Mobile Display SONY

BMAS 2007

Macro–modeling of Liquid Crystal Cell with VerilogA

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Outline

1. Background
2. Proposed Model
3. Implementation
4. Evaluation
5. Application to LCD Design
6. Conclusion

1. Background

Background

T V

Portable Game

Digital Still Camera (DSC)

Liquid Crystal Displays (LCDs) pervade in our daily life

Portable DVD Player

Digital Video Camera (DVC)

Portable Music Player

Personal Digital Assistance (PDA)

Personal Computer (PC)

Mobile Phone (MBL)

Background

High Image quality

- High Contrast
- Fast Response
- Low Power Consumption
- Image Uniformity (Low noise), etc.

Compact Design

- Narrow Frame
- Thinner Profile, etc.

Higher expectation from customers

No room and no time to waste in LCD design

Necessity of more accurate and fast simulation

Inexpensive Price

Background

Basic operation of general LCDs

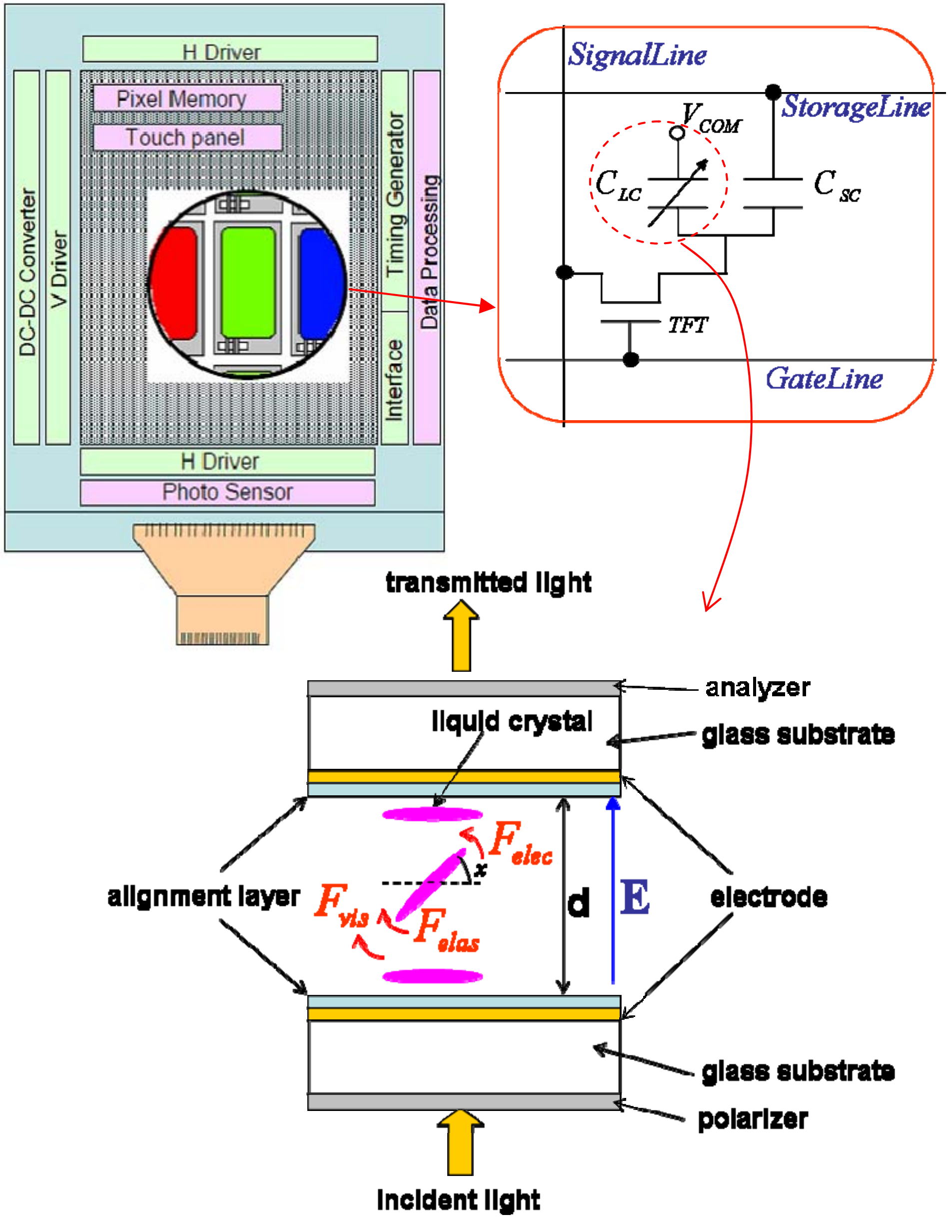
1. Signal pulses for driving LCD are generated in the peripheral circuit.

2. Thin Film transistor (TFT) acts as a switch transferring electrical charges from a signal line to a liquid crystal capacitor (Clc).

3. The charges in Clc generate the electric field E in LC cell.

4. The electric field E tries to align liquid crystal (LC) parallel to E.

5. The transmittance of incident light changes as the orientation of LC.



Liquid Crystal Cell (LC Cell)

Mobile Display

Background

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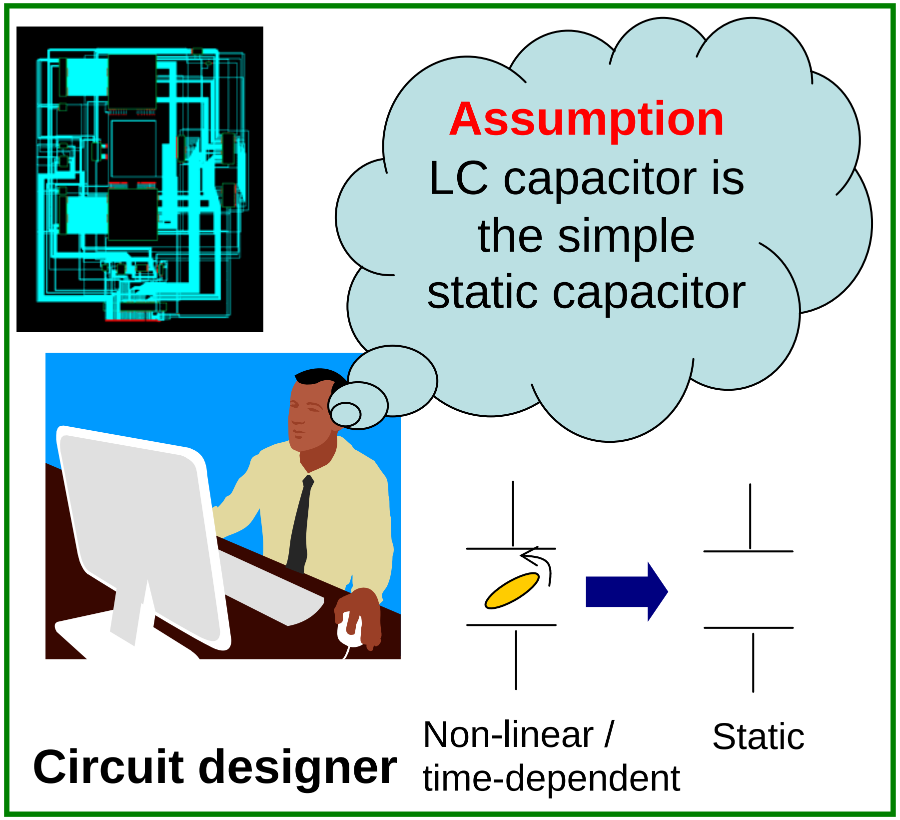
Issues in conventional LCDs' design

In typical circuit simulators…..

- Non-linear and time-dependent capacitor is NOT prepared.
- The influence of electrical behaviors on optical properties can NOT be estimated.

Issues

- **Designers tend to have excessive design margin.**
- **Optical properties of LCDs may not meet the customers' requests.**



Background

The direct method to improve this situation is …

to integrate LC simulator into a circuit simulator.

