Electrical Characterization of Organic Electronics

“Radical new model for TFTs”
(thin-film field-effect transistors)

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Overview

Introduction of Faro, Opto-EI and CEOT

History examples: DLTS, $H_2O$, LE-FET

Modeling of Thin-Film Transistors
Organic Electronics

Phils MP3 Player 512MB, SA 177
Your music, your data – on the go.
Enjoy up to 12-hour music playback (MP3/WMA), make voice recordings and transfer your files easily through direct USB 2.0. The SA177 has large 2-color OLED display and an elegant mirror surface.

Other features: Clock function screen saver; Equalizer for optimized sound; Folder view display to find songs in a simple fast way.

Accessories: Headphones; USB extension cable; Quick start guide and neck strap; Includes software for Windows 98 SE and higher.

RRP: € 109,00 € 88,00
FB members: earn 176 Miles

KLM in-flight brochure
AMS-WAW, 24 sep 2005
The Algarve is famous for tourism:

300 days per year sunshine
Temperatures all year pleasant: 15 - 30°C
Great food, low prices, friendly people
300 km of clean sand beaches
Good airport and other infrastructures

“Ieder voordeel heb z’n nadeel”
(Every advantage has its disadvantage)

- Johan Cruyff
10,000 students, 5 Faculties, 4 Campi, 700 teachers, 60 courses.

Faculdade de Ciências e Tecnologia (FCT), 90 profs.

Departamento de Engenharia Electrónica e Informatica (DEEI), 20 profs.

3 Courses (ESI, EI and I)

Areas of ESI: Electronics, Control, Signal Processing, Telecommunications

The university is the heart of The Algarve

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Although being a young university, The university of the Algarve is the second most science productive university of Portugal (2004)*. … and still improving.

Our course (ESI) is becoming first choice for Portuguese students of electronic engineering.

* counting number of papers per head
Opto-Electrónica
Universidade do Algarve
Founded: 1997
2 members (PhD)

Centro de Electrónica,
Opto-Electrónica e Telecomunicações
Founded in 2001
9 members (PhD)
In 2003, CEOT was evaluated by an external committee of FCT (Portuguese foundation) as “very good” and received a 640 k€ equipment investment bonus in 2004 apart from the normal individual project grants.
Opto-EI

Specialized in characterization of organic electronic materials and devices

Apart from that, recently started sensors: TNT, DNA
instrumentation: quartz-crystal oscillator, MEMs, etc.

Organic electronics  HIV detector
example: DLTS

Opto-EI. First successful implementation of a DLTS experiment in an organic material

All organic materials suffer from the detrimental effects of water*. 

\*H.L. Gomes et al., submitted (2005).

**phase transition at 200 K**

Above 200 K all organic materials are electrically unstable.
example: Light-emitting FET

source

drain

1 mm
You are looking at the first picture ever taken showing light coming out of an FET … (Bologna, 2003)

Main topic for today: (organic) thin-film transistors

Tradition is to use the inversion-channel metal-oxide field-effect-transistor (MOS-FET) model for TFTs

I will show you this is nonsense and then present an alternative
(“If you don’t give a solution, you are part of the problem!”)
Inversion-channel MOS-FET

\[ C_{ox} = \varepsilon_{ox}/d \]

taken from our OptoEl theory pages,
http://www.ualg.pt/fct/adeec/optoel/theory
Inversion-channel MOS-FET

Next slide: look at cross-section of device
Inversion-channel MOS-FET

“Flat-band” situation
bulk is p-type

Starting structure: MIS diode
(= FET without electrodes)
Inversion-channel MOS-FET

“Depletion” Applying bias

“gate” “source-drain”

V_{ext}
“Onset of inversion”

Free charge density, \( n \), grows exponentially with bias.
Inversion-channel MOS-FET

“Strong inversion”

Free charge density $n$ grows linearly with bias

Defines “threshold voltage” $V_t$ as voltage needed to start a channel

Electron channel

$V_{ext}$

Degraded and unoccupied states

Strong accumulation

Accumulation

Normal (bulk)

Depletion

Inversion

Strong inversion

Filled band

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Inversion-channel MOS-FET: 1

IV curves

transfer curves

FET = MIS diode with lateral electrodes connected to measure the channel conductivity (charge density)
Inversion-channel MOS-FET

“Accumulation”

Convention in literature

Just reverse band bending!

$p$?
Inversion-channel MOS-FET

“Strong Accumulation”

Convention in literature

Just reverse band bending!

hole channel

$V_{ext}$

- strong accumulation
- accumulation
- normal (bulk)
- depletion
- inversion
- strong inversion
- filled band
Thin-film transistors (TFTs)

Two fundamental problems:

1: This doesn’t work for TFTs!
- thin films cannot accommodate band bendings!
  (there is simply no space for them)
  band-bendings are of order 300 nm ($N_A = 10^{16} \text{ cm}^{-3}$),
  films are 1 monolayer (5 nm), without loss of functionality.

2: Concept of band-bending in accumulation is nonsense!
- There are no electronic levels to store immobile charge
  needed for band bending.
Thin-film transistors (TFTs)

Only first monolayer is important*

*F. Biscarini et al.
Band bending in accumulation? Nonsense!

2: Concept of band-bending in accumulation is nonsense!

Poisson’s Equation:

\[ V(x) = \int \int \rho(x) dx^2 \]

Inversion:
Negative charge needed
Band bending is caused by uncompensated ionized acceptors

Accumulation:
Positive charge needed. but:
Acceptors can only be neutral or negative
2: Concept of band-bending in accumulation is nonsense!

