Feasibility Study of a Dual-gate Photosensitive Thin-Film Transistor for Fingerprint Sensor Integrated Active-Matrix Display

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Abstract

By placing a transparent conductive ITO layer atop a display driver thin-film transistor (TFT), a dual-gate photosensitive TFT is formed to integrate a fingerprint sensing function in a display pixel. An analytical model is proposed to elaborate its working principles in achieving both fingerprint imaging and display driving functions.

Author Keywords

Dual-Gate Photosensitive TFT; Fingerprint Sensor; Active Pixel Sensor; Sensor Integrated Display

1. Introduction

Current fingerprint-enabled smartphones unanimously rely on a separate sensor to perform fingerprint identification (ID). However, such a conventional design only provides static identification and limited authentication. For instance, today's smart phones cannot continuously monitor user's ID over time of usage. In other words, current fingerprint ID solutions are incapable of offering dynamic biometrics with improved security measure. The separate sensor design also incurs higher material and manufacturing cost. As the demand for a thinner, lighter, and more secure handset grows, mobile makers have been dedicated to integrating an image sensor in the display panel to capture fingerprint images. However, all integrative designs proposed to date still encompass a separate imaging sensor in the display pixel and therefore lead to reduced display brightness, aperture ratio, and spatial resolution in addition to increased cost of manufacture and process complexity. We aim to design an amorphous silicon (a-Si:H) dual-gate photosensitive TFT working in either fingerprint imaging mode or display driving mode. By adopting the dual-gate TFT, we expect that the driver TFT in an active-matrix liquid crystal display (AMLCD) can have additional photo-sensing function enabling a high-resolution, high-fidelity, and dynamic fingerprint sensor.

This paper proposes a novel concept of a photosensitive device embedded in the display pixel and detects the reflected light from the finger touch. Our approach differs from the existing optical imaging-based technologies in that it transforms the display driver TFT into a dual-gate photosensitive TFT instead of placing a separate imaging sensor unit in the display pixel [1]. This unique design not only greatly preserves aperture ratio and maintain spatial resolution, but also enables an active pixel sensor to improve signal-to-noise ratio (SNR) for imaging the fine details of a fingerprint by harnessing the amplification effect of a TFT. Analytical modeling and numerical simulation will be conducted to verify the device design and finally a single-pixel device will be fabricated and characterized to prove the device concept with consideration of process viability.

2. Design and Modeling

The device we hereby propose is only composed of a single dual-gate photosensitive TFT (Fig. 1), which allows for the construction of a completely in-pixel dual-mode device for both display driving and fingerprint imaging. The dual-gate photosensitive TFT consists of four terminals: Photo G, S, D, and Dark G), two gate dielectric layers, and an active amorphous a-Si:H layer. It can be regarded as a device with two back-to-back TFTs.

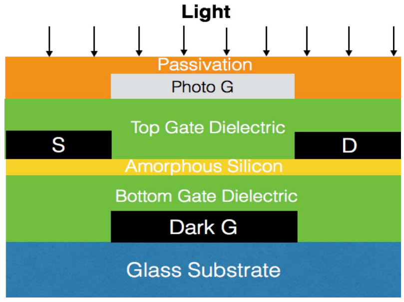
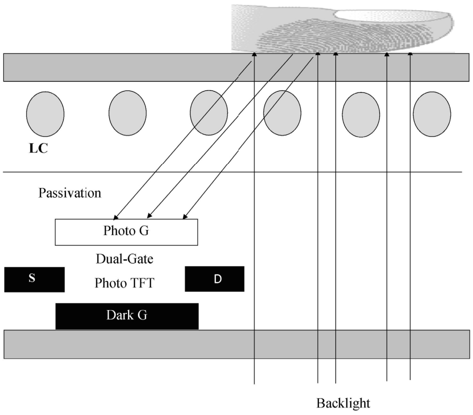
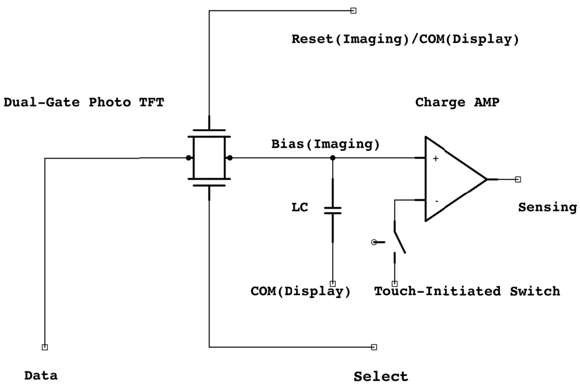


