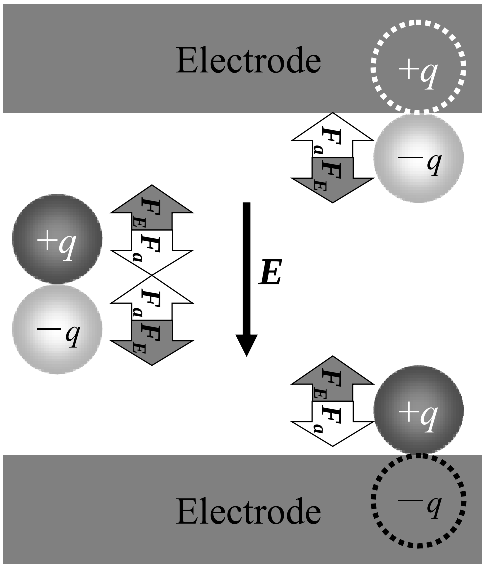

Fig. 2. Fundamental principle of QR-LPD®.

The force from the field is given by $F_E = qE$, where the q is the charge on a particle, and the attractive force is represented by $F_a = F_q + F_V = k\,q^2/r^2 + F_V$, where the force F_V is independent of the charge q. According to these equations, a range of applied electric field E where F_E is stronger than F_a will exist if appropriate values of q and F_V can be obtained. Thus the key point of this technology is to carefully control the charge on a particle and the Van der Waals force.

3. Basic driving method

Figure 3 contains a plot showing the relationship between the applied voltage and the reflectance R. The origin of bistability is due to the large hysteresis observed in this plot. In QR-LPD® the threshold voltage, V_{th}, can be obtained very clearly, thus enabling passive addressing with a large number of scanning lines. The operation principle can be simply stated such that the pixels that are to be switched

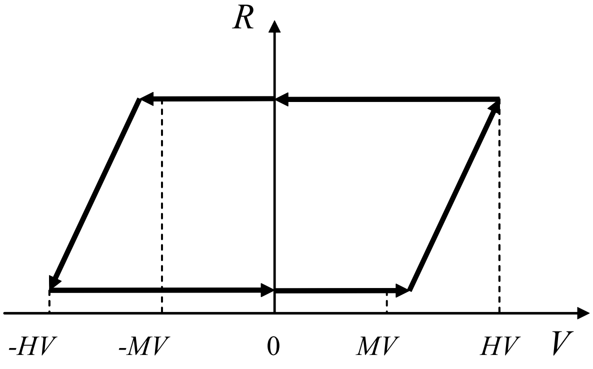

Fig.3. Reflectance hysteresis loop.

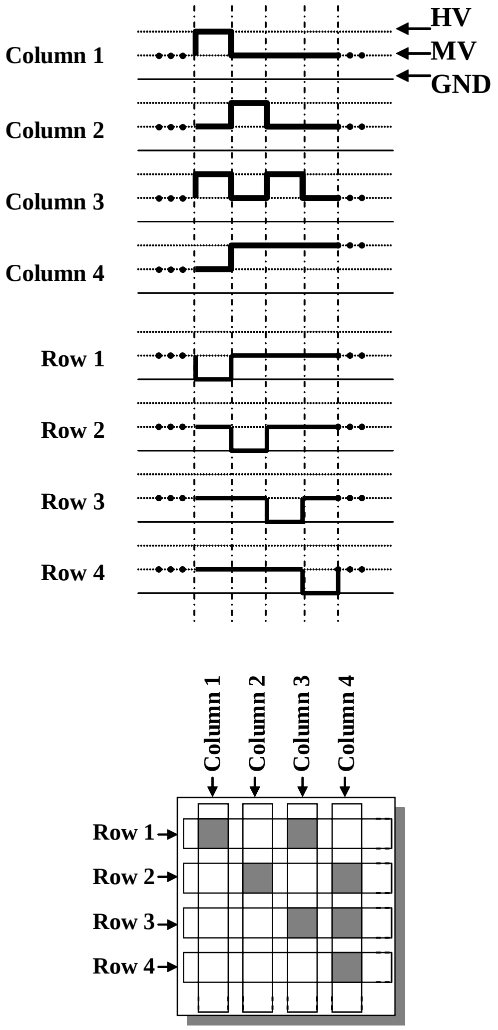

Fig. 4. Basic driving scheme of QR-LPD®.

should have an applied voltage of less than -V_{th} or greater than V_{th}, while all other remaining pixels should have an applied voltage between -V_{th} and V_{th}.