Accumulation:
Positive charge can only appear in the material as free holes. They will therefore always move towards the interface. No space charge (band bending)
Postulate for TFT: Purely two-dimensional treatment

All charge is at the interface.

\[
\rho(x) = C_{ox}[V(x) - V_g]
\]

C/m², F/m², V

(note the two-dimensional units)
Is this allowed? How thick is an accumulation layer?

\[ \rho(x) = C_{ox} [V(x) - V_g] \]

Example: Silicon TFT, typical values:

\[ V_g = -1 \text{ V}, \quad d_{ox} = 200 \text{ nm} \quad (C_{ox} = 170 \mu\text{F/m}^2) : \]
\[ \rho = 0.17 \text{ mC/m}^2 \]

with \( N_V = 1.04 \times 10^{19} \text{ cm}^{-3} : \)
\[ h < 1 \text{ Å} \]
I: Assume $\rho = p$, free holes

II: Locally, current is proportional to charge density, mobility, electric field and channel width

\[
p(x) = C_{ox} [V(x) - V_g] \quad \text{(I)}
\]

\[
I_x(x) = p(x) q \mu W \frac{dV(x)}{dx} \quad \text{(II)}
\]
Boundary conditions:

\[ V(0) = 0 \]
\[ V(L) = V_{ds} \]
\[ I_x(x) = I_{ds} \]

Solution:

\[ I_{ds} = \frac{W}{L} \mu C_{ox} (V_{ds} V_g - \frac{1}{2} V_{ds}^2) \]
Simulation

\[ I_{ds} = \frac{W}{L} \mu C_{ox} (V_{ds} V_{g} - \frac{1}{2} V_{ds}^2) \]

Exactly equal to MOS-FET model!
The basic model doesn’t include

• Donors or acceptors
• Flat-band voltage
• Diffusion currents

and still explain the data better
**“Contact effects”**

**Theory:**

- Drain-Source Current (nA) vs. Drain Source Voltage (V)
  - IV Curves
  - $V_g$:
    - 10 V
    - 9 V
    - 8 V
    - 7 V
    - 6 V
    - 5 V
    - 4 V
    - 3 V

**Experiment:**

- Drain Source Voltage (V) vs. Drain Source Voltage (V)
  - $I_D$ (pA)

- $V_G = -10V$
- -8V
- -6V
- -4V
- -3V
- 0V

**Literature:** contact effects

“Contact effects”

Literature: contact effects.

The idea is simple. Non-low-ohmic contacts hinder the injection of carriers and can cause non-linearities.

(Too) often used to explain the data.

“sweep-under-the-carpet” argumentation.

Next slides: simulations of high-resistive contacts and Schottky barriers.
"Contact effects", simulation of contact resistance

current crowding observed for high $R$ (curves indep. of $V_g$)

No non-linearities
“Contact effects”, simulation with Schottky barriers

Double Schottky barrier:

\[ I_{ds} = \tanh(V_{ds}) \]

No non-linearities!
Simulation with Poole-Frenkel

\[ p(x) = C_{ox}[V(x) - V_g] \]  

(I)

\[ I_x(x) = p(x)q\mu(x)W \frac{dV(x)}{dx} \]  

(II)

\[ \mu(x) = \mu_0 \exp(dV(x)/dx) \]  

(III)

Poole-Frenkel: “Field-assisted thermal activation from traps”

Simulation:
Modeling the contacts

This is, of course, only half the story. If contacts are not resistance nor Schottky barrier, what are they?
Modeling the contacts

First observation. Analysis of an MOS-FET n-p-n Si-Si-Si device

zero bias:

\[ E_C \]
\[ E_F \]
\[ E_V \]

\( V_g = V_t \):

Barrier disappears exactly at start of strong inversion
1: charge will raise potential of channel \( p = C_{ox} V \)

2: charge will move Fermi level \( p = \text{Exp}(-E_F/kT) \)
Metal-1/2con-metal contact

The channel has a potential $\Delta V$, up to $\sim 1$ V even without bias

There exists a residual barrier $q\phi_B$ of order 50-100 meV (depends on bias)
In-channel voltage profiling of Bürgi et al.

The channel has a potential $\Delta V$, up to $\sim 1$ V even without bias

There exists a residual barrier $q\phi_B$ of order 50-100 meV (depends on bias)


Pentacene TFT with gold electrodes

We obtained direct evidence of a gate-voltage-dependent contact resistance change: the induced charge significantly reduced contact resistance and increased source–drain current. Furthermore, the temperature dependence of the device clearly indicated that the contact resistance was much higher than the channel resistance and was dominated in the two-terminal total resistance of the device below 120 K. An observed activation energy of 80 meV for contact resistance was higher than that of 42 meV for pentacene channel resistance.

Summary

New model can explain

- Basic electrical characteristics
- Contact effects
- Ambipolar devices

where conventional model fails.

Adding a **HUGE** density of traps can explain

- Bias-dependent mobility $\mu = V_g^\alpha$, $I_{ds} = V_g^{\alpha+1}$
- Temperature dependence, $\mu = \exp(-E_a/kT)$
- Transients, exponential and non-exponential,
  $I_{ds} = \exp(-(t/\tau)^\beta)$

where conventional models fail.
Final remark: Occam’s Razor

The basic model **doesn’t** include

- Donors or acceptors
- Flat-band voltage
- Diffusion currents

and still explain the data better

**Occam’s Razor:**

“One should not increase, beyond what is necessary the number of entities required to explain anything”

- William of Occam
Final remark: Occam’s Razor

The basic model **doesn’t** include

- Donors or acceptors
- Flat-band voltage
- Diffusion currents

and still explain the data better

Occam’s Razor:

“No all the models explaining the data, that one with the least features is the best”

- William of Occam