Liquid Crystal Optical Co-Simulation with Advanced TFT Model In Electrical Simulator MSIM-LCD

Heng-Liang Huang, Shih-Chia Lin and You-Pang Wei
[1]Legend Design Technology, Inc., 5F, No. 176, Sec.2 Gong-Dao-Wu Rd., Hsin-Chu 300, Taiwan, R.O.C.
Chun-Yao Huang and Pei-Chun Liao
AU Optronics Technology Center, No.1, Li-Hsin Rd. 2, Hsinchu Science Park, Hsin-Chu 30078, Taiwan, R.O.C.

ABSTRACT

Although the performance is mostly judged from its optical performance, array designers usually evaluate the behavior of a pixel just by its voltage due to lack of methods for including optical model in electrical circuit simulators. To conquer this problem, a new scheme is developed on the platform of MSIM-LCD for the optical co-simulation when doing electrical simulation of the TFT arrays. In addition, a hybrid TFT model that utilizes measurement data and comprehensive equations derived from recent literatures to accurately model the TFT leakage current is proposed in this paper. The results show that both hybrid TFT model and liquid crystal (LC) dynamic data, the optical behavior of a pixel can be clearly depicted for flicker examination, design optimization or process selection.

Keywords: TFT, Liquid Crystal, Leakage Current, Electrical Simulator, Optical Co-simulation

摘要

雖然一個 LCD 面板的品質好壞大部份是由它的光學表現來決定，但是由於缺乏在電性模擬器中模擬光學反應的方法，幾乎所有的 Array 工程師，都是靠著像點上的電壓來看一個像點的表現。為了解決這個問題，我們以 MSIM-LCD 為平台，發展出一個新的方法可以在對陣列電路進行模擬的同時，也把液晶的狀態及表現顯示出來。除此之外，一個混合的 TFT 模型也在本論文中被提出。它利用許多最新的文獻中所提到的公式把 TFT 關閉時的漏電流模擬地非常正確。結果顯示，利用這樣準確的 TFT 模型及液晶動態資訊所模擬的結果，我們可以為液晶的閃爍、電路設計參數或是製程配方調整做出最佳的選擇。

關鍵詞：**薄膜電晶體，液晶，漏電流，電路模擬軟體，光學同步模擬。**

1 INTRODUCTION

In public domain, there are many commercial tools for structural analysis of the LC dynamics. Approaches with different number of dimensions were taken to analyze numerous structures including TN (twisted nematic: TN, B-TN), VA (vertical alignment: CPA, MVA, P-MVA, A-MVA, S-MVA, VAextreme, PVA, S-PVA, C-PVA, etc) or IPS (in-plane switch: IPS, S-IPS). No matter which software is used for analyzing a structure, the purposes are all to analyze the characteristics of the LC including transmittance, capacitance and response time. It is already very time-consuming to analyze the steady state of the structure, not to mention analyzing the dynamics or the transient response of the LC. However, when designing the TFT array that controls the voltages across LC, designers usually need to optimize the TFT array according to the LC performance because that is what a TFT-LCD's performance is judged by. Therefore, some solutions were proposed for the optical co-simulation when doing electrical simulation.

In [1], Verilog-A approach was used to model the turning mechanism of the LC cells by analyzing the electrical, elastic and viscosity forces on the LC cells. It is a very inspiring work that includes the LC behavior in an electrical circuit simulator. In spite of some difficulties in building the equations and extracting coefficients for the equations, the work is still very remarkable because of implementing the equivalent electrical model [2] in an electrical simulator. Besides the difficulties in building the dynamic equations for LC analytically, the accuracies of the equations are very questionable too.

In 2009, another solution available for calculating the LC behavior while doing electrical simulation was proposed [3]. In the solution, the electrical simulator invoked the optical simulator through application programming interface (API), and sent terminal voltages into optical simulator for detailed and accurate pixel analysis. In return, the optical simulator passed the effective capacitance of the pixel for electrical simulator to simulate TFT array with. The solution did overcome the accuracy issue with the Verilog-A solution. But, due to the high complexity of the structural analysis for a pixel and the huge number of times that the optical simulator needs to be called, the simulation speed is degraded to more than 100x slower compared with pure electrical simulation.