Fig. 1 Cross-sectional structure of an a-Si:H dual-gate photosensitive TFT

In AMLCD, backlight travels across the liquid crystal (LC) and reaches the surface of the screen. When a finger touches the screen, the sensor collects the photons reflected from the finger and immediately captures its fingerprint as illustrated in Fig. 2 (a). In the corresponding pixel circuit diagram shown in Fig. 2 (b), the top TFT is manipulated by three terminals: Reset, Data, and Bias while the bottom TFT acts as a switch controlled by the Select. In the display-driving mode, the bottom TFT is turned on by the Select, the Bias, and the Data terminals. The top TFT instead is biased positively by the COM terminal and functions as a storage capacitor in parallel with the LC self capacitor. In the fingerprint-imaging mode, the light reflected from the finger passes through the Photo G (e.g. ITO) and gets absorbed in the a-Si:H layer where the electron-hole pairs are generated and stored temporarily in the top TFT capacitor. When the Select, Data, Reset, and Bias terminals are biased properly, the photo-generated charges are transferred to the external charge amplifier. To reduce power consumption, fingerprint images will be only captured when the fingers touch the screen and the touch sensor IC can conveniently control the switching from display mode to fingerprint-imaging mode through a touch-initiated switch connected with the charge amplifier.



(a)



(b)

Fig. 2 (a) Schematic diagram of LCD pixel with dual-gate photosensitive TFT as integrated fingerprint sensor; (b) Simplified dual-mode pixel circuit diagram for fingerprint imaging and display driving

To design such a dual-gate photosensitive TFT to meet the requirements for both display driving and fingerprint imaging, we need to develop an analytical model for the proposed device by starting with the classical TFT transfer characteristics which can be divided into four regions: OFF, subthreshold, linear, and saturation. In the subthreshold region, the output current, I_{DS}, is given by:

$$I_{DS} = I_{D0}\exp[\frac{q(V_{GS}-V_T)}{\eta kT}][1-\exp(-q\frac{V_{DS}}{kT})] \quad (1)$$

I_{D0} is the output current at V_{GS}=V_T and for $V_{DS}\gg KT/q$, and η is related to S as:

$$\eta = \frac{qS}{(ln10)kT}, \quad (2)$$

where S represents the subthreshold swing, q is the electron charge, T is the absolute temperature in Kelvin, V_{GS} is the applied gate-source bias, k is the Boltzmann's constant, V_{DS} is the applied drain-source bias, and t is the thickness of a-Si:H. The output current in the linear region can be expressed by the Square-Root Law as follows:

$$I_{DS} = \frac{WC_i\mu_{FE}}{L}[(V_{GS}-V_T)V_{DS}-\frac{1}{2}V_{DS}^2], \quad (3)$$

where W and L are the channel width and length respectively, C_i is the bottom TFT capacitance, μ_{FE} denotes the field-effect mobility of the bottom TFT, V_{GS},V_T and V_{DS} are the gate-source voltage, threshold voltage and drain-source voltage, respectively. In the saturation region, I_{DS} is a function of (V_{GS}-V_T):

