Organic-Transistor Based Systems and Platforms

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Outline

- Organic transistor based systems
  - Large-area electronics applications
  - Bio-compatible applications
- Other nano-electronics devices
- What is lacking: platform for systems
Acknowledgement (organic FET part)

Circuits and systems design

Process and device technologies (team Someya)

The University of Tokyo & JST/ERATO

T. Sakurai

H. Kawaguchi

M. Takamiya

K. Ishida

H. Fuketa

Yokota

Sekitani

Someya

T. Sakurai
Electronics to support people’s life

Organic electronics: more physical-space apps

Natural user interface

IoT, IoE, CPS, M2M, Ambient, Swarm, whatever you name it

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Flexible organic electronics

- Flat Panel Display
- Organic LED Display
- Organic RFID tag
- Organic Photovoltaic
- Message Boards
- Gyroicon
- OLED Lighting
- Organic Photovoltaic
- Poly IC
- Sensors
- Wearable Electronics
- University of Tokyo
- Pioneer
- Heliatek
- OSRAM
- Samsung
Organic transistor

Advantages
- Low-cost manufacturing for large area
  (Cost per transistor > $10^4$ of Si)
- Mechanical flexibility

Disadvantages
- Low density  (<$10^{-4}$ of Si: 10nm vs 10µm)
- Low speed   (<$10^{-4}$ of Si: 100GHz vs kHz)
$V_{DS}$-$I_{DS}$ characteristics

Modeled by level 1 SPICE MOS model with 200kΩ

Pentacene (PMOS)

Organic semiconductor

Insulator (polyimide)

Source  Gate  Drain

L=100μm  W=2mm

Level 1 SPICE MOS model

Measurement  Model simulation

S  G  D

200k  200k

Cadence layout tools

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Organic semiconductors

P-type: low molecular weight

- Pentacene (stable and high mobility)
  - $1 \text{ cm}^2/\text{Vs}$

- perfluoropentacene
  - $0.7 \text{ cm}^2/\text{Vs}$

N-type: low molecular weight

- trifluoromethylphenyl groups

Polymer: soluble

- poly(9,9'-n-dioctylfluorene-alt-bithiophene) (F8T2)
  - $0.02 \text{ cm}^2/\text{Vs}$
By adding one more gate, $V_{TH}$ can be controlled.

Bending proof

Less than 3% of $I_{DS}$ change for bending over 0.5mm radius
No $I_{DS}$ change for 50k cycles of bending & flattening
Heat cycles

Measurement temperature: 30 °C

Up to 150°C with good encapsulation

In N₂ (Parylene)

In air (Parylene/Metal)

In air (Parylene)
Organic TFTs with SAM

* SAM: Phosphonic acid-based self-assembled monolayers

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## Technical advances in organic circuits

<table>
<thead>
<tr>
<th>Year</th>
<th>Target</th>
<th>FET</th>
<th>VDD</th>
<th>New technology</th>
<th>New circuits</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>e-Skin</td>
<td>PMOS</td>
<td>40V</td>
<td>FET on plastic</td>
<td>Active matrix</td>
</tr>
<tr>
<td></td>
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<tr>
<td>2005</td>
<td>Scanner Sheet</td>
<td>PMOS</td>
<td>40V</td>
<td>Photo-diode</td>
<td>Logic</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Double WL/BL</td>
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<tr>
<td>2006</td>
<td>Braille Sheet</td>
<td>PMOS</td>
<td>40V</td>
<td>Double gate Arti. mussle</td>
<td>SRAM</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Adaptive VTH</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Level shifter</td>
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<tr>
<td>2008</td>
<td>Comm. Sheet</td>
<td>PMOS</td>
<td>30V</td>
<td>NVRAM</td>
<td>Organic</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+Si LSI</td>
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<tr>
<td>2009</td>
<td>EMI Furoshiki</td>
<td>CMOS</td>
<td>2V</td>
<td>SAM Stretch wire</td>
<td>OTFT+Si MOS</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Direct connect</td>
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<tr>
<td>2010</td>
<td>FPGA paper</td>
<td>CMOS</td>
<td>2V</td>
<td>Printing wire</td>
<td>FPGA arch.</td>
</tr>
</tbody>
</table>

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Non-volatile memory using double SAM gates

T. Someya: IEDM'09

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## Organic FETs (OFETs) vs. Silicon