In section 2, we will propose a new method for the optical co-simulation that utilizes the output data from an optical simulator to keep the accuracy for LC dynamic model while preventing the performance drawback of using an LC equivalent circuit and preventing invoking the optical simulator when doing electrical simulation.

In additional to the desire for optical co-simulation, array designers are generally suffering from the lack of accuracy with the existing conventional RPI model. There are many behaviors that a TFT device depends on and not properly modeled. For example, the self-heating effect [4], threshold voltage shifting [5] [6] and off-state leakage current [7] are all very important TFT behaviors for different simulation purposes. In section 3 of this paper, we will pick the leakage current for detailed discussion and propose a hybrid TFT model to improve the conventional flow with minimum modification for the existing modeling flow.

In section 4, we will combine the proposed hybrid TFT modeling flow with the optical co-simulation to see how an accurate TFT model can help to correctly indicate the behavior of a pixel and help designers optimize their TFT designs and operating parameters. Lastly we will conclude this paper in section 5.

2 LC OPTICAL CO-SIMULATION

2.1 LC Data Tables – Static and Dynamic

A typical pixel contains LC cells filled in the space between two alignment layers. Outside the alignment layers, there are electrodes providing the electric field that turns the LC cells to the desired angle.

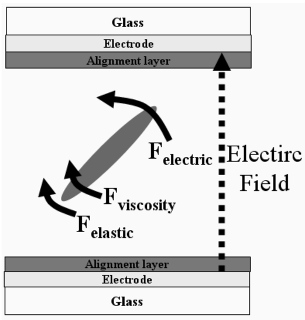

Fig. 1 : Typical Cross Section of a Pixel

When applied with a voltage on the electrodes, there will be an electric force working against the viscosity and the elastic forces from the LC cells. After a certain amount of time when the three forces are balanced, the LC cells stabilize in a certain angle and result in a different transmittance for the lights to pass through the pixel.

There are many structural simulators that are capable to simulate the LC dynamic data [8][9][10]. They may take different approaches for analyzing the structure, but the outcomes from optical simulators are similar. That is to calculate the transmittance, LC cell angle, effective capacitance and transient responses. Transmittance is for the inspection of brightness of a pixel when the condition and specification of the back-light module is given. Effective capacitance is for checking the driving capability of TFT, and transient response is to understand the speed of the LC responses.

To get the static LC data is like solving for the steady state of it after applying a terminal voltage to the electrodes. Therefore, the static LC data table contains at least terminal voltages (*V*), transmittance (*T*) and effective capacitance (*C*). For a simple pixel, the angles of the LC cells are uniform so the angle (*A*) is available too, as shown in Table 1.

Opposed to the static data table is the dynamic data table. It is the transient response of the LC cells after applying a voltage step. Therefore it contains the values of the parameters in the static data table changes along with time, as shown in Table 2.

Table 1 : Static LC Data Table

V	T	C	A
0.0	0.356	8.074	0.000
1.0	0.341	8.290	0.213
2.0	0.288	9.014	8.395
3.0	0.143	10.143	40.213
4.0	0.094	12.109	67.981
…	…	…	…

Table 2 : Dynamic LC Data Table

Time	V	T	C	A
0.0ms	0.0	0.356	8.074	0.000
1.0ms	0.0	0.356	8.074	0.000
2.0ms	0.0	0.356	8.074	0.000
2.1ms	4.0	0.356	8.074	0.000
2.2ms	4.0	0.241	9.545	24.213
2.3ms	4.0	0.114	10.009	39.981
…	…	…	…	…

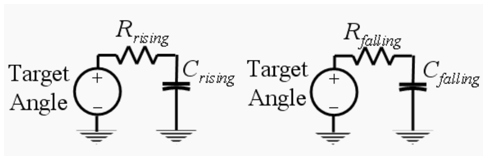

Fig. 2 : Equivalent Circuit for LC

Static data and dynamic data are then used to extract the coefficients for the equivalent circuit proposed in [2]. In figure 2, the target angle is from the static data table corresponding to the external voltage applied on the LC. R_{rising} and C_{rising} are derived from the dynamic data table with which the time constant of the LC rising τ_{rising} can be calculated. With any combination of R_{rising} and C_{rising} that satisfies equation (1) can imitate the transient behavior of the LC cell.

$$\tau_{rising} = R_{rising} \times C_{rising} \quad (1)$$

Parameters for a falling LC can be derived in a similar fashion.