Liquid Crystal simulation

Poisson equation

$$\nabla \cdot \mathbf{E} = \rho / \varepsilon$$

Iteration until convergence

Torque balancing equation

$$\gamma \frac{\partial \psi}{\partial t} = K \frac{\partial^2 \psi}{\partial z^2} + \Delta\varepsilon \cdot \sin\psi \cos\psi \cdot E^2$$

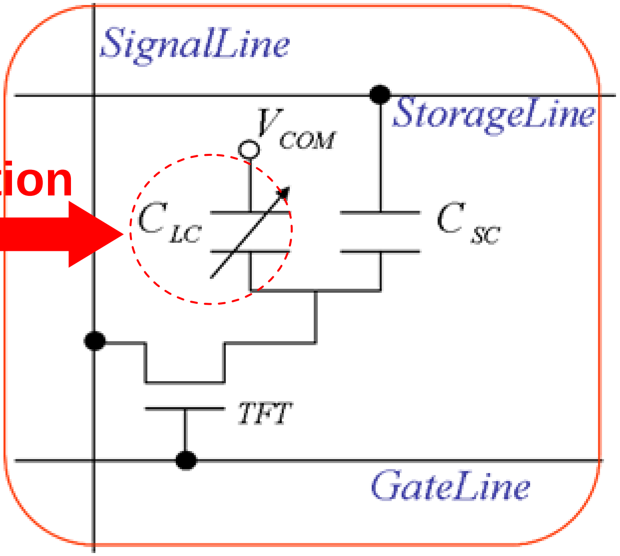
After convergence…

Optical equation

Berreman 4x4 matrix method

implementation

Circuit Simulation



However ….. this way costs huge amount of simulation time due to its heavy iterative algorithm.

Macro-model for LC cell is strongly demanded.

2. Proposed Model

Smet's macro-model

(Liquid Crystal, 31(5):705-711, May 2004)

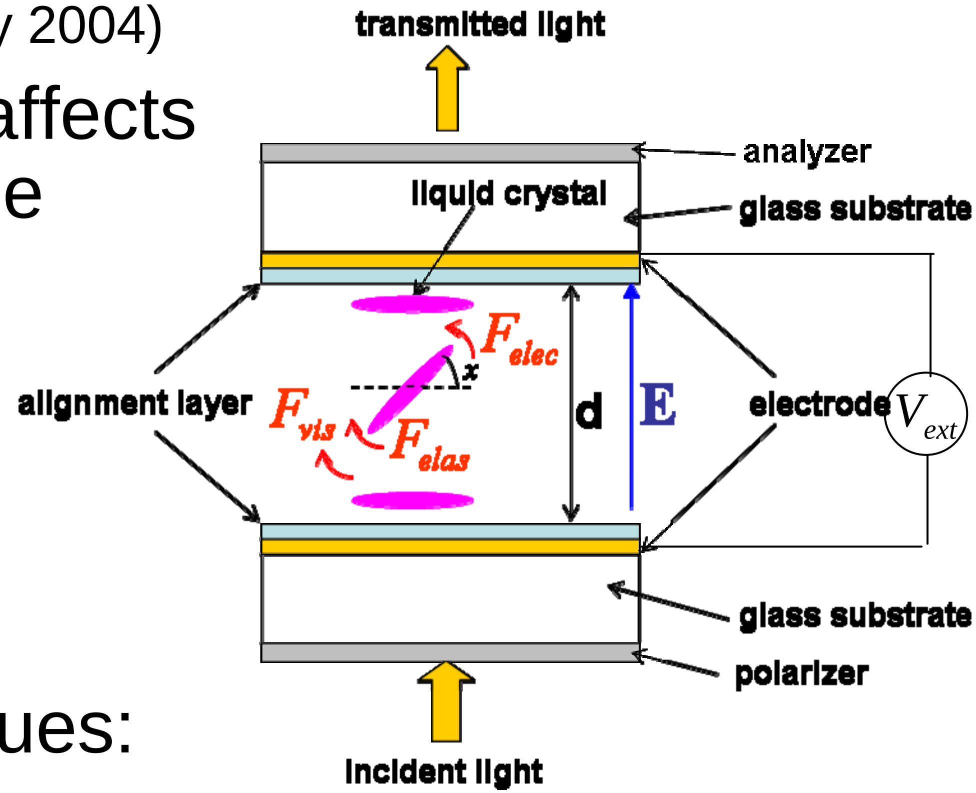
- Three kinds of torque affects a liquid crystal molecule

Elastic : $F_{elas} = Kx$

Electrical : $F_{elec} = cE^2$

Viscosity : $F_{vis} = \gamma \dfrac{dx}{dt}$

$(K, c, \gamma : constatnt)$



- The equilibrium of torques:

$$cE^2 = Kx + \gamma \frac{dx}{dt}$$

➡

Well-known first-order system

- ***Time constant :*** $\tau = \gamma / K$
- ***Steady state :*** $x(t) \rightarrow \dfrac{c}{K}\left[\dfrac{V_{ext}}{d}\right]^2 \quad (t \rightarrow \infty)$

Smet's macro-model (Cont.)

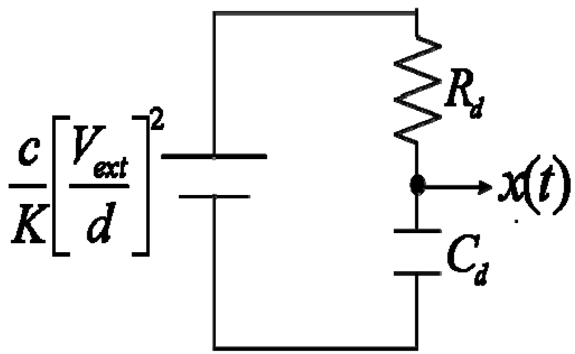
Well-known first-order system

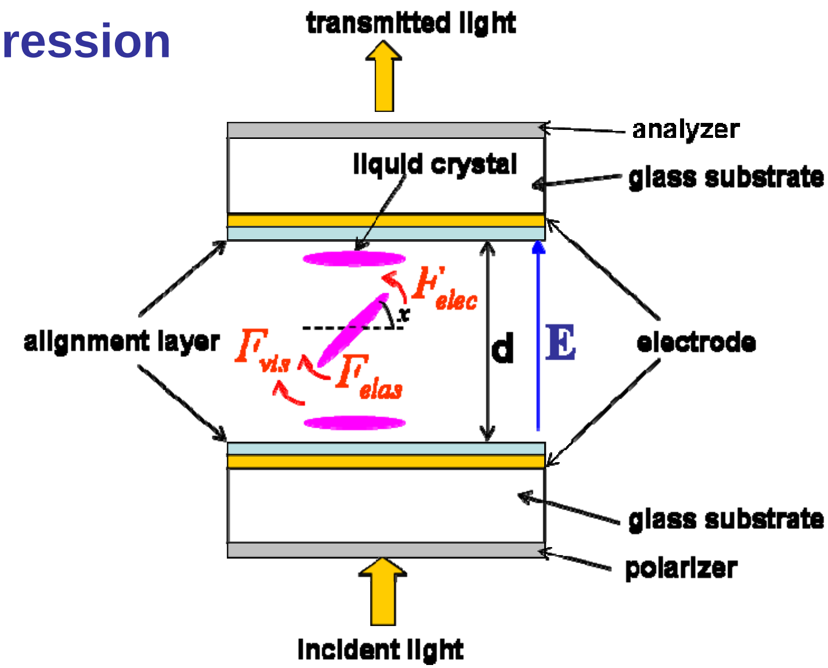
- Time constant : $\tau = \gamma / K$
- Steady state : $x(t) \rightarrow \frac{c}{K}\left[\frac{V_{ext}}{d}\right]^2 \quad (t \rightarrow \infty)$