$$I_{DS} = \frac{WC_i\mu_{FE}}{2L}(V_{GS}-V_T)^2. \quad (4)$$

These TFT characteristics can be simply regarded as a function of V_T in the subthreshold, linear and saturation regions. As such, an analytical model for V_T would be used to describe its photo-sensing behavior. Typically, the threshold voltage of the dual-gate TFTs follows a linear function with the top gate bias (V_{PG}):

$$V_T = V_{T0} + \gamma V_{PG}, \quad (5)$$

where V_{T0} is the threshold voltage of the bottom TFT at the top gate bias of 0V, and γ is the sensitivity parameter indicating the dependence of the top gate bias on the threshold voltage of the bottom TFT. Upon light exposure, the photo-generated charges in the a-Si:H layer will migrate to the bottom TFT if the top Photo G is biased negatively. As a result, it seems that a "virtual" negative gate bias (V_{PHOTO}) is applied to the top gate and accordingly causes the threshold voltage shift in the bottom TFT upon light exposure. Thus, the threshold voltage of the bottom TFT in response to the light, V_T', can be described as:

$$V_T' = V_{T0} + \gamma(V_{PG} + V_{PHOTO}). \quad (6)$$

In order to determine V_{PHOTO}, we need to attain the number of photo-generated charges from the electron-hole pair generation rate:

$$G = \eta_0\frac{I\lambda(1-R)}{hc}\alpha e^{-\alpha y}, \quad (7)$$

where η_0 is the internal quantum efficiency, which represents the number of electron-hole pairs generated per photon absorbed, I is the light intensity received by the device, R is the reflectance loss of the device, y is a relative distance of the ray to the bottom layer of a-Si:H, λ is the wavelength, h is the Planck's constant, c is the speed of light and α is the absorption coefficient of a-Si:H. By integrating the generation rate over the entire a-Si:H layer, we can obtain the total number, n, of electron-hole pairs as a function of a-Si:H layer thickness, light intensity, reflectance loss, and wavelength.

$$n = \eta_0\frac{I\lambda(1-R)}{hc}(1-e^{-\alpha t}). \quad (8)$$

Subsequently, V_{PHOTO} can be obtained using the following equation:

$$V_{Photo} = \frac{nq}{C_{top}} = \frac{q\eta_0 I\lambda(1-R)}{hcC_{top}}(1-e^{-\alpha t}), \quad (9)$$

where C_{top} is the top TFT gate capacitance. By putting this photo-induced portion to the existing threshold model in Eq. (6), we can attain the analytical model of the threshold voltage of the bottom TFT as follows:

$$V_T = V_{T0} + \gamma [V_{PG} + \frac{q\eta_0 I\lambda(1-R)}{hcC_{top}}(1-e^{-at})]. \quad (10)$$

Apparently, the key parameters for a sensitive device are the reflectance of the device, R, the light intensity received by the device, I, the top TFT capacitance, C_{top}, and the thickness of a-Si:H, t. The sensitivity of the device essentially comes from the photo-induced threshold voltage shift as shown below:

$$\Delta V_T = \gamma \frac{q\eta_0 I\lambda(1-R)}{hcC_{top}}(1-e^{-at}). \quad (11)$$

In case that the device is operated in the subthreshold region, the ratio between photo current and dark current corresponding to light exposure will be:

$$\frac{I_{Photo}}{I_{Dark}} \propto \exp[-\frac{\gamma q\eta_0 I\lambda(1-R)(1-e^{-at})}{hcC_{top}\eta kT}]. \quad (12)$$

If the device works in the linear region, such a ratio will be:

$$\frac{I_{Photo}}{I_{Dark}} = \frac{W\mu_{FE}C_i V_{DS}}{L} \times [-\frac{\gamma q\eta_0 I\lambda(1-R)}{hcC_{top}}(1-e^{-at})]. \quad (13)$$

Thus, the output current is amplified in both cases. In other words, when operating in the subthreshold and linear regions, the dual-gate photo TFT will have an in-pixel amplification factor (i.e. the ratio between photocurrent and dark current) and it can act as a single-transistor active pixel sensor. Operating the device in the subthreshold region is preferred because it will have larger amplification factor, hence higher SNR.

