Detection of explosive vapors using organic thin-film transistors

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Wien, 26 October 2004
Specialized in electronic characterization of organic electronic devices.

Sensitive equipment with custom made control software.
- DLTS (the only “organic” DLTS)
- Organics-specific FET measurement system
- Admittance spectroscopy
- Environment ideal for studying solar cells

Faro, 6 Oct. 2004; 26 °C
Overview

Need for a reliable and cheap sensor.

… so many mines to be deleted from this planet.
Why an organic FET?

FETs are multi-parametric
Organics can be functionalized easily
Organics are cheap to produce
Organic Electronics are our expertise
Devices

Organic layer: sexithiophene (T6) or PMeT or DH4T

C_6H_{13}
How does an FET work?

For a “normally-off hole-channel FET”, the current is zero when the gate bias is off because there are no free holes in the channel.

\[ V_g = 0 \rightarrow \text{channel resistivity is infinite} \]
How does an FET work?

When the gate bias reaches a certain threshold voltage, a channel with free carriers is established and the channel resistivity is finite.

\[ V_g > V_t \quad \rightarrow \quad I_{ds} \neq 0 \]
4 basic types of inversion channel FETs

normally on

<table>
<thead>
<tr>
<th>p-channel</th>
<th>n-channel</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="p-channel depletion" /></td>
<td><img src="image2.png" alt="n-channel depletion" /></td>
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<tr>
<td><img src="image3.png" alt="p-channel enhancement" /></td>
<td><img src="image4.png" alt="n-channel enhancement" /></td>
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S.M. Sze, Physics of semiconductor devices, p.455
Standard inversion channel FETs

LIN: \[ I_{DS} = \mu(Z/L) \, C_{ox} \, [(V_G - V_T)V_{DS} - (1/2)V_{DS}^2] \]

SAT: \[ I_{DS} = (1/2)\mu(Z/L) \, C_{ox} \, (V_G - V_T)^2 \]

http://www.ualg.pt/fct/adeec/optoel/theory/fet/
Organic FETs

Organic FETs are different:

1) They are of accumulation type. $V_t = 0$.
   (we cannot use textbook $V_t = V_{FB} + 2\psi_B + \sqrt{(2\varepsilon_s qN_A 2\psi_B)/C_{ox}}$)

2) Traps control the conduction processes (like in $\alpha$-Si)
   a: mobility depends on in-plane field ($V_{ds}$)
   b: mobility depends on transverse field ($V_g$)
   c: temperature activation of current ($T$)
   d: stressing; $V_t$ depends on time $t$

our related works:


A TNT molecule is very reactive and can interact with the organic layer.

for example:
(1) stealing electrons (acceptor) or
(2) introducing deep traps or
(3) changing the charge mobility.
1) TNT molecules are acceptors and create new free holes in the active layer. Thus increasing the zero-bias conductivity of the channel.
2) TNT molecules create scattering centers, thus reducing the carrier mobility $\mu$. 

The detection principle
3) TNT molecules create deep traps, thus changing the conduction mechanism.

change of conduction mechanism (trap conduction)
The detection principle

Thus, the detection is multi-parametric:

- changes in $V_t$
- changes in leakage current
- changes in mobility
- changes in conduction model (band conduction to hopping conduction)
A top-gate FET design is not a good detector for neutral molecules. Poisson’s equation, $E(x) = \int \rho(x) \, dx$, tells us that the field at the interface will not increase because of neutral charges. No effect on current.
Experimental set-up

Diagram showing an experimental set-up with components labeled as follows:
- N2
- Flow meter
- Vacuum chamber
- Electrical measurement system
- Electrical source
- Computer
- TNT powder

The diagram illustrates the flow of N2 from a tank, through a flow meter, into a vacuum chamber, and the interaction with TNT powder.
Response to TNT

Organic active layer: DH4T

$V_g = 0 \text{ V}, \ V_{ds} = -0.5 \text{ V}$
Response to air

$V_g = -10\, \text{V, } V_{ds} = -0.5\, \text{V}$
Response to $N_2$

$V_g = -10 \text{ V}, \ V_{ds} = -0.5 \text{ V}$
Organic FETs suffer from a phenomenon known as “stress”; a gradual increase of threshold voltage over time when (gate) bias is applied.
Response to O$_2$

Threshold voltage shift equal in O$_2$ and vacuum

Response to $O_2$

Mobility change similar in $O_2$ and vacuum

data2004\Lasca\Dia4\slope_vac_oxi.m
Stress

Organic FETs suffer from a phenomenon known as “stress”; a gradual increase of threshold voltage over time when (gate) bias is applied.

This can be reduced by using pulsed mode; ex. 99% of time at zero bias; 1% of time in measuring mode.
Pulsed mode; response to TNT

Active layer: T6

Current

Voltage

$V_{on} = -10 \text{ V}; \ V_{off} = +5 \text{ V}$

Reduced effect of stressing
Changes caused by ambient

Changes caused by bias in vacuum and $N_2$ are fully reversible and can be reduced by pulsed mode.

Changes in $O_2$ are reversible when not in presence of UV.

Changes caused by TNT are permanent.
The big advantage of organic FETs

One of the advantages of organic materials, apart from being very cheap to produce is that they can be functionalized to react only with certain agents.

This is future work.
Summary

Successful fabrication of a TNT FET sensor

- Sensitive to TNT
- Selective: response to $N_2$ is zero, to $O_2$ is less
- In pulsed mode the stressing is reduced

Future work:

- Increase selectivity by functionalizing
- Reduce duty cycle in pulsed mode
- Calibrate sensitivity
- Verify dependence on film thickness
- Implement in ready-to-use device (electronics)
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