<table>
<thead>
<tr>
<th></th>
<th>Organic FETs</th>
<th>Si MOSFETs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum gate length</td>
<td>20 μm</td>
<td>45 nm</td>
</tr>
<tr>
<td>Mechanical flexibility</td>
<td>Flexible, thin &amp; stretchable</td>
<td>Very limited</td>
</tr>
<tr>
<td>Normalized ON current</td>
<td>3 nA / μm @ 3 V</td>
<td>1 mA / μm @ 1 V</td>
</tr>
<tr>
<td>Gate delay</td>
<td>0.1 s @ 3 V</td>
<td>10 ps @ 1 V</td>
</tr>
<tr>
<td>Cost / area</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Cost / transistor</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Lifetime</td>
<td>Months</td>
<td>Years</td>
</tr>
</tbody>
</table>

- Large-area electronics
- Bio-compatible applications
Unique manufacturing process:
Printing large-area
organic transistor array
Manufacturing process
Printable electronics

Screen printing
Inkjet printing
Gate electrodes & Word line

Gate electrodes : 45 x 45
Word line : 45 lines

28 x 28 cm²
3 mm

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Examples of organic circuits & systems
Large-Area OFET Applications

- e-skin (ISSCC’04)
- Scanner (ISSCC’05)
- Braille display (ISSCC’06)
- Wireless power (ISSCC’07)
- Communication (ISSCC’08)
- EMI measurement (ISSCC’09)
- User customizable logic paper (ISSCC’10)
- 100-V A.C. energy meter (ISSCC’11)
- Insole pedometer (ISSCC’12)
- Electromyogram (ISSCC’13)
- Wet sensor (ISSCC’14)

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Large-area electronics
Human-scale interfaces

- E-skin
  - Sheet scanner
    - IEDM’03
    - ISSCC’04
    - Pressure sensors + OFETs
- Braille display
  - IEDM’04
  - ISSCC’05
  - Actuators + OFETs
- Power sheet
  - IEDM’05
  - ISSCC’06
  - Photodetectors + OFETs
- Comm sheet
  - IEDM’06
  - ISSCC’07
  - Coils + MEMS + OFETs
  - IEDM’07
  - ISSCC’08
    - Organics + Si co-design

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Large-area electronics

Human-scale interfaces

Hyper-skin
EMI Furoshiki
Organic FPGA
Energy Harvester

IEDM’08
ISSCC’09
ISSCC’10
ISSCC’11
ISSCC’12

Org CMOS + Si CMOS
direct communication
Manufacturing IC
at home with printer
System on a film
Energy harvesting

Sheet-type ultrasonic
sensing without touch

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Large-area electronics

Electromyogram
Flexible bio-sensor

ISSCC’13  ISSCC’14  ISSCC’??

Solution for totally wireless
System: energy, data,
Sensor & ESD protection

Human vital data measurement

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E-skin: large-area pressure sensor


Artificial Skin Systems

Pressure sensitive rubbery sheet

Column selectors

Top electrode

16 x 16 FET matrix

Row decoders

Cut-and-paste feature (16x16 sencels)

Row decoder

16x16 FET matrix

Column selectors

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Cut-and-paste feature (convex shape)

Row decoder

Convex sencel matrix

4x4 matrix

Column selectors

Convex matrix

Row decoders

Column selectors

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Photograph of artificial skin system

Cuttable here

40mm

40mm

Row decoders

16x16 sensor matrix

Widened wires for connecting tapes

Column selectors & output

Connecting tapes

4 x 4 version

Cuttable here
Scalable circuit (row decoder)

1 out of 16 row decoders

1 out of 4 row decoders

R3 R2 R1 R0 V_D0 φ_R GND VDD

D0 D1 D2 D3

Sencels

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Access time measurement

Access time in 16 x 16: 23ms
~2s (16 x 4 x 30ms) to scan sheet @ L=100µm
~0.3s to scan sheet @ L=25µm
e-skin works for years by now
Braille display by organic FETs


Conventional methods for Braille display

(A) Piezo
- Voltage input

(B) Solenoid
- Current input

Thick and heavy
~5cm / ~1kg

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Plastic actuators (artificial muscle)

Up  Braille dot

Actuator

Down

100\mu F

Equivalent circuit

Displacement takes seconds \textarrow{sloooow} to drive 144 dots.