Equivalent expression

Low pass filter circuit

$$\tau = R_d C_d = \frac{\gamma}{K}$$



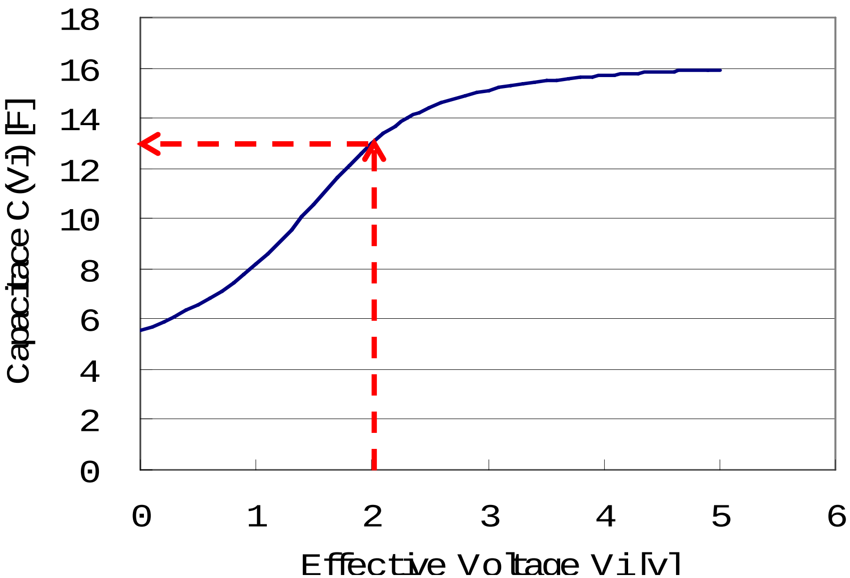


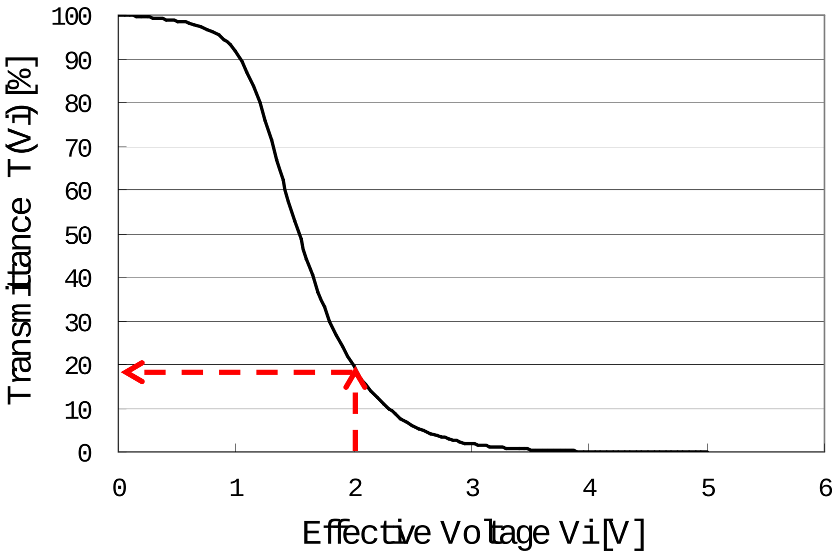
The orientation of liquid crystal molecule x(t) is given as a node voltage of low pass filter circuit.

Smet's macro-model (Cont.)

$$cE^2 = Kx(t)$$: **Equilibrium equation in steady state**

$$V_i = \sqrt{\frac{Kd^2}{c}x(t)}$$: **Effective voltage**





$$C(V_i) = C_\perp + \frac{2}{\pi}(C_{||} - C_\perp)\arctan\left[\frac{\alpha + (\alpha^2 + \delta^2)^{\frac{1}{2}}}{2}\right]$$

$$\alpha = \frac{V_i - V_{tc}}{V_{mc}}$$

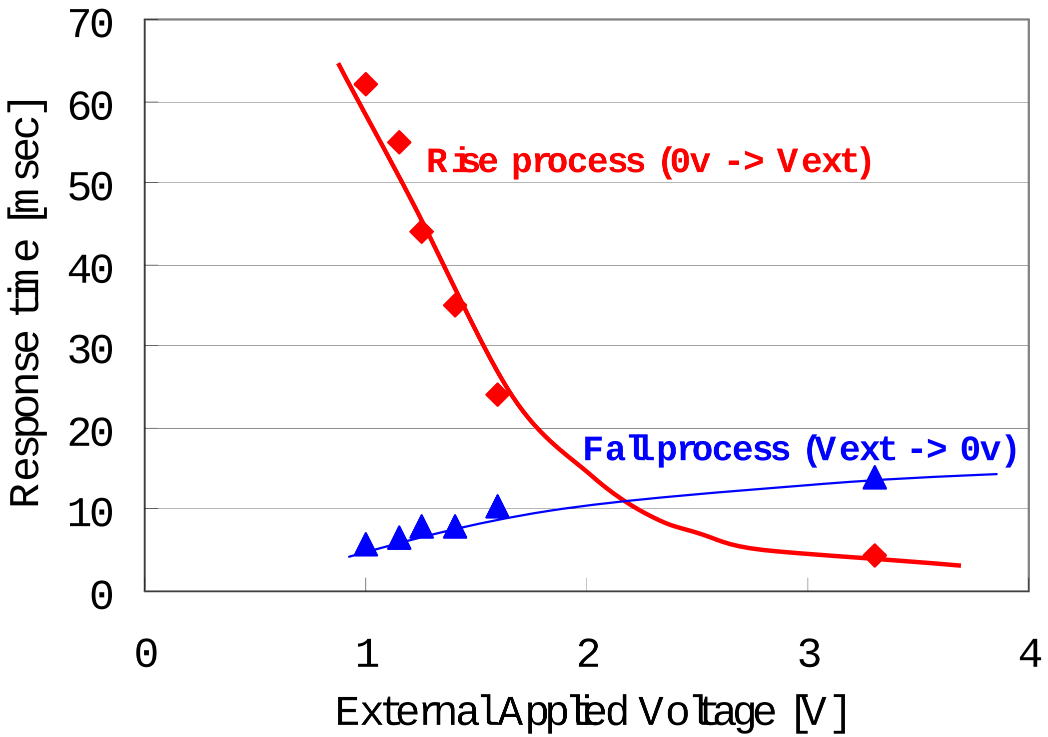
$$T(V_i) = T_{min} + (1 - T_{min})\tanh\left[\frac{\beta + (\beta^2 + \eta^2)^{\frac{1}{2}}}{2}\right]$$

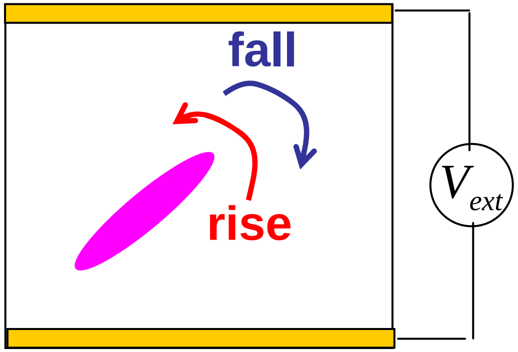
$$\beta = \frac{V_i - V_{to}}{V_{mo}}$$

Issues in Smet's model

Following trends are not supported.

1. **External applied voltage dependency**
2. **Individuality of rise/fall process**





Response time dependencies on the external applied voltage (Measured)

*** Response time is defined as the time constant**

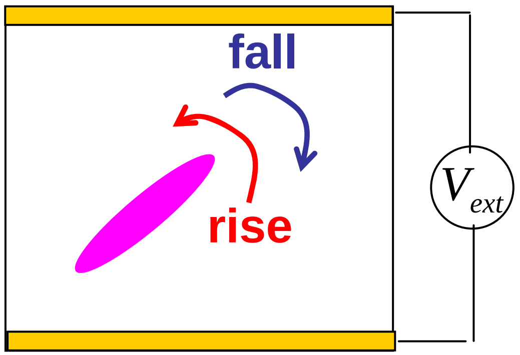
Proposed model

Model enhancements to improve accuracy by authors

(1) External applied voltage dependency

$$\tau = R_d \cdot C_d = \frac{1}{a_1 + a_2 V_{ext}^m}$$

(a1, a2, m : model parameters)



(2) Individuality of rise/fall process

if

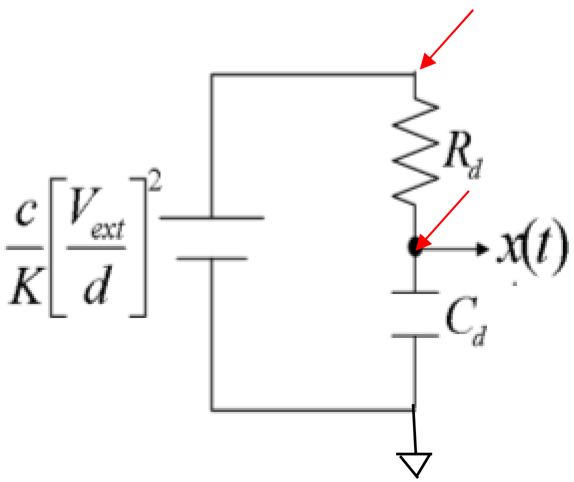
$$\frac{c}{K}\left(\frac{V_{ext}}{d}\right)^2 \geq x(t)$$

then

$$a_1 = a1\_r,\ a_2 = a2\_r \quad (for\ rise\ process)$$

else

$$a_1 = a1\_f,\ a_2 = a2\_f \quad (for\ fall\ process)$$



3. Implementation

SONY

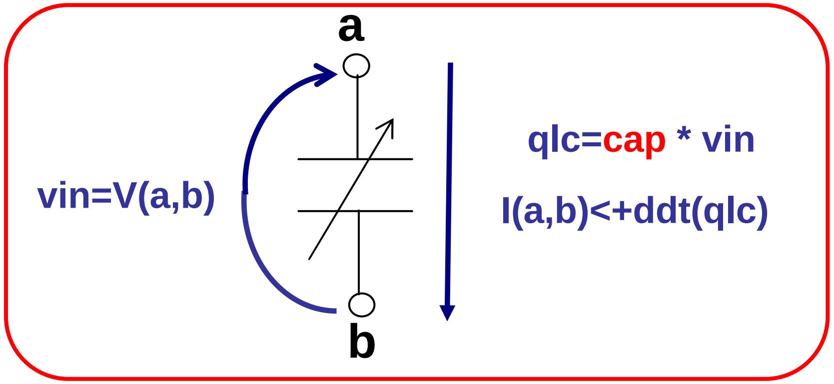
Why with VerilogA?