2.2 Dynamic LC Co-Simulation Flow

The static and dynamic data tables are fed into simulation engine in dot data format [11]. The coefficients for the LC equivalent circuit can then be extracted and used when simulating the LC or when being asked for the status of the LC. The flowchart in Fig. 3 shows the detailed input specifications for the simulation with dynamic LC data.

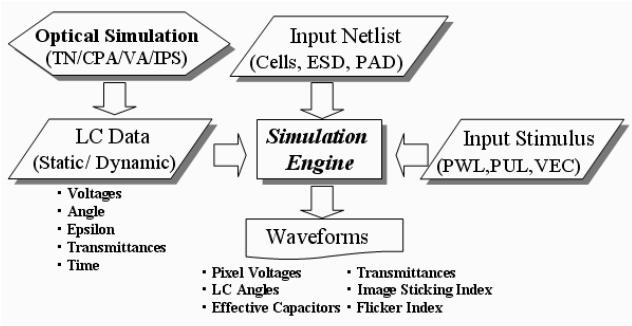

Fig. 3 : Simulation flow with dynamic LC data

2.3 Optical Outputs

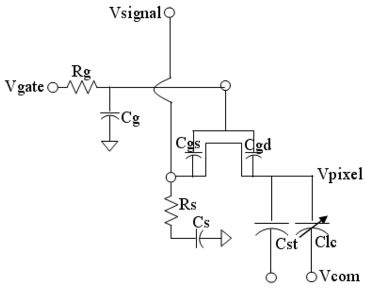

Fig. 4 : Schematic of a single pixel example

Fig. 4 is the schematic of a single pixel. Parameters for all parasitic devices are available after layout extraction except for the capacitance of the LC (Clc). It is voltage-dependent as can be seen in the static LC data. Therefore, the simplest way to simulate it is to take its maximum value to test the driving capability of the TFT, and we call this 'constant' Clc model. A more accurate approach is to model it with its static C-V relation, and we call it 'static' Clc model. With the dynamic LC data provided, we are able to extract its rising and falling characteristics and build the 'dynamic' Clc model. After simulating the circuit with different Clc models, we can check the voltage waveform of the pixel (Vpixel) as depicted in Fig. 5.

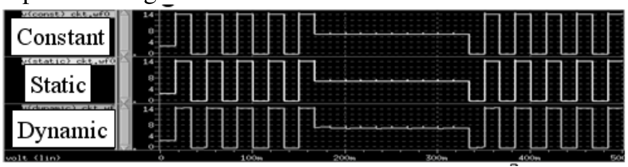

Fig. 5 : Pixel voltage waveform with different Clc models

In Fig. 5, the pixel voltages with different Clc models do not show much difference and that is the reason why optical co-simulation is needed because pixel voltage is not capable of expressing the optical behavior. On the other hand, with the transmittance data provided in the static LC data table, we can translate the pixel voltages of 'constant' and 'static' Clc models into transmittances. With the dynamic LC data table, we can simulate the turning process of the LC cells by extracting the time constant and get the waveforms of transmittance as shown in Fig. 6.

In Fig. 6, for 'constant' and 'static' Clc models, the transmittances change abruptly because of lacking the LC equivalent circuit for imitating the slow LC movement. The transmittance changing corresponding to the slow LC movement can be correctly simulated with 'dynamic' LC model. With the transmittance waveform, we can also check the rising and falling speed of the LC or the flicker condition by checking the amplitude of the transmittance oscillation when it is required to keep steady.