3. Results

To prove the linear dependency of threshold voltage on the bias of top gate as indicated in Eq. (5), we simulated the current-voltage (IV or transfer) characteristics and the conduction band diagrams for the structure shown in Fig. 1. The a-Si:H active layer thickness is set at 50nm and the channel width and length are set to 250μm and 20μm, respectively. Fig. 3 presents the simulated IV curves of bottom TFTs under various bias conditions for the top gate. The shift of IV curves is in accordance with the increase of the threshold voltages. The threshold voltages of bottom TFTs were exacted from the intersection of the X axis and the extrapolated line from the linear portion of each IV curve. The values exhibit linear dependence with the top gate biases as shown in the insert of Fig. 3. Further simulation on conduction band diagrams from top gate towards bottom gate indicates that conduction channels at top and bottom gate/dielectric interfaces are likely formed as highlighted by the magenta circles in Fig. 4. The threshold voltage of the bottom TFT is determined by the band bending at these two interfaces. At the positive top gate biases, the conduction band bends down at the top gate/dielectric interface and electron accumulation occurs leading to a smaller threshold voltage (i.e. the device is easy to turn on). At the negative gate biases, the conduction band at this interface shifts up causing electron depletion. However, an internal electric field is built in favor of migrating photo-generated electrons to bottom gate/dielectric interface. As a result, the threshold voltage will be smaller as if a "virtual" gate is applied in the presence of light.

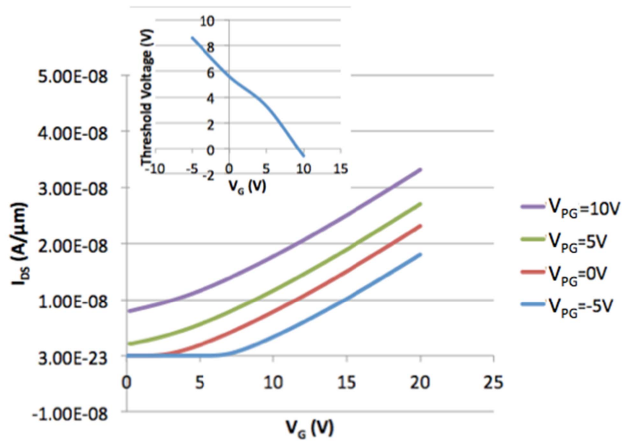


Fig. 3 Simulated IV curves of bottom TFT at different top gate biases.

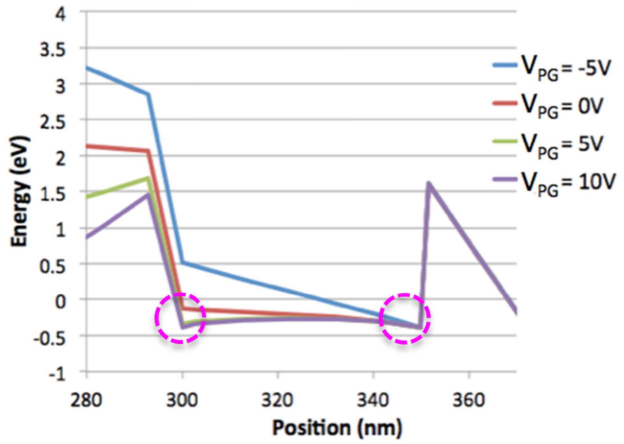


Fig. 4 Simulated conduction band diagrams of dual-gate TFTs in various top gate biases along vertical direction. The bottom gate is biased at a constant voltage of 5V.