- **Flexibility**
  - High potential in mixed technology modeling
- **Simple implementation**
  - Many commercial simulators support VerilogA interface.
- **Availability of ADMS** (To get much higher performance)
  - Easier implementation compared with that of C-Code
  - Superiority in keeping the confidentiality of models

Implementation

VerilogA Code

~ Electrical property block (Excerpt) ~



Interface with a circuit simulator

```
// VerilogA for Liquid Crystal Capacitor
`include "discipline.h"
module lccap(a,b);
inout a,b; //Interface ports
electrical a,b;
electrical nvc; //Internal node
                              ...
analog
begin
  @(initial_step)

     begin
                              ...
//Initial voltage for internal node
     vi_c = vini * vini;
end

begin
//Probing terminal voltage
  vin = V(a,b);
  vv = vin * vin;

//Detection of rising or falling
    if (vv >= vi_c)
     begin //rising
       a1c = a1c_r;
                              ...
     end
    else
     begin //falling
       a1c = a1c_f;
                              ...
     end
//
  rdc = 1/(a1c + a2c * pow(vin, mc) );

// Calculation of Internal node voltage
  I(nvc) <+ ddt(cdc * V(nvc));
  I(nvc) <+ (V(nvc)−vv)/rdc;
  vi_c = V(nvc);
//
  vrms_c = sqrt(vi_c);
  alpha = (vrms_c − vtc)/vmc;

// Capacitance calculation
cap = scale * area * (cv + cdiff * atan((alpha
     +sqrt(alpha * alpha + delta * delta ))/2));

// Description for device behavior
qlc = cap * vin;
I(a,b) <+ ddt(qlc);

   end
  end
endmodule
```

VerilogA Code

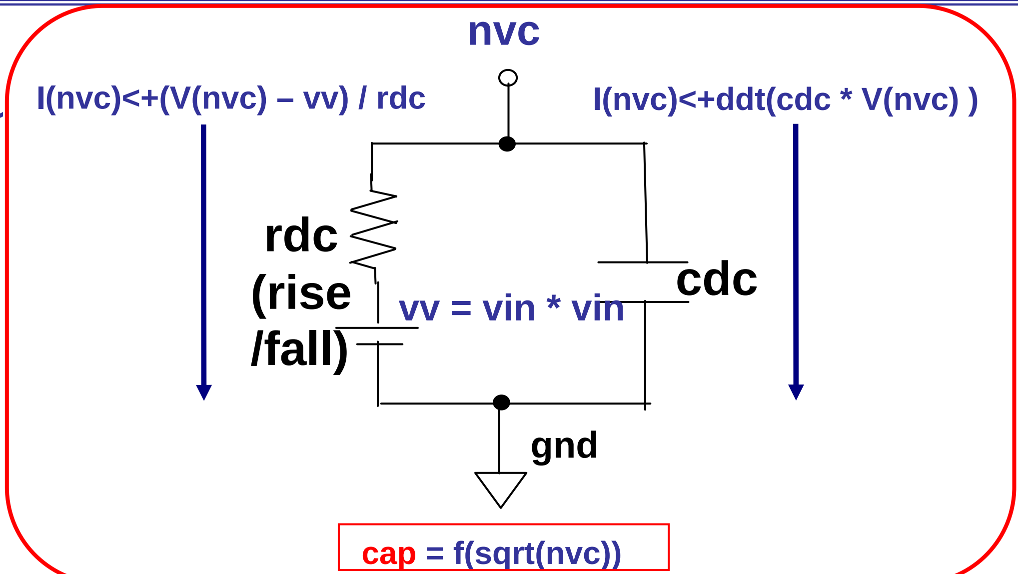
~ Electrical property block (Excerpt) ~

```
// VerilogA for Liquid Crystal Capacitor
`include "discipline.h"
module lccap(a,b);
inout a,b; //Interface ports
electrical a,b;
electrical nvc; //Internal node
                    ...
analog
begin
 @(initial_step)

    begin
//Init
    vi_
end

begin
//Pro
 vin =
 vv = vin * vin;

//Detection of rising or falling
 if (vv >= vi_c)
  begin //rising
     a1c = a1c_r;
                    ...
  end
 else
  begin //falling
     a1c = a1c_f;
                    ...
  end
```



This circuit is only used for the evaluation of the liquid crystal orientation and should not behave as the load of the actual external circuit.

```
//
 vrms_c = sqrt(vi_c);
 alpha = (vrms_c − vtc)/vmc;

// Capacitance calculation
cap = scale * area * (cv + cdiff * atan((alpha
      +sqrt(alpha * alpha + delta * delta ))/2));

// Description for device behavior
qlc = cap * vin;
I(a,b) <+ ddt(qlc);

  end
 end
endmodule
```

Judge whether it's rise or fall process

Implementation

ADMS has been used to attain much higher performance.

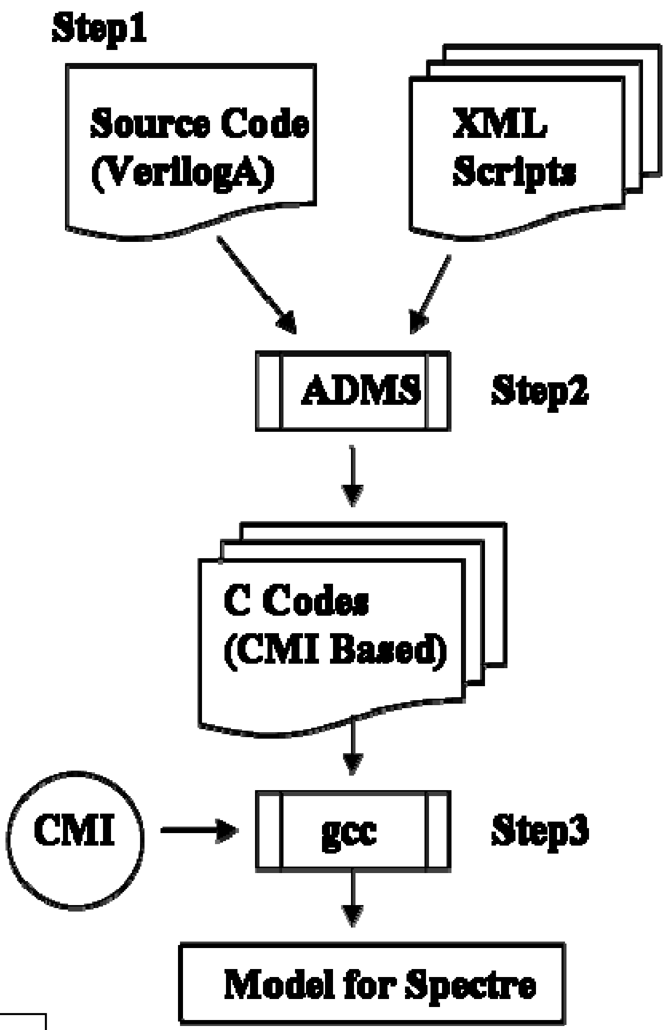
Procedure

Step1. Prepare a "Source code" in VerilogA and XML Scripts provided by Cadence.

Step2. ADMS translates VerilogA code into some C-codes.

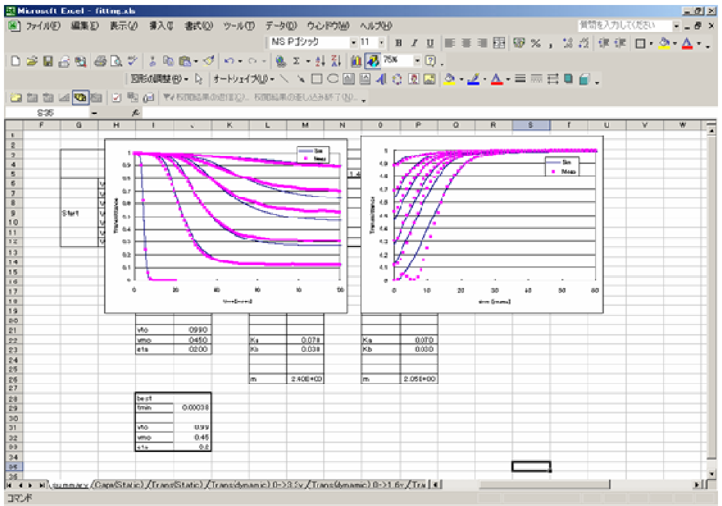
Step3. C-codes is compiled by gcc with Spectre-CMI library.