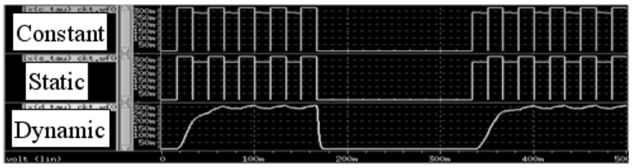

Fig. 6 : Transmittance waveform with different Clc models

3 HYBRID TFT MODEL

3.1 Advanced Leakage Current Model

There are three mechanisms that are responsible for the source of reverse current: Ohmic conduction, front channel conduction and backchannel conduction [7]. Ohmic conduction is due to intrinsic conductivity. Back and front channel are caused by the accumulation of holes and electrons respectively when the negative gate bias goes further and further. However, conventional RPI model only models the front channel hole leakage current thus with obvious error as shown in the following figure.

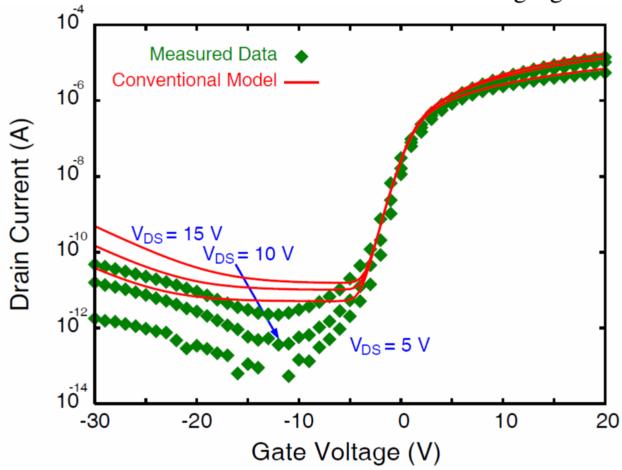

Fig. 7 : I_d-V_g from measured data and conventional model

Moreover, leakage current is also dependent on the strength of the light exposure because the intensity of the light will generate carriers in the reverse biased source junction and result in higher diffusion and tunnel current [12]. With similar method for handling the LC data tables, we can take in the raw data for TFT I_d-V_g to extract the parameters for the leakage current equations [7] and then enhance conventional RPI model into a hybrid one.

The hybrid TFT model we propose here is to utilize the conventional RPI model and the raw measurement data so that there is no need of extra measurement or any additional model parameter extraction to improve the accuracy. What we need is to calculate the difference between the raw data and conventional RPI model and then model the difference into the leakage current equations. After including the difference, the Id-Vg graph from raw data and the hybrid model is shown in Fig. 8.

By correctly modeling for the front and back channel leakage current, the Id-Vg relation from hybrid TFT model (the red line) is much closer to measured data than the conventional model is.

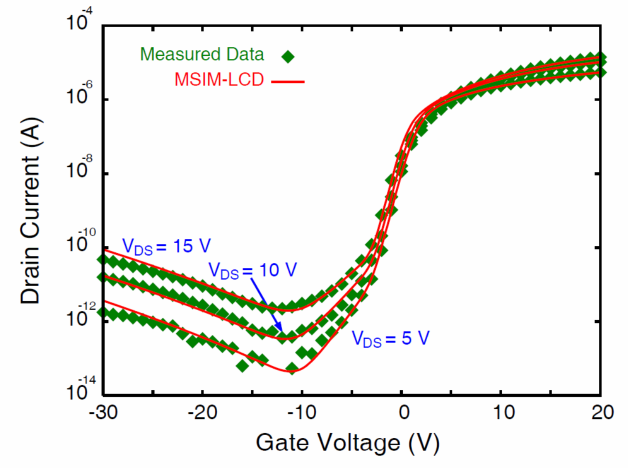

Fig. 8 : I_d-V_g from measured data and hybrid TFT model

4 SIMULATION RESULTS

4.1 Simulation Flow

The simulation flow for the hybrid TFT model is similar to the simulation flow for dynamic LC model and is also integrated into the simulator to become one program that extract the TFT model parameters and LC model parameters at the same time as shown in the following figure.