Several driving schemes to achieve this can be considered. Figure 4 shows one example of how to write a black image. The row lines are selected sequentially during the writing period and a GND level signal is applied while a voltage corresponding to MV is applied during the unselected period. Voltages HV or MV are applied to the column lines for switched and unswitched pixels, respectively. For switched pixels HV is applied and for non-selected or unswitched pixels, MV or GND is applied in this manner. The actual values of HV and MV are set to be more than the threshold voltage and less than the threshold voltage respectively, and MV is set to be a half of HV. This scheme must be performed after all pixels are reset to the opposite color, white in this case, by applying a voltage of –HV. This may be done either simultaneously for all pixels at the same time or line by line.

Table 1 shows the voltages for all possible driving schemes. There exist a total of 6 possible cases with the top three cases corresponding to the writing of a black image and the lower three cases corresponding to the writing of a white image. To set all pixels to the white state, the line-by-line erasing method as mentioned above can be used. For case 1 the unselected or unswitched pixels have an applied voltage of either MV or zero. The applied voltage to unselected or unswitched pixels is either MV or –MV for case 2 and zero or –MV for case 3. The cases from 4 to 6 also have the same differences for the voltages applied to unselected pixels. The different driving schemes each result in a slight difference in the resulting image quality but the main difference between these schemes is given by the power consumption.

Table 1. Driving voltages

	Row		Column	
	Selected	Unselected	Switched	Unswitched
1	GND	MV	HV	MV
2	GND	MV	HV	GND
3	GND	HV	HV	MV
4	HV	MV	GND	MV
5	HV	MV	GND	HV
6	HV	GND	GND	MV

4. Driver LSI

The row and column drivers are required to apply three potential levels, HV, MV and GND. Drivers which supply only two voltage levels are also available, however these are more difficult to implement since, for example, these drivers must be insolated by a photo-coupler to change the ground level of the driver LSI, or a high voltage source must switch between the HV and MV levels quickly to in order to achieve the write and erase processes. The use of such drivers will require a complicated high voltage source circuit resulting in high cost. In addition, for drivers which supply only two voltage

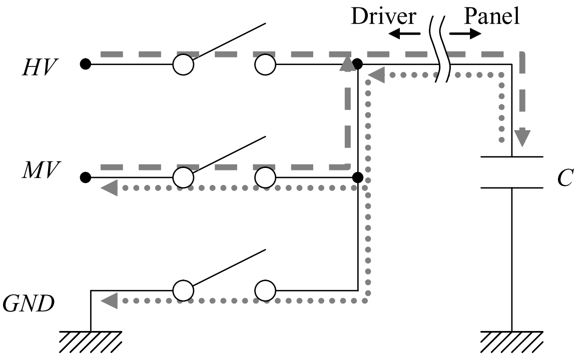

Fig. 5. Output circuit of row or column driver and panel load

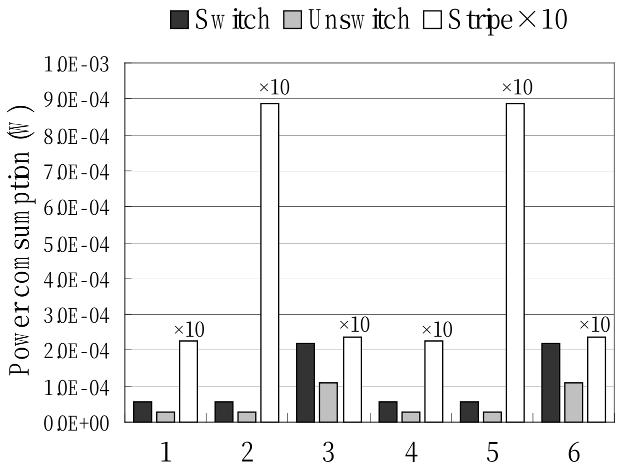

Fig. 6. Power consumption for the driving methods in Table 1.

levels, the number of driving methods available are limited and thus cannot be optimized for minimum power consumption. Thus, a unipolar driver with three output levels is the most desirable.

Figure 5 shows a simplified representation of the output circuit of a driver that can provide three voltage levels, and the load in panel. The panel of a QR-LPD® can be considered to be a simple capacitance load except during the time when the charged particles are moving. The moving particles generate current and consume more power. Experimental results indicate that the amount of charge due to the moving particles is approximately the same as that of the induced charge to the capacitance, meaning the pixel consumes more power when it switches.