In order to predict its behaviors under light illumination, we simulated the transfer characteristics with and without light exposure (Fig. 5). The blue dot and solid lines represent transfer characteristics at the top gate bias of 0V with and without light illumination. The red dot and solid lines are the transfer characteristics at the top gate bias of 2V. The photo-induced threshold voltage shift is more obvious at 0V than that at 2V. By comparing dark and photo IV curves, we found that the photocurrent increases exponentially due to the threshold voltage shift at the top gate bias of 0V. Hence, it proves the concept of an active pixel sensor. This result also implies that in fingerprint-imaging mode, the top gate should be zero or negatively biased to gain an exponential increase in the output current as described in Eq. (12). In display mode, the top gate must be positively biased to make the device insensitive to light illumination when driving display.

To experimentally prove the concept of active pixel sensor, we fabricated a dual-gate photosensitive TFT using a typical BCE TFT process and performed an initial test. The photo to dark current ratio is as high as 10^4 in the subthreshold region (Fig. 6), which is an evidence that an exponential increase in the photocurrent is likely the case.

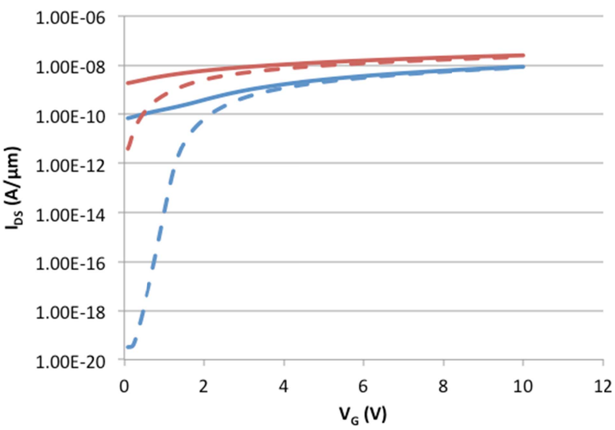


Fig. 5 Simulated transfer characteristics of the bottom TFT at V_{PG}=0V and 2V with (red) and without (blue) light illumination.

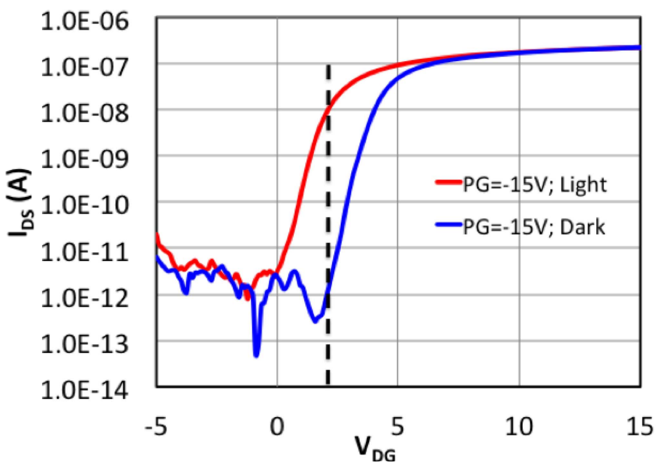


Fig. 6 Transfer characteristics of the fabricated dual-gate photosensitive TFTs with W/L ratio of 250/20µm. The process is compatible with BCE TFT process in LCD manufacture. White light source with 3.8 Lux is used for testing.

4. Conclusions

By incorporating light sensing function in an active-matrix device, a display pixel can act as a fingerprint-imaging sensor in addition to a display driver. A dual-gate photosensitive TFT is proposed to achieve the aforementioned functions. It also makes least changes in conventional a-Si:H TFT processes and is therefore compatible with TFT-LCD manufacturing. Although there remain further works such as device optimization and experimental demonstration of a pixel array, the dual-gate photosensitive TFT is proven feasible to drive active-matrix display and image fingerprint without compromising optical aperture, resolution, thickness, and manufacturing cost.

5. References

[1] Brown C J, Kato H, Maeda K and Hadwen B 2007 A Continuous-Grain Silicon-System LCD With Optical Input Function IEEE J. Solid-State Circuits 42 290.