Model module running on Spectre

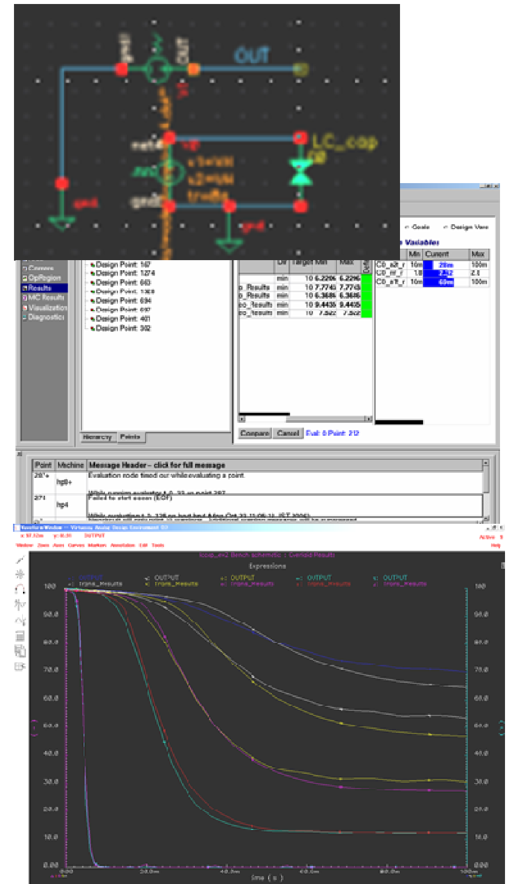


Implementation

Parameters Extraction



Rough fitting with spread sheet



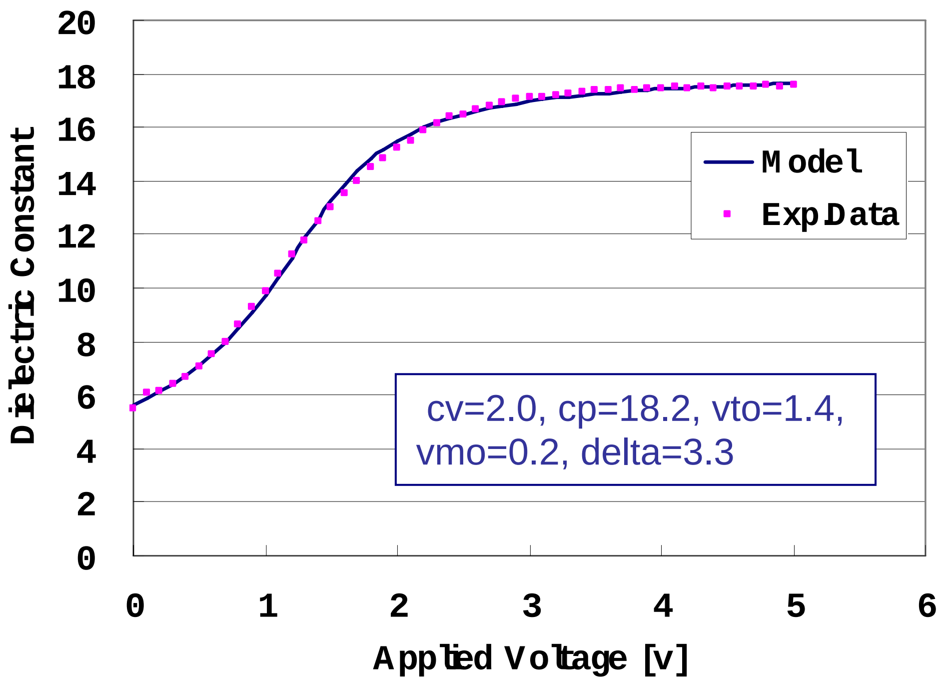
Accurate fitting with Genetic Algorithm (GA) tool

* Neocircuit ® (Cadence)