The arrows in Fig. 5 show the current flow between the load and the source. The HV setting should have a current source function to the load and the GND setting should have a current sink function from the load. However, the MV setting should have both source and sink functions depending on the voltage on the load capacitance. This added functionality requires a more complicated circuit but the sink current will enable power recovery from a transition from HV to MV and from the point of view of cross talk, this is a critical function.

We are currently developing a custom driver LSI, in which the three voltage levels can be output and the middle level has source/sink functions, using a high voltage CMOS process.

5. Analysis of power consumption

The power consumption for each driving scheme has been calculated. Simulation and calculations were performed on a display with a 160×160 array of pixels and a 3.1-inch diagonal size. A pure capacitance was assumed for an equivalent pixel circuit and in order to account for the effect of moving charges in the cell, the value was doubled when the pixel was switched. The energy dissipated in a pixel can be calculated with the equation $\varepsilon = C \Delta V^2$, where C is the cell capacitance of a pixel and ΔV is the difference in applied voltage. The summation of the energy dissipated in individual pixels during one scanning line, divided by the total scanning time will provide a figure of the power consumption. The total scanning time is calculated by multiplying 0.2msec, the response time of QR-LPD®, by 160, the number of scanning lines. The effect of power recovery was not taken into account in these calculations. We adopted a voltage level 80 V for HV and 40 V for MV. These voltage levels are necessary for the present state of the technology and the calculations for power dissipation represent the maximum case. The power dissipated will decrease as the required driving voltages decrease as the properties of the powder are optimized.

Figure 6 shows the results of each driving scheme in Table 1 and on the special three images. “Switch” refers to an image where all pixels are switched to the opposite color. The column line voltage is always kept at the voltage indicated in the “Switched” column in Table 1. The power consumption corresponds to that required to erase an image. “Unswitch” refers to an image where none of the pixels are changed. The column line voltage is kept at voltage indicated in the “Unswitched” column in Table 1. This image obviously requires the least amount of power to be consumed. "Stripe" refers to an image where black and white lines are alternately shown on every row. This type of image is shown to consume the most power since all column lines must be switched during every selecting time.

From Figure 6, it is evident that the driving schemes that result in the greatest power consumption are 2 and 5. This is due to the large voltage swing required on column lines. The calculated results show that these schemes require about four times more power than the other schemes when the "Stripe" image is written. The stripe image consumes at least ten times more power than the other images. The lowest power consumption corresponds to driving methods 1 and 4. Compared to reflective type LCD, the power consumption is relatively low and if the scanning time is increased, the maximum power dissipated can be reduced even further.

Analog circuit simulation was also conducted in order to evaluate the practical amount of power consumption. The power consumption on row and column drivers was also included in this simulation. Only the analog part of the driver was simulated since the power consumption of the digital part is negligible compared to the analog part. The circuit currently in development is designed to reduce the through current in the output circuit as much as possible. However, we got results that the drivers consume almost the same power as that consumed in the panel with the size discussed above. It means that it is very difficult to reduce the power consumed in the driver circuit. The main reason is due to the through current in the bias circuit at the high voltage part. Current data suggests that the optimization of power consumption will depend greatly on the driver LSI design.

6. Summary

We have demonstrated the basic driving method of QR-LPD® and evaluated the power consumed according to the driving method and the type of image displayed. The power consumption of QR-LPD® is sufficiently small compared with that of LCD. Once an image is updated, QR-LPD® no longer requires any power. Thus, especially for applications that require infrequent updating of images, this display consumes an extremely low amount of power. Analog circuit simulation shows that the power consumption by the driver LSI is almost in the same level for the driver LSIs that have been carefully designed for low power operation.

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References

[1] Reiji Hattori, Shuhei Yamada, Yoshitomo Masuda, Norio Nihei: "A novel bistable reflective display using quick-response liquid powder" Journal of Society for Information Display, Vol.12, No.1, pp.75-80 (2004)

[2] Reiji Hattori, Shuhei Yamada, Yoshitomo Masuda, Norio Nihei, Ryo Sakurai:"A quick-response liquid-powder display (QR-LPD®) with plastic substrate" Journal of Society for Information Display, Vol.12, No.4(1), pp.405-409 (2004)