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Braille sheet display

Soft actuators powered by OTFT-AM

Lightweight  Flexible
Thin  Inexpensive

The displacement of actuators to read Braille is 0.2 mm.
Wireless power transmission sheet with plastic MEMS switches and OFETs


Position-sensing and selective activation

<table>
<thead>
<tr>
<th>Large coil</th>
<th>Receiver coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>30x30 cm² X 1 coil</td>
<td>Efficiency ~ 0.1%</td>
</tr>
<tr>
<td>Electro- magnetic induction works</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Many coils &amp; one selected</th>
<th>Receiver coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 inch² X 64 coils</td>
<td>Efficiency &gt; 60%</td>
</tr>
<tr>
<td>Selective activation is the key.</td>
<td></td>
</tr>
</tbody>
</table>

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MEMS switches

Electrode for power transmission

Electrode for electrostatic attraction

~ 5mm x 10mm
Making two coil sheets to one by circuit ideas

LS: Level shifter

For lower cost

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Wireless power transmission sheet

Large-area & Low cost
Contactless position sensing
High power
Lightweight & Printable

Size: 21 x 21 cm²
Thickness: 1 mm
Weight: 50 g
Efficiency: 62.3%
Max received power: 29.3 W
X’mas tree w/o a battery wirelessly powered

21 LEDs
13.56 MHz
Received power : 2 W
Wirelessly powered room in the future
Providing infrastructure ubiquitous electronics

In the wall

TV on a wall
Mobile phone & PC & e-accessories
(data can be wireless but USB’s wire delivers power)

In the table

Home-care robot Vacuum cleaner

Ambient illumination

In the floor
No electrical shock

I touched it by my hand. No problem 😊
Stretchable wire with carbon nanotube

Current control > 500 mA

30mm, 12Ω

42mm, 17Ω

Pull

Stretch (+40%)
Elastic conductors


Carbon nanotubes

Fluorinated copolymer

Ionic liquids

R = n-C$_4$H$_9$
X = (CF$_3$SO$_2$)$_2$N

10 nm
2V Organic & Si CMOS collaboration

3-input to 8-output CMOS decoder

Binary-code input from PC

ISSCC 2009

128 CMOS (256 organic TFTs)

To Si CMOS LSI

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Prototype of EMI measurement sheet

12cm

Rubber sheet
(Silicone elastomer)

Antenna coil

Si CMOS LSI
EMI measurement circuit

Stretchable Interconnect
(CNTs)

2V organic CMOS decoder circuits

Conventional

- EMI measurement sheet
- Mechanical scan
- Analog
- DC to DC converter
- Magnetic field probe

Proposed

- EMI measurement sheet
- Easy without mechanical scan

Movie of proposed EMI measurement
EMI measurement
Integrated circuit fabricated by home-use printer


Ink is provided by Mitsubishi Paper Mills Ltd.

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Prototype of “Logic paper”

✓ **Paper** with via array
Interconnects are customized by **Ink-jet printer**

✓ **Film** with 10x10 organic CMOS Sea of Transmission Gates

Each user can fabricate one’s own logic circuits by ink-jet printing interconnects on paper.

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Interconnection customized paper is stacked on plastic Sea of Transmission Gates
Ink-jet printed interconnects

- Ink-jet printing
- Nozzle
- Conductive Ag nanoparticle ink
- Interconnects formed under room temperature
- Pre-coated nanoconductive base

**Sheet resistance:** 0.2Ω/square
**Via resistance:** 2.7Ω/via.
Schematic of SOTG unit cell

SOTG unit cell includes a couple of complementary transmission gates and 4 terminals.

Transistor-level schematic

Symbol definition

PSW and NSW can be connect to $V_{SS}$, $V_{DD}$, and any signals.

6 transistors
4 terminals

L : 20µm
W: 150µm

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Comparison of unit logic cell

<table>
<thead>
<tr>
<th></th>
<th>Gate array (Conventional)</th>
<th>SOTG (This work)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of transistors</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Number of vias</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Area*</td>
<td>81mm²</td>
<td>36mm²</td>
</tr>
</tbody>
</table>

*Calculated on a fixed via spacing of 3mm.

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8x8 SOTG cell array

pMOS LED driver

8 x 8 SOTG cell array

pMOS LED driver

Fabricated organic CMOS on polyimide film

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Examples of logic function in SOTG

- **Inverter**
  - $V_{SS}$
  - $V_{DD}$
  - $A$ to $Y$

- **Buffer**
  - $V_{SS}$
  - $V_{DD}$
  - $A$ to $Y$

- **Exclusive OR**
  - $A$ and $B$ to $Y$
  - $AB + AB$

Buffer can be implemented with one unit cell. Any 2-input logic function can be implemented with only 2 cells.