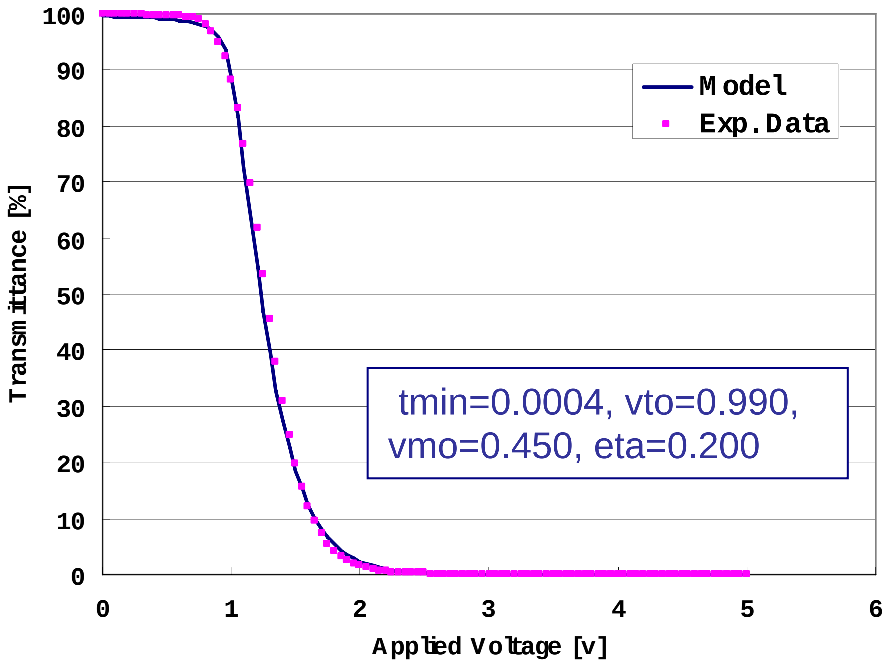
4. Evaluation

Model Validity

- Static electrical /optical behavior



(a) Capacitance



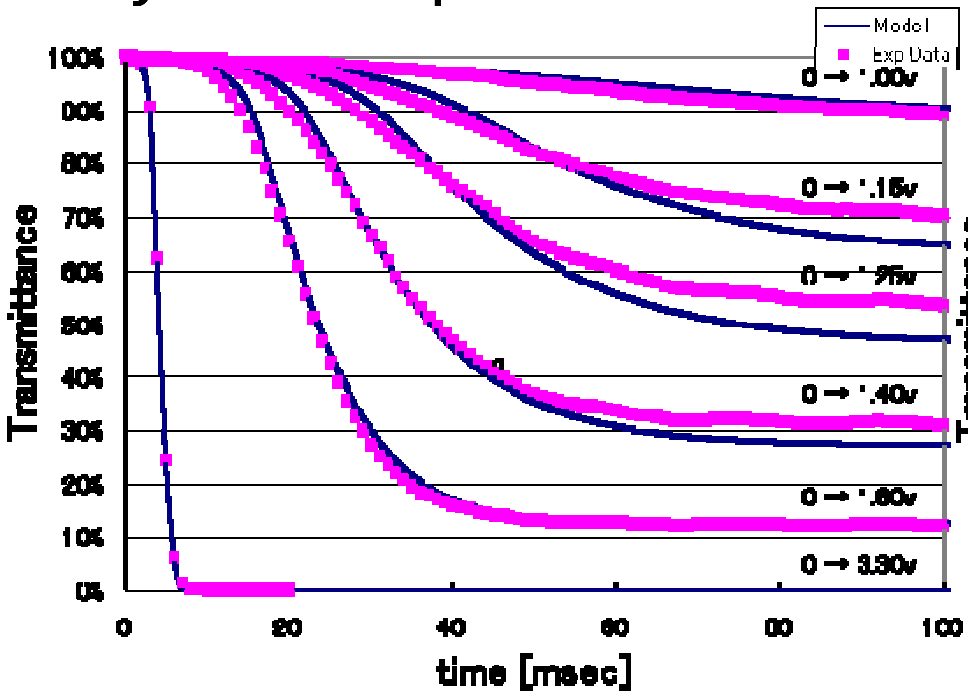
(b) Transmittance

Good agreement with the experimental data

Model Validity

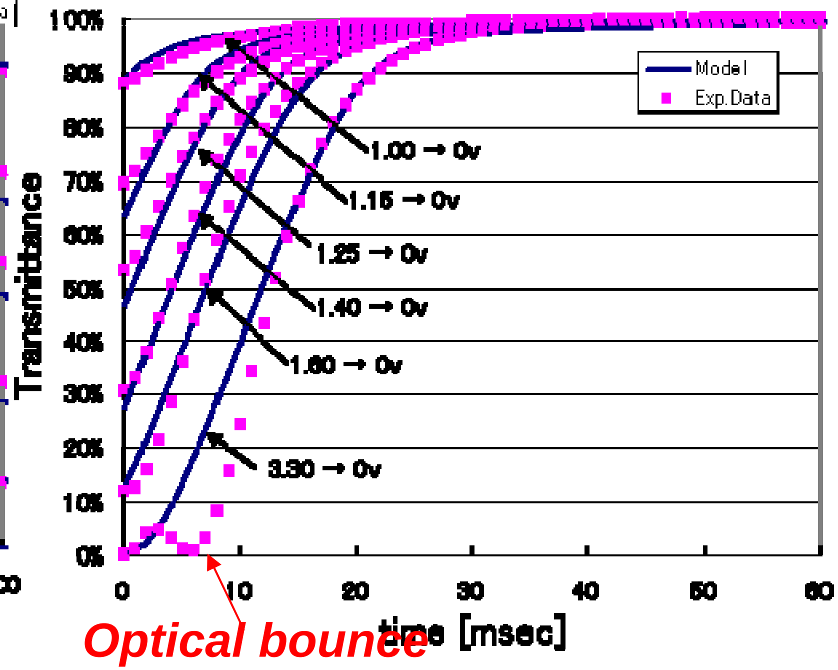
* Method to measure the dynamic capacitance of LC cell has not been established.

- Dynamic optical Behavior



a1t_r=0.070, a2t_r=0.030, mt_r=2.40

(a) Rise process



a1t_f=0.070, a2t_f=0.030, mt_f=2.05

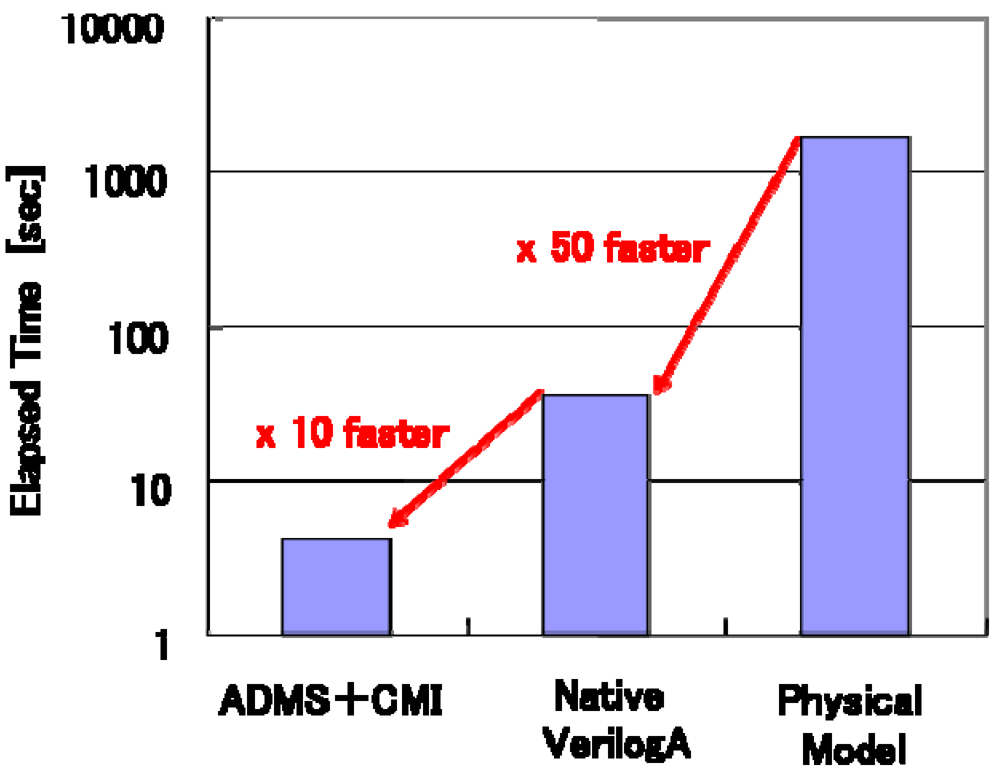
(b) Fall Process

Good agreement with the experimental data

Performance

- "ADMS+CMI" is …
  - 10 times faster than " Native VerilogA"
  - 500 times faster than "Physical Model"
- All bench mark tests are performed on Spectre®.
- Physical model is implemented by Spectre CMI®.

500 times faster than the conventional physical model



Simulation Condition

- 720 liquid crystal cells array
- transient time : 200msec
- CPU : 3.2GHz Intel® Xeon™
- Memory : 4GB

