24.3 Late-News Paper: In-Cell Capacitance Touch-Panel With Improved Sensitivity

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Abstract
We present a novel pixel circuit for an in-cell capacitive type force-sensitive touch panel. The TFT based capacitance sensor system comprises an active pixel sensor circuit with novel sensing capacitor structure and in-pixel amplification to achieve a high sensitivity. The observed 8.5x increase in sensitivity over standard methods provides a practical solution to obtain a robust, mechanically compact and low-cost force sensitive multi-touch panel.

1. Introduction
Touch panels have gained significant interest and market penetration in recent years due to the significant usability benefits they provide for portable electronic devices such as mobile phones, digital cameras and personal media players. However, the large range of application, technical and commercial requirements that touch panels must meet has led to the development of a range of technological solutions of which none are entirely satisfactory. For example, whilst projected capacitance solutions have received much attention due to their ability to recognize multi-touch input, they are incapable of detecting pen input, add significant cost and thickness to the display module and degrade image quality due to increased reflection of ambient light from the display surface.

In addition, the emerging class of mobile displays targeted at eBook readers and Tablet PCs demand new capabilities not provided by current touch panel technologies. Amongst these, the capability to detect the force of touch input is arguably the most desirable since it enables two essential functions to be realized. Firstly, text input to these devices via a virtual keyboard is significantly improved with the ability to distinguish between those fingers merely resting on a screen and those tapping a key. Secondly, paper-like hand-writing and drawing input become possible as force sensitivity can be used to digitally re-create more realistic and natural strokes - for example by modifying line width according to force.

Several technologies have been proposed to achieve force-sensitive touch panels suitable for integration into display panels, for example using transparent force sensor [1] or quantum tunneling composite [2] materials. These technologies however, remain conceptually based the addition of touch sensitive layers to the front of the display and thus suffer from the aforementioned problems of cost, module thickness and display image quality.

2. In-Cell Touch Panel
LCD manufacturers have responded to the touch panel challenge by developing both “on-cell” and “in-cell” devices which are easily integrated into the display module and as such offer both lower cost and mechanically compact designs. In particular, the in-cell approach, which may be realized by micro-switch [3], capacitance [4] or optical image [5][6] sensing structures embedded within the LCD layer itself, requires no additional layers to be added to the display thus maximizing image quality, minimizing module thickness and reducing cost.

Further, both micro-switch and capacitive type in-cell sensing techniques utilize mechanical deformation of the display upon touch and are therefore, in theory, capable of detecting the force of touch input. These devices therefore offer a promising touch panel solution. However, in practice the manufacture of in-cell structures that simultaneously meet the conflicting mechanical requirements of the display and sensor functions has proven to be a significant challenge. In essence, for conventional in-cell type touch panels to operate with an acceptably low activation force of 0.1-0.2N (10-20gf) the display must be designed to have an easily deformable cell-gap. However, a display with an easily deformable cell-gap is vulnerable to damage by wear and tear or excessive force and exhibits image artifacts when touched that may extend beyond the touch contact area and temporarily remain after the touching object is removed.

For this reason, the micro-switch approach is difficult to realize since a relatively large change in cell-gap is required to ensure reliable switch contact and separation. The in-cell capacitance approach offers a more practical solution although a high sensitivity to capacitance changes in the liquid crystal material (caused by deformation of the display upon touch input) is required. Whilst active pixel type capacitance sensors provide a higher sensitivity than passive sensor arrays, systems reported to date exhibit a poor signal-to-noise ratio (SNR) and therefore remain incapable reliably detecting touch input with a small activation force – especially for finger input where the input force is spread over a large area.

In this paper we present a novel in-cell type capacitance sensor for use as a force-sensitive multi-touch panel. The capacitance sensor overcomes the limitations of previously reported systems
3. Novel Pixel Circuits

3.1. Liquid Crystal Capacitor Structure
LCD integrated in-cell capacitance sensors operate via the principle of detecting the change in capacitance of the liquid crystal material due to mechanical deformation of the display cell-gap. In this system a vertically aligned LC mode is used. In order to avoid interference between display and sensor operation, the sensor capacitor is constructed separately from the display pixel electrodes using a novel planar type structure in which both electrodes of the sensor capacitor are formed in the ITO layer of the TFT substrate (Fig.2). To increase the relative change in capacitance to cell-gap deformation and therefore improve the sensor response, a protrusion is fabricated on the counter substrate opposite this pair of electrodes. The counter electrode ITO layer is then formed over the protrusion and etched to form an electrically floating ITO region. A guard ring is also formed in the ITO layer of the TFT substrate around the sensor capacitor structure to electrically isolate the liquid crystal material in the region of the sensor from the display pixel region. A key advantage of the resulting structure over the conventional vertical structure - in which one terminal is located on the counter electrode - is that the isolation between the sensor and display operation is improved. The resulting reduction in noise enables in-pixel amplification of the sensor signal to be performed without risk of saturation of the pixel output.

3.2. Pixel Circuit with In-Pixel Amplification
The capacitance sensor pixel circuit itself is a variation of the 1-transistor active pixel sensor (1T APS) circuit which has been reported previously for use as an image sensor [8]. In this case, as shown in the schematic diagram of Fig.3b, the pixel circuit comprises an amplifier transistor, M1, a liquid crystal sensor capacitor, CLC, a read-out capacitor, C1, and a DC biasing diode, D1. The planar type liquid crystal sensor capacitor CLC is connected between the sensing node of the pixel circuit, V_{SENSE}, and the pre-charge input signal, PRE. The read-out capacitor C1 is formed by a voltage-dependent integration capacitor (embodied as a p-type TFT) to provide an in-pixel amplification function. Each APS circuit is integrated into each (RGB) pixel of the display matrix alongside the pixel display elements as shown in Fig.4.

