Transparent Amorphous Oxide Semiconductors and Their TTFT Application

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Thin Film Transistor: Switching device in display

Present: TFT on glass
Semiconductor: a-Si:H

Future: TFT on plastic

Giant-microelectronics → flexible electronics

http://www.pioneer.co.jp/
Electronics everywhere
TFT: Active Matrix Display
Market Forecast of Flexible Display

Sources: iSuppli
Examples of Flexible TFT

\textbf{a-Si on SUS foil}

- \textit{LG. Philips LCD}
- Heavy
- Expensive (Passivation)

\textbf{poly-Si (Transfer Technique)}

- \textit{SEIKO EPSON}
- Difficulty in large area fabrication
- Expensive

\textbf{Organic TFT}

- \textit{Philips & Polymer Vision}
- \textit{Plastic Logic}
- Low mobility
- Poor stability

\textbf{Novel Material}

- Low process temperature
- Long-term stability
- High mobility
Why amorphous semiconductor

- Excellent controllability of carrier
- Low T formation of large area thin films

Amorphous semiconductor
Why Amorphous oxide semiconductor (AOS)?

- Wide controllability of carrier concentration.
- High optical transparency in invisible region.
- Room temperature and large area deposition.
- Unique carrier transport properties

**Transparent & Flexible electronics**

AOSs based flexible pn diodes

![Image of AOS-based flexible diode structure]


- A rectifying ratio: $>10^3$
- $V_{th}: \sim 2$V
History of amorphous semiconductor


- Photoconductivity in a-Se (Xerography)
- Glassy semicond. (V₂O₅ based oxide)
- Chalcogenide glass (DVD)
- Switching and memory effect in a-chal. film
- a-Si:H ‘Giant-Microelectronics’
- Flexible electronics (novel a-sc)
Proposal of materials design concept for a-TAOS with large mobility

Proc. of ICAMS-16

Working hypothesis to explore novel wide band gap electrically conducting amorphous oxides and examples

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\textsuperscript{b} Institute for Molecular Science, Myodaiji, Okazaki 444, Japan

Abstract

A working hypothesis for exploring optically transparent and electrically conducting amorphous oxides is proposed on the basis of simple considerations concerning chemical bonding. The hypothesis predicts that amorphous oxides composed of heavy metal cations with an electronic configuration of \((n-1)d^{10}ns^{2}\) may be converted into transparent conducting amorphous oxides when doped by Li ion implantation or heating at temperatures below crystallization. Three new materials, amorphous \(\text{Cd}_2\text{GeO}_4\), \(\text{AgSbO}_3\) and \(\text{Cd}_2\text{PbO}_4\), have been prepared as examples.
Ionic Amorphous Oxide Semiconductor: novel class of a-Semicon.
Material design concept (electron pathway)

crystal

covalent semicon. ionic oxide semicon.  
\[ M: (n-1)d^{10}ns^0 \ (n \geq 4) \]

amorphous

\[ \mu = \sim 200 \text{ cm}^2 \text{ (Vs)}^{-1} \]  
(\text{Ne} 1 \times 10^{19} \text{ cm}^{-3})

\[ \mu = \sim 1 \text{ cm}^2 \text{ (Vs)}^{-1} \]  
(\text{Ne} 1 \times 10^{19} \text{ cm}^{-3})

J NCS(1996)
Ionic amorphous oxide semiconductors

Advantages

- Optical transparency in visible region
- Electrical conductivity

Amorphous

Transparent amorphous oxide semiconductors

e.g. a-2CdO·GeO₂, a-CdO·PbOₓ, a-AgSbO₃, a-InGaO₃(ZnO)ₓ

(found in 1995-2001)

- a-In₂O₃:Sn

- Low temperature deposition ➔ flexible electronic device
- No long range ordering ➔ reduction of severe requirements for PN-junction
- Large electron mobility compared to the conventional a-semiconductors.
Conductivity change upon H\textsuperscript{+}- implantation

Sample: sputtered thin film (300 nm\textsuperscript{t})

\[ \text{H}^+: 40\text{kV} + 70\text{kV} \]

\[ \begin{align*}
\text{T (K)} & \quad 300 \quad 200 \quad 120 \quad 60 \quad 13 \\
\log \sigma & \quad 0 \quad -5 \quad -10 \\
1000 / T (K^{-1}) & \quad 4 \quad 6 \quad 8 \quad 10 \\
2 \times 10^{14} \text{cm}^{-2} & \quad E_a = 1 \text{eV} \\
2 \times 10^{15} \text{cm}^{-2} & \quad 2 \times 10^{16} \text{cm}^{-2} \\
E_a = 0.06 \text{eV} & \quad E_a < 1 \text{m eV} \\
\text{before implantation} & \quad \text{after implantation}
\end{align*} \]

\[E_F\text{ is continuously controllable from } \sim E_g/2 \text{ to above mobility gap} \]

Mobility amorphous 15 cm\textsuperscript{2}/(Vs)\textsuperscript{-1} cf. crystal 20 cm\textsuperscript{2}/(Vs)\textsuperscript{-1}

\[\text{APL(1995)}\]
a-Si:H doping limit

$E_F$ cannot exceed mobility gap
Why doping is inefficient for a-Si:H?