5. Application to LCD Design

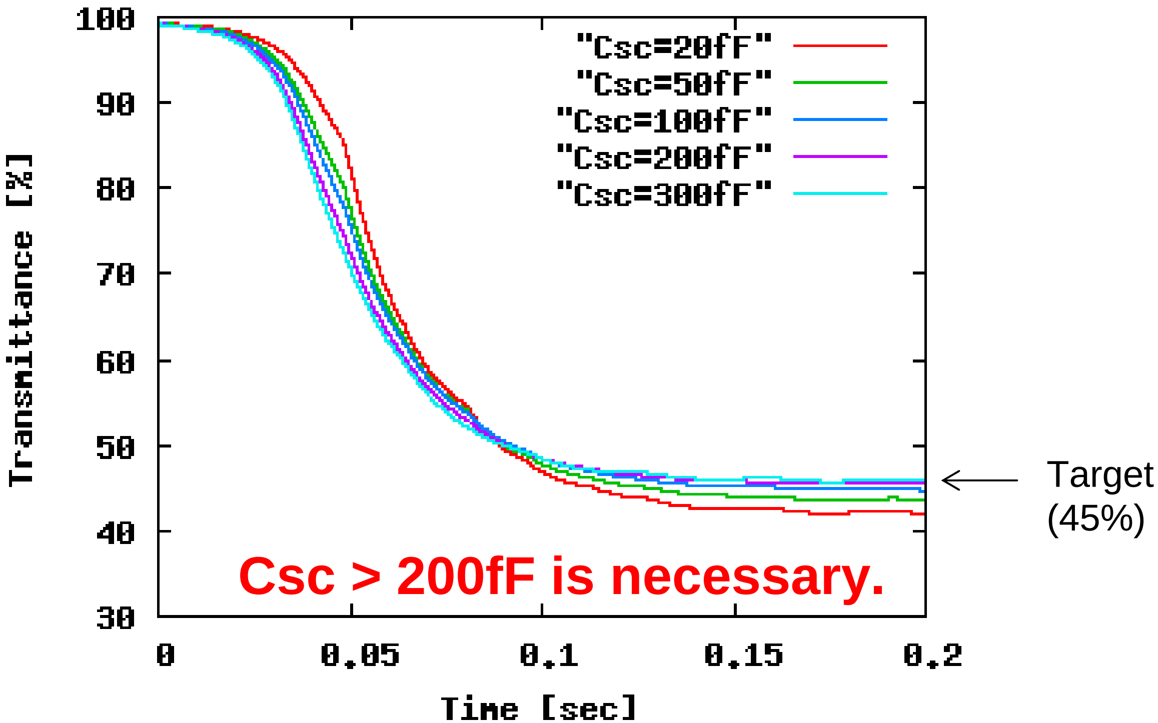
Application to LCD design

1st Example : Storage Capacitor (Csc) optimization

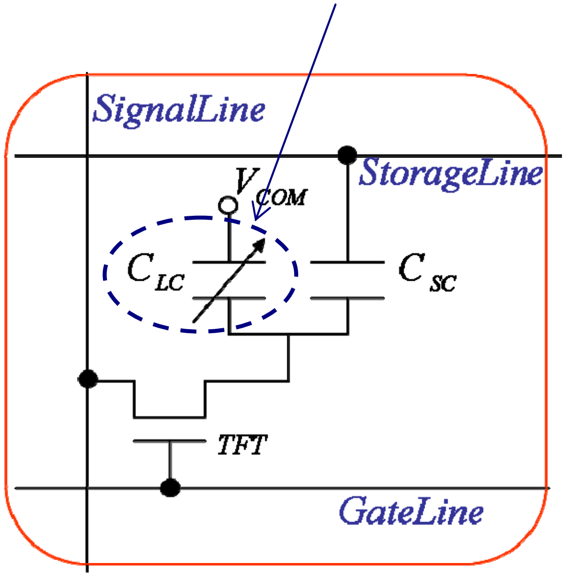
Insufficient Csc causes…

A) Low-speed response time

B) inadequate transmittance



Macro-model



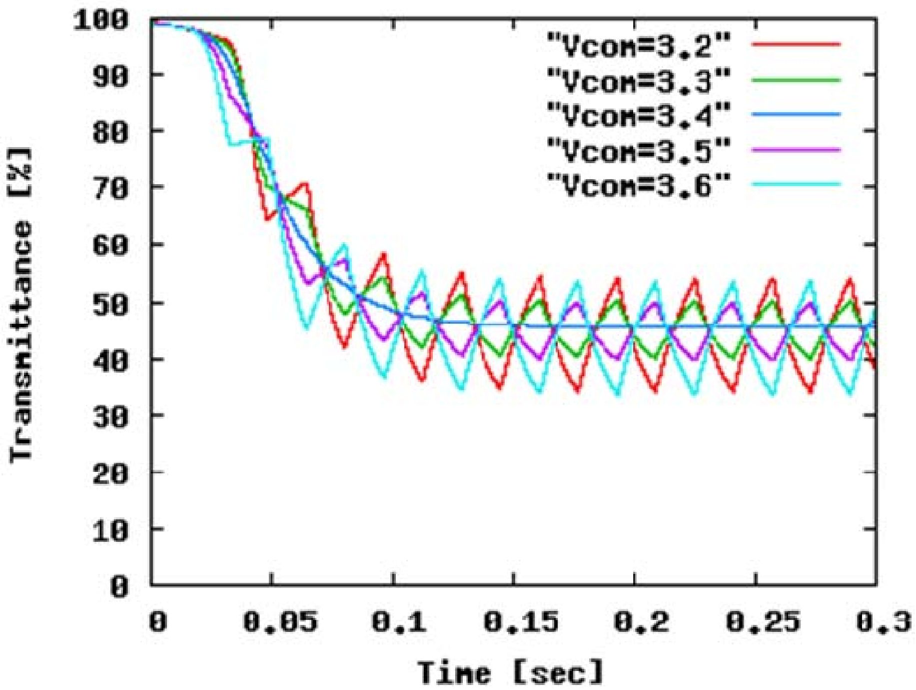
Designers can estimate the optimum size of Csc.

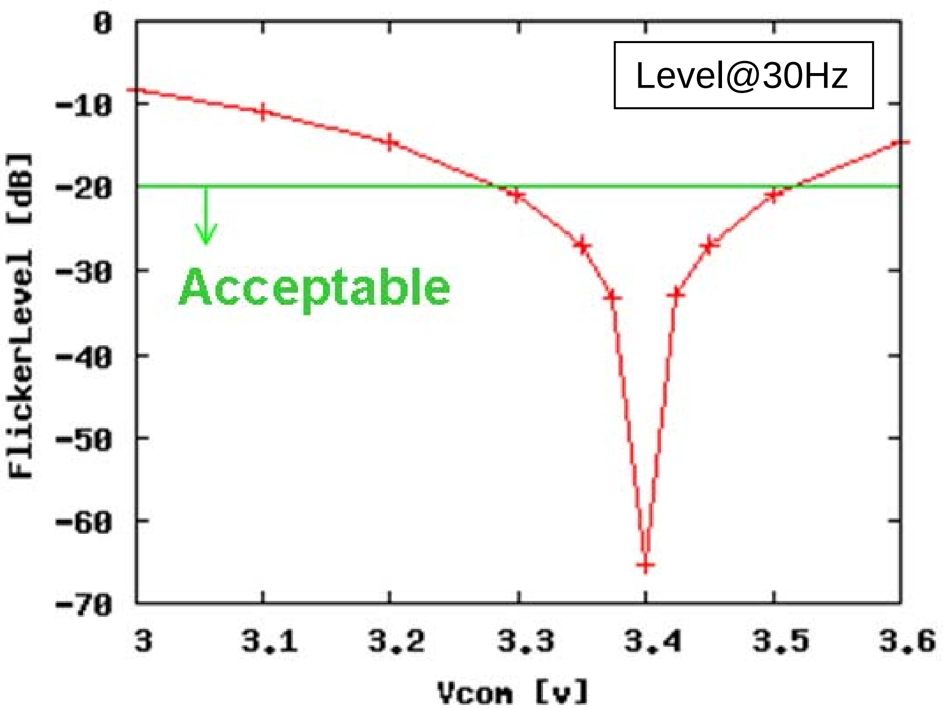
Application to LCD design

2nd Example : Common voltage (Vcom) optimization

Failure to optimize Vcom induces flicker image.

Flicker image terribly degrades the display quality.





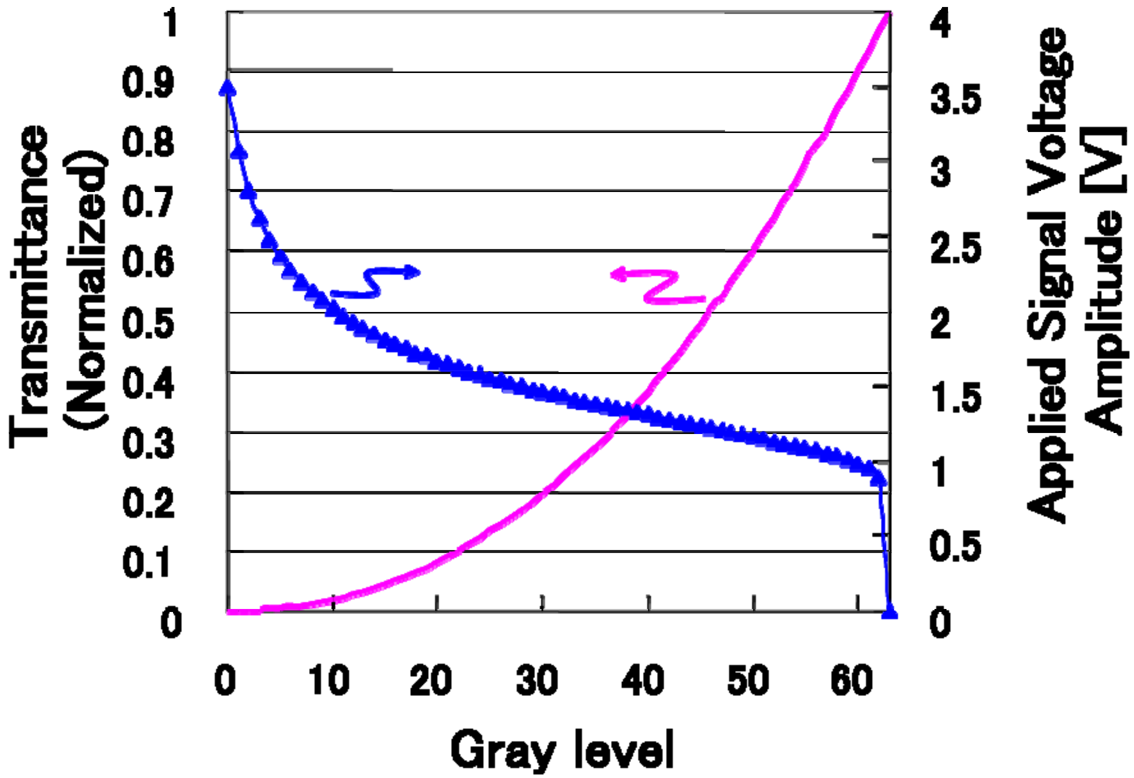
Vcom should be set to 3.3 ~ 3.5 v

Designers can estimate the optimum Vcom

Application to LCD design

3rd Example : Signal voltage optimization for each gray level

Generally, the relationship between the gray level and the transmittance is given by customers.



Designers can optimize the signal voltages for each gray level.

6. Conclusion

Conclusion

- Developed an accurate macro-model for a LC cell
  - Included some enhancements to the model based on Smet’s
  - Verified its validity by fitting it to measurement data

- Integrated into Spectre® with VerilogA and ADMS
  VerilogA : suitable for multi-technology modeling (electrical / optical)
  ADMS : realize much higher performance
  (x500 faster than physical model)

- Provides useful information for optimum LCD design
  We took following property of LC cells into account
  - Non-linear time-dependent capacitor
  - Optical device varied with the applied voltage

Acknowledgement

We are grateful to Dr.Laurent Lemaitre and Cadence Design Systems for helpful advice and discussion in implementing our model into Spectre® on Cadence Virtuoso® platform.