The operation of the pixel is now briefly described with reference to the timing diagram of Fig.5. Firstly, when inactive, the pre-charge signal, PRE, is normally high and provides a steady-state DC bias for the sensing node via the biasing diode D1. The high potential of this signal, V_{PRE,H}, is chosen to be less than the threshold voltage of the amplifier transistor, M1, ensuring it is normally turned off and does not interfere with the display operation. During the display horizontal blanking period, the pixel sampling operation is initiated when the pre-charge signal, PRE, is brought low such that charge is removed from the sensing node and V_{SENSE} falls in proportion to the value of the sensor capacitance, CLC. The row select signal, RWS, is then brought high such that charge is injected onto the sensing node via the read-out capacitor, C1. At this time, the voltage of the sensing node, V_{SENSE}, may rise above the threshold voltage of the amplifier transistor, M1, turning it on and forming a source follower amplifier with the bias transistor, M2, located at the end of each column source line. The output voltage generated by the
source follower amplifier, $V_{PH}$, is now sampled and held by the sensor column read-out circuits. This signal is subsequently driven off panel via a chip amplifier where it is digitized and processed to extract both the touch co-ordinates and the touch force data.

As illustrated in Fig.6, the high sensitivity of this APS is achieved through an in-pixel amplification effect generated during read-out through the voltage-dependent capacitor, $C_1$. The low voltage of the row select signal, RWS, is chosen to be less than the voltage of the sensing node, $V_{SENSE}$, both when inactive and during the pre-charge stage when the pre-charge signal, PRE, is low. Thus, before the read-out stage begins at $t_0$ the p-type TFT structure forming the read-out capacitor is turned on and, when RWS begins to rise, charge is therefore injected onto the sensing node at a rate proportional to the total gate capacitance of $C_1$. The injected charge is shared across the total capacitance of the sensing node including the liquid crystal sensor capacitor and $V_{SENSE}$ begins to rise - at a rate slower than the RWS rising edge and inversely proportional to the capacitance of $CLC$. At some point during the rise time of RWS the voltage across the read-out capacitor, $V_{CAP}$, will fall below the threshold voltage, $V_{TC}$, of the p-type TFT forming $C_1$ causing it to turn off. At this point, charge will continue to be injected onto the sensing node but at a significantly lower rate proportional to only the overlap and parasitic capacitance of the structure forming $C_1$. In the case of a small sensor capacitance (generated by a small input force), $V_{CAP}$ is large at the start of the sample period and a large amount of charge is injected onto the sensing node before the read-out capacitor turns off at $t_2$. However, in the case of a large sensor capacitance (generated by a large input force), $V_{CAP}$ is closer to $V_{TC}$ at the start of the sample period and relatively little charge is injected before turn off at $t_1$. This difference in injected charge combined with the difference in initial rate of voltage increase is the source of the amplification effect i.e. the difference in $V_{SENSE}$ due to the capacitance of the sensor capacitor $CLC$ during the read-out period, $\Delta V_{SENSE}@t_3$, is much larger than during the pre-charge period, $\Delta V_{SENSE}@t_0$.

### 4. Results

In order to prove the operation of these new circuit concepts, a set of miniature 64x64 pixel test displays were fabricated using a CG Silicon TFT process in which the sensor pixel circuit and read-out circuits were co-integrated onto the TFT substrate alongside basic display elements. The block diagram of a miniature test display is shown in Fig.7.

To investigate the effectiveness of both the pre-charge technique and the in-pixel amplification effect, four different types of test display with variations in the APS circuit were designed, fabricated and evaluated: (1) standard design with vertical capacitor structure (i.e. no pre-charge operation) and no in-pixel amplification; (2) planar capacitor structure with pre-charge operation; (3) vertical structure with in-pixel amplification and (4) combination of both pre-charge operation and in-pixel amplification. Force was applied to each test display through a metallic rod with a flat circular tip of contact area 3.1mm$^2$ and the sensor output voltages recorded. Defining the sensitivity as the rate of change in output voltage with applied force at the touch panel activation force of 0.2N, it was observed (Fig.8) that the
5. Conclusions

LCD integrated in-cell type touch panels based on detecting mechanical deformation of the display are a leading candidate to realize force-sensitive input devices. The main obstacle to the introduction of these devices to date, however, has been the conflicting requirements between display and sensor performance. To overcome this limitation we have developed a novel pixel circuit for an in-cell capacitive type touch panel which includes a planar sensor capacitor structure and in-pixel amplification and provides a high sensitivity to changes in the display cell-gap. The work described in this paper therefore represents the first practical display-integrated force sensitive touch panel and, as such, forms a platform to create a highly usable, natural and intuitive user interface for next-generation portable electronic devices.

6. Acknowledgements

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7. References


Figure 8. Experimental results (a) applied force vs. output voltage (b) sensitivity comparison between pixel types

Combination of the pre-charge operation and the in-pixel amplification resulted in a 8.5x increase in sensitivity compared to the standard design. As a result, by back-calculation we have confirmed that this novel pixel circuit is capable of detecting changes in the cell-gap as small as 10nm. The mechanical design of the display therefore does not have to be compromised in order to realize the touch panel function.

In addition, the combination design exhibited greatly improved linearity over an input force range of 0-2N further confirming its potential for use as an accurate touch force sensor.