E_F never enters conduction band extended states by doping

\[ \text{P}_3^0 + \text{Si}_4^0 \rightarrow \text{P}_4^+ + \text{Si}_3^- \]

Doping creates D^- state

Mott-Street model

Carriers are NOT generated
Observed and calculated DOS

Contour map of wave function @ conduction band bottom

(a) crystalline

(b) amorphous
Cd-Cd correlations in RMC-fitted model

$\text{d(Cd}^{2+}-\text{Cd}^{2+}) < 2r(\text{Cd 5s})$

3D-percolated!

crystalline

PRB(2002)
Electron Transport in a-IGZO

![Graphs showing electron mobility vs carrier concentration and Hall mobility vs inverse temperature.]

$m^* = 0.35$

*APL (2004)*
Carrier Concentration and conduction

\[ N_e > 10^{18} \text{ cm}^{-3} \]

\( E_{\text{th}} \ll E_F \)

\( E_{\text{th}} > 10 \text{ cm}^2(\text{Vs})^{-1} \)

\[ E_{\text{th}} > 10 \text{ cm}^2(\text{Vs})^{-1} \]

\[ N_e > 10^{18} \text{ cm}^{-3} \]

\( \mu_{\text{Hall}} > 10 \text{ cm}^2(\text{Vs})^{-1} \)

### Ionic Amorphous Oxide Semicon.

<table>
<thead>
<tr>
<th>Material system</th>
<th>Chemical bond</th>
<th>Mechanism</th>
<th>Hall effect</th>
<th>Mobility (cm²/(Vs))</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tetrahedral</td>
<td>covalent</td>
<td>hopping</td>
<td>abnormal</td>
<td>~1</td>
<td>Si:H</td>
</tr>
<tr>
<td>Chalcogenide</td>
<td>covalent</td>
<td>hopping</td>
<td>abnormal</td>
<td>&lt; 10⁻³</td>
<td>Tl₂Se-As₂Se₃</td>
</tr>
<tr>
<td>Oxides (glass semiconductors)</td>
<td>covalent + Ionic</td>
<td>hopping</td>
<td></td>
<td>~10⁻⁴</td>
<td>V₂O₅-P₂O₅</td>
</tr>
<tr>
<td>(Ionic amorphous oxide semiconductors)</td>
<td>Ionic</td>
<td>Band conduction</td>
<td>normal</td>
<td>10~60</td>
<td>In-Ga-Zn-O</td>
</tr>
</tbody>
</table>
Transparent FET on plastic

Device structure

W / L : 200 / 50 (µm)

200 µm

(a-IGZO)

PET sheet

(no passivation)

Reflectivity

Thickness ~31 nm

W / L : 200 / 50 (µm)
Amorphous InGaZnO$_4$ Thin Films

Stable up to ~500 °C

t=200 nm thick
Pulsed Laser deposition @ RT

Stable up to ~500 °C
Transistor Performance

\[ \mu_{\text{sat}} = 12 \text{ cm}^2(\text{Vs})^{-1} \]

ON/OFF ratio = 10^6

**Output Transfer**

**Transfer**

\[ W / L : 200 / 10 \ (\mu\text{m}) \]

High performance transparent FET was fabricated on PET substrate

- N-type AOS, In-Ga-Zn-O (a-IGZO)
  - \( \mu_{\text{Hall}} > 15 \, \text{cm}^2/(\text{Vs})^{-1} \) : \( \text{Ne} < 10^{15} - 10^{21} \, \text{cm}^{-3} \)

- Localized to extended state
  - \( > 10 \, \text{cm}^2/(\text{Vs})^{-1} \) @ \( \text{Ne} > 10^{18} \, \text{cm}^{-3} \)

- \( Y_2O_x \) (high k) as gate insulator & RT

- \( \mu_{\text{sat}} \approx 12 \, \text{cm}^2/(\text{Vs})^{-1} \)
  - cf. \( \approx 1 \) for a-Si:H, pentacene

- ON / OFF ratio \( \approx 10^6 \)

- Normally-Off (\( V_{\text{th}} \approx +1 \, \text{V} \))