Thanks to your attention

Auxiliary Slides

Deviation of equation

In this appendix, we derive the form of the voltage dependent time constant shown in equation(4).
$\boldsymbol{n}(|\boldsymbol{n}|=1)$ is director vector of liquid crystal. The director vector $\boldsymbol{n}$ roughly denotes the averaged orientation of the liquid crystal molecules. $\boldsymbol{E}$ is the electric field in the cell. As easily derived, the projection of $\boldsymbol{E}$ parallel to $\boldsymbol{n}$ is $(\boldsymbol{E},\boldsymbol{n})\boldsymbol{n}$ and perpendicular to $\boldsymbol{n}$ is $\boldsymbol{E}-(\boldsymbol{E},\boldsymbol{n})\boldsymbol{n}$ respectively. Therefore the displacement field vector $\boldsymbol{D}$ can be written as in equation (5). Note that the dielectric constants of liquid crystal differs in value along the parallel to the axis($\epsilon_{\|}$) and perpendicular to the axis($\epsilon_{\perp}$).

$$\boldsymbol{D}=\epsilon_0[\epsilon_{\|}(\boldsymbol{E},\boldsymbol{n})\boldsymbol{n}+\epsilon_{\perp}\{\boldsymbol{E}-(\boldsymbol{E},\boldsymbol{n})\boldsymbol{n}\}] \qquad (5)$$

In this case, the electromagnetic energy density U can be written in equation(7).

$$U = -\frac{1}{2}\epsilon_0(\boldsymbol{E},\boldsymbol{D}) \qquad (6)$$

$$= -\frac{1}{2}\epsilon_0[(\epsilon_{\|}-\epsilon_{\perp})(\boldsymbol{E},\boldsymbol{n})^2+\epsilon_{\perp}|\boldsymbol{E}|^2] \qquad (7)$$

Here z-axis is parallel to $\boldsymbol{E}$, θ is the angle between $\boldsymbol{n}$ and z-axis, and ϕ is the angle between the projection vector of $\boldsymbol{n}$ into x-y plane and x-axis. $\boldsymbol{E}$ and $\boldsymbol{n}$ are expressed as $\boldsymbol{E}=(0,0,E_z)$, $\boldsymbol{n}=(\cos\theta\cos\phi,\cos\theta\sin\phi,\sin\theta)$, then equation (8) can be derived from equation (7).

$$U=-\epsilon_0(\epsilon_{\|}-\epsilon_{\perp})E^2(\epsilon_{\|}\sin^2\theta+\epsilon_{\perp}\cos^2\theta)+\epsilon_{\perp}E_z^2 \qquad (8)$$

Applied torque to director by the electric field is shown in equation(10).

$$f = -\frac{\partial U}{\partial\theta} \qquad (9)$$

$$= \frac{1}{2}\epsilon_0(\epsilon_{\|}-\epsilon_{\perp})E^2\sin(2\theta) \qquad (10)$$

Under the assumption that $\sin\theta\approx\theta$ when θ is very small,

$$f=\epsilon_0(\epsilon_{\|}-\epsilon_{\perp})E^2\theta \qquad (11)$$

For the convenience, the dielectric anisotropy $\Delta\epsilon$ is defined as $\Delta\epsilon\equiv\epsilon_{\|}-\epsilon_{\perp}$. Then,

$$f=\epsilon_0\Delta\epsilon E^2\theta \qquad (12)$$

When equation (12) replaces the electrical term in equation(1), torque balance equation(1) can be rewritten by equation(13).

$$\epsilon_0\Delta\epsilon E^2\theta = K\theta+\gamma\frac{d\theta}{dt} \qquad (13)$$

$$\frac{d\theta}{dt} = \left(\frac{\epsilon_0\Delta\epsilon E^2-K}{\gamma}\right)\theta \qquad (14)$$

Therefore the time constant for equation(14) can be expressed as follows.

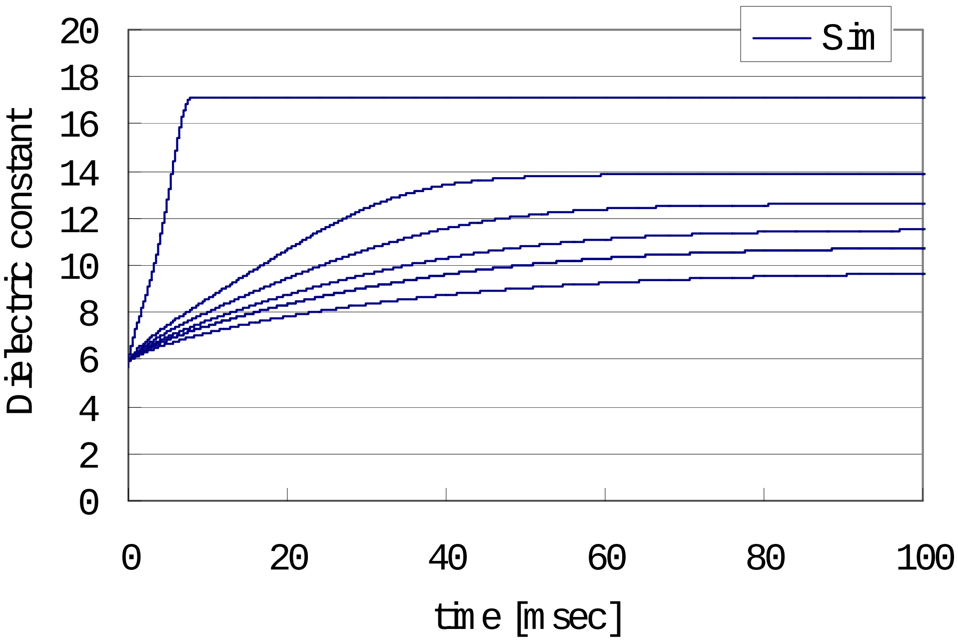
$$\tau = \frac{\gamma}{\epsilon_0\Delta\epsilon E^2-K} \qquad (15)$$

$$= \frac{1}{\left(\frac{\epsilon_0\Delta\epsilon}{\gamma}\right)\left(\frac{V}{d}\right)^2-\left(\frac{K}{\gamma}\right)} \qquad (16)$$

$$\equiv \frac{1}{a_1+a_2V^2} \qquad (17)$$

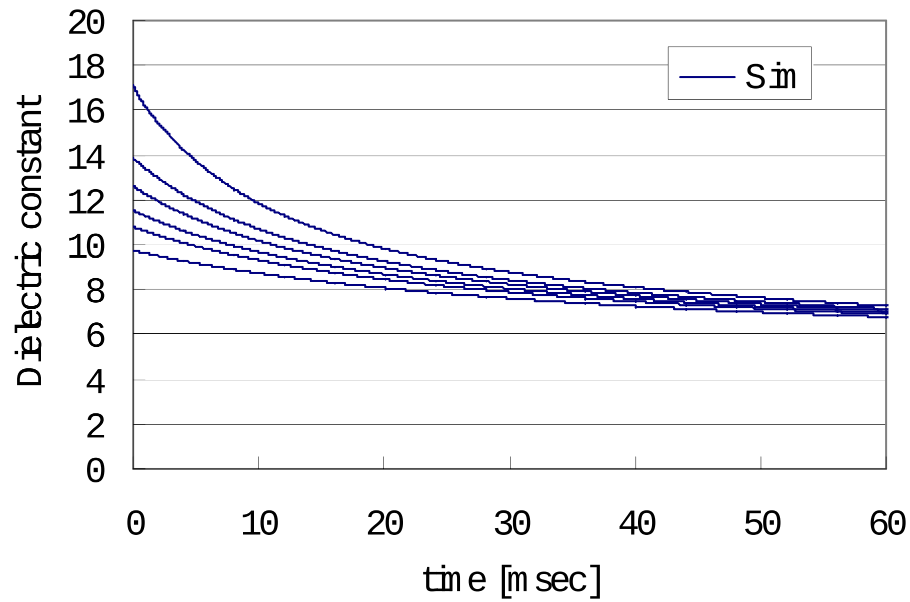
Model Validity

- Dynamic electrical Behavior



a1c_r=0.070,
a2c_r=0.030, mt_c=2.40

(a) Rise process



a1c_f=0.070,
a2c_f=0.030, mt_c=2.05

(b) Fall Process