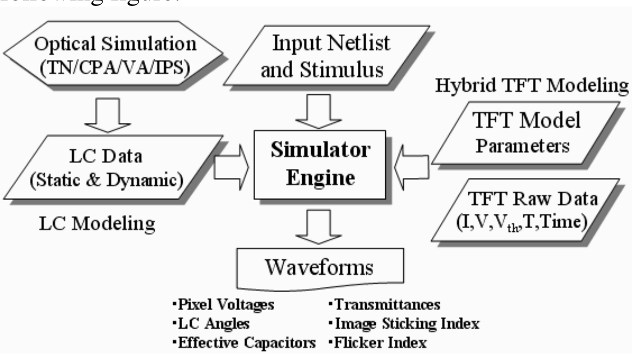

Fig. 9 : Hybrid TFT model with optical co-simulation

4.2 Simulation Results

With a 3x3 test circuit that contains 9 pixels, waveforms of the transmittances for all pixels can be simulated. First, we simulated it with conventional TFT model that over estimates the leakage current. Then, we simulate it with hybrid TFT model that accurately models the leakage current. The false leakage current by conventional model shall cause misjudging the flickering effect because an off-state TFT is supposed to hold the charges stored on the Clc and Cst in Fig. 4.

Table 3 : Comparison of Conventional and Hybrid Model

Model	Max T	Min T	DB	Pass/Fail
Conventional	343.5m	305.3m	-18.61	Fail
Hybrid	321.1m	322.4m	-47.89	Pass

Normally, the transmittance is required to be under -20db at 30 Hz for the flickering to be acceptable [1]. With conventional model, the transmittance ranges from 343.5m to 305.3m and thus results in -18.6db and a 'Fail' judgment, while the numbers from hybrid model is between 321.1m and 322.4m, and the check for the flickering is actually a 'Pass'.

5 CONCLUSION

In this paper, a dynamic modeling approach is proposed to include the LC data from the optical simulators into the electrical circuit simulator MSIM-LCD. So that designers can use the circuit simulator to judge and optimize the TFT designs with the optical behavior of the LC. Moreover, we have developed hybrid modeling technology for TFT off-state leakage current in RPI TFT model so that the flickering problem can be correctly checked when doing design optimization or process selection. We believe the proposed solution can bridge the gap between electrical and optical simulation in a very efficient and accurate way.

6 REFERENCES

[1] M. Watanabe, K. Ishihara, T. Tsuruma, Y. Iguchi, Y. Nakajima and Y. Maki, "Macro-modeling of Liquid Crystal Cell with VerilogA," *IEEE Int. Behavioral Modeling and Simulation conf. Session 5.1*, 2007.

[2] H. Smet, J. Steen, D. Cuypers, "Electrical model of a liquid crystal pixel with dynamic, voltage history-dependent capacitance value," *Liquid Crystals*, Vol 31, issue 5, pp705-711, May 2004.

[3] Jedat, LegendDesign and DaouXilicon, "Jedat, DaouXilicon and Legend Design Jointly Provide True LCD Panel Simulation", *Business Wire*, July 20, 2009.

[4] Ling Wang, M. S. Shur, "Self-Heating and Kink Effects in a-Si:H Thin Film Transistors," *IEEE, Trans. on Elec. Device*, *Vol.47, No.2*, 2000.

[5] S. Sambandan, A. Nathan, "Markov Model for Threshold-Voltage Shift in Amorphous Silicon TFTs for Variable Gate Bias," *IEEE Electronic Device Letters, Vol. 26, No. 6*, June 2005.

[6] Chun-Yao Huang and Huang-Chung Cheng "Study on the Characteristics and Reliability of a-Si:H Thin Film Transistors under AC Gate Bias Stress," *NCTU PhD dissertation*, 2000.

[7] P. Servati, A. Nathan, "Modeling of the Reverse Characteristics of a-Si TFTs," *IEEE Trans. Elec. Devices., vol. 49, pp.812-819*, May. 2002.

[8] DaouXilicon (www.davan.co.kr), ExpertLCD.

[9] SANAYI (www.sanayisystem.com), TechWiz LCD.

[10] ShinTech (www.shintech.co.jp), LCD Master.

[11] MSIM-LCD Manual Version V1001, pp. 3-36.

[12] Y. Yamaji, M. Ikeda, M. Akiyama and T. Endo, "Characterization of Photo Leakage Current of Amorphous Silicon Thin-Film Transistors," *Japan J. of Appl. Phy.*, pp. 6202-6206, 1999.