- \( S = \approx 0.2 \, \text{V/dec} \)

*a-IGZO can be deposited on plastic by the same process as ITO*

Large process merit
## Current Status of TFT for Flexible Displays

<table>
<thead>
<tr>
<th>Channel material</th>
<th>Vacuum Evap.</th>
<th>CVD</th>
<th>PLD</th>
<th>a-IGZO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin Film Fabrication</td>
<td>&lt;100</td>
<td>300</td>
<td>300</td>
<td>RT</td>
</tr>
<tr>
<td>Max. Tem. (°C)</td>
<td>0.5</td>
<td>0.5</td>
<td>~5</td>
<td>~12</td>
</tr>
<tr>
<td>Mobility (cm²V⁻¹s⁻¹)</td>
<td>5~6</td>
<td>&gt;6</td>
<td>~5</td>
<td>~8</td>
</tr>
<tr>
<td>Current ON/OFF (log₁₀)</td>
<td>0.2</td>
<td>0.4</td>
<td>1.3</td>
<td>0.2</td>
</tr>
<tr>
<td>S (V/decade)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Spec for Large-sized OLED TV Panel

SID2006

70.1: Invited Paper: Large-Sized Full Color AMOLED TV: Advancements and Issues
Kyuha Chung, Namdeog Kim, Joonhoo Choi, Changwoong Chu and Jong-moo Huh
OLED Development Team, LCD Business, Samsung Electronics Co., Ltd., Kyunggi-do, Korea

<table>
<thead>
<tr>
<th>( \mu_{FE} )</th>
<th>1-10 cm(^2)/Vs</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta V_{TH} )</td>
<td>(&lt; 1 ) V for (10^5) hrs</td>
</tr>
</tbody>
</table>

W/L=200/4 \( \mu \)m, 3 \( \mu \)A/Pixel x 300hrs

<table>
<thead>
<tr>
<th>Active Layer</th>
<th>ZnO</th>
<th>IZO</th>
<th>IGZO</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta V_{TH} (V) )</td>
<td>5.0</td>
<td>3.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>
5-stage RO

\[ V_{DD} \]

\[ V_{GG} \]
$L_{Ld} = L_{Dr} = 10 \ \mu m$

$\beta_R = (W / L)_{Dr} / (W / L)_{Ld} = 5$
410 kHz (0.24 µs/stage), 7.5 V_{p-p} @ V_{dd} = +18 (V)
amorphous/oxide TFT-based Ring Oscillators

<table>
<thead>
<tr>
<th></th>
<th>a-Si:H</th>
<th>Organic</th>
<th>Oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>P3HT</td>
<td>IGO</td>
</tr>
<tr>
<td>$L$ ($\mu$m)</td>
<td>5</td>
<td>2 – 5</td>
<td>60</td>
</tr>
<tr>
<td>$V_{DD}$ (V)</td>
<td>+30</td>
<td>-80</td>
<td>+80</td>
</tr>
<tr>
<td>$f_{OSC}$ (kHz)</td>
<td>83</td>
<td>106</td>
<td>9.5</td>
</tr>
<tr>
<td>$\Delta t$ ($\mu$s/stage)</td>
<td>0.54</td>
<td>0.68</td>
<td>11</td>
</tr>
<tr>
<td>materials</td>
<td>TIT Canon</td>
<td>Toppan</td>
<td>Braunschweig TU</td>
</tr>
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<td>-----------</td>
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</tr>
<tr>
<td>circuits/devices</td>
<td>IGZO</td>
<td>IGZO</td>
<td>ZTO</td>
</tr>
<tr>
<td>circuits/ devices</td>
<td>RO</td>
<td>AM switch</td>
<td>stacked OLED</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FPD application</th>
<th>AMOLED</th>
<th>AM-ePaper</th>
<th>stacked OLED</th>
<th>AM-LCD</th>
<th>-</th>
<th>AM-OLED</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPD application</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>
OLED
monolithic
2Tr-1C
pixel driver
3.5’ OLED using TAOS-FET Backplane

<table>
<thead>
<tr>
<th>Specification of OLED panel driven by IGZO TFTs</th>
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<tr>
<td>Display size</td>
</tr>
<tr>
<td>Resolution</td>
</tr>
<tr>
<td>Display device</td>
</tr>
<tr>
<td>TFT</td>
</tr>
</tbody>
</table>

Gate insulator; Si₃N₄

LG (IDW ‘06)
Images of Flexible Electrophoretic Displays Driven with a-IGZO TFT Array

Thickness: 320 µm
Weight: 1.3 g

Electrophoretic imaging film supplied by E·INK
Toward New Continent of Transparent Oxide Electronics

Flexible displays