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A D-flip flop can be implemented with 4 unit cells.
Power monitoring of each electric outlet

Past

Current commercial AC power meter

Future (This work)

Large size, hard...

Flexible, low cost...

Printable organic devices on flexible films have potential to realize low-cost System-on-a-Film.

100V AC power meter: System-on-a-Film (SoF)

- Analog circuits (20V organic CMOS with floating gate)
- AC connector
- Rectifiers (100V organic PMOS)
- Bar indicator (OLED)
- Logic circuits (20V organic CMOS)
Organic 100V AC power meter (SoF)
Organic insole pedometer

Energy harvester for wearable systems

2V organic circuits

22cm

PVDF* sheet
(Piezoelectric energy harvester)

*PVDF: Polyvinylidene difluoride

Proposed insole pedometer

K. Ishida, et al., ISSCC 2012

Insole pedometer

Stepping on

PVDF for power supply

PVDF for pulse generation (step detection)

Pulse shaping

Count up the number of pulses ( =steps)
Harvesting experiment
Bio-compatible applications with flexible OFETs
Integrated on skin with 5µm thickness


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Amazing robustness: Crumpling

Minimum bending radius $\sim 5\mu m$
From Robotics to Human


Bionic Skins (2013)

Thickness: 1/1000

\[ t = 1 \sim 2 \text{ mm} \]

T. Someya et al., PNAS 102, 12321 (2005).


\[ t = 2 \mu \text{m} \]
Electromyogram measurement sheet

Surface electromyogram measurement sheet (SEMS)

8 x 2 amplifier array

Stacked 2 sheets

8 x 8 EMG electrode array

1μm thickness ultra-flexible PEN film

45 mm

40 mm

EMG electrodes (0.7mm x 0.7mm)

Organic transistors

Electrode pitch = 5mm


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Electromyogram (EMG) measurement
Electronic Diaper: Background

Wet sensor for biomedical, nursing-care, elderly-care, etc.

- Thin and mechanically flexible
- Wireless power and data transmission
- Low-cost (disposable)
  - Organic flexible fully integrated circuit
  - Can be applied to various bio-sensors

Elderly care

For babies
Electronic diaper

Sensing
Wireless power
Wireless data
ESD

12.5mm thick PCB
Organic circuits
Electrodes

35 mm
78 mm
40 mm
53 mm

Fully integrated thin and flexible system w/o external components


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Electronic diaper use-case

- Magnetic resonance (13.56MHz)
- Wet sensors
- ESD
- Organic diodes
- Integrated large C
- Integrated large R

Battery operated

Reader

Organic sensor sheet

Diaper cover
In repeated use

Disposable diaper

Ex.BLE
Sensing: RC oscillator

Dry: $R_{\text{SENSE}}$ → $\infty$ → No oscillation

Wet: $R_{\text{SENSE}}$ → MW (normal saline) → Oscillation

Sensor electrodes

MIM capacitor (7nF)

Organic pseudo-CMOS* inverters

* T.-C. Huang, et al., DATE 2010.

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Sensing with RC oscillator

Resistance dependence of oscillation period

- Oscillation period is proportional to $R_S$.
- Power dissipation: 1.4µW @ 3Hz
Wireless power transmission

Magnetic resonance (13.56MHz)

Power transmission efficiency varies due to:

- Increase in distance between reader coil ($L_1$) and sensor sheet coil ($L_2$)
- Bend of sensor sheet coil ($L_2$)

To reduce power consumption of battery-operated reader

Reader should transmit minimum necessary power.
Adaptive amplitude control (measured)

- AAC reduces amplitude up to 92% compared with conventional worst case design.

\[ V_{IN} = 9.7 \times V_{OUT} \]
ESD protection

Sensor electrodes may experience high voltage (2kV) by charged-up human body.

→ ESD protection is imperative in sensor sheet.

ESD protection has not been taken into account for organic circuits.

- ESD protection circuit is investigated for organic circuits.
- ESD tolerance is checked according to ESD standard of IEC 61000-4-2.
Problem of ESD in organic transistors

Organic transistors are fabricated on insulating film. ➔ ESD protection in organic transistors is difficult.

ESD in Si transistors vs ESD in organic transistors

- **Parasitic junction diode** in Si transistors
- **No parasitic diode** in organic transistors
ESD protection with organic diodes

Schottky diode with copper phthalocyanine (CuPc)

- Vertical structure *

  - Larger current drivability
  - Better frequency characteristic

(Also used for rectifier)

ESD protection with organic diodes

ESD measurement (IEC 61000-4-2)

- ESD tolerance is checked by measuring gate current.

→ 2kV ESD tolerance is achieved.

### Table: ESD Tolerance with and without Protection

<table>
<thead>
<tr>
<th>Step</th>
<th>Voltage</th>
<th>Initial</th>
<th>0.5kV</th>
<th>1kV</th>
<th>2kV</th>
<th>4kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Step 1)</td>
<td>0.5~4kV</td>
<td>Without ESD Protection</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>(Step 2)</td>
<td>2V</td>
<td>With ESD Protection</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
</tbody>
</table>

(*) $T_{di}$: Thickness of gate dielectric (parylene)

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Electronic diaper use-case

- Magnetic resonance (13.56MHz)
- Wet sensor
- Organic diodes
- Integrated large C
- Integrated large R
- Reader
- Organic sensor sheet
- Battery operated
- Ex.BLE
- Disposable diaper
- Diaper cover
- In repeated use
- Wet sensor
- ESD
- AAC
- Data receiver

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Outline

- Organic transistor based systems
- Large-area electronics applications
- Bio-compatible applications
- Other nano-electronics devices
- What is lacking: Platform for systems
Japan’s National Projects for Next-Generation Nano-electronics Devices

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<tbody>
<tr>
<td>METI / NEDO MIRAI Ⅲ project</td>
<td>EIDEC (Advanced Mask &amp; Resist)</td>
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<tr>
<td>METI Nanoelectronics project (Non-Si channel, Nanowire, XMOS)</td>
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<td>JST Watanabe-CREST project (2007 start)</td>
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<tr>
<td>Cabinet’s Sai-sentan Research Support Program</td>
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<tr>
<td>METI, MEXT, AIST, NIMS, Tsukuba Univ. Tsukuba Innovation Arena (TIA)</td>
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<tr>
<td>NEDO ASET 3D Dream Chip Project</td>
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Innovative Nano-electronics through Interdisciplinary Collaboration among Material, Device and System Layers

Started 2013 for 7 years.

Courtesy: Seiichiro Kawamura (JST)

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Nano-electronics CREST
Core Research for Evolitional Science and Technology

Collaboration among layers
Low power and novel functions
Demonstration at the end

Architecture / system
Many-core
Bio-inspired
Bio-inspired
Plarformization

Circuit / assembly
Drift learning
Storage-class
Auto-pilot

Nano-device
Ultra-low power
Wireless comm
Near field wireless

Nano-material
Si
Compound semicon.
High-mu
High-k

Cyber-space
Beyond CMOS
Steep-S
Spintronics
Small variation
More-than-Moore
Interconnect
New storage

Physical space
NEMS
Meta-material
Organic material
Sustainable

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6 projects on-going so far

Multi-functional sensor platform by nano electric channel and thermal management (Prof. Ken Uchida)

TFET for integrated circuits with ultra-low power consumption (Shinichi Takagi)

Innovative magnetic image sensors and app. based on carbon nano-electronics (Prof. Mutsuko Hatano)

Tera-hertz video imaging device (Prof. Tanemasa Asano)

Computing by via-switches (Prof. Masanori Hashimoto)

Nano inertia measurement device and system (Prof. Kazuya Masu)

Open to international proposals


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Outline

- Organic transistor based systems
  - Large-area electronics applications
  - Bio-compatible applications
- Other nano-electronics devices
- What is lacking: platform for systems
Electronics to support people’s life

Organic electronics: more physical-space apps

IoT, IoE, CPS, M2M, Ambient, Swarm, whatever you name it
Wide variety in small quantities

Typical IoT nodes

Battery
Wireless power
Harvesting

Various sensors

Actuators
Speaker
Motor
Display
Ultra-sonic etc.

Power supply

Analog ADC/DAC

Digital

RF

WiFi
BlueTooth
Zigbee
Special

Various combinations of non-digital and non-IC components.
High NRE cost

Millions of Dollars

- Mask
- Embedded software
- Design, test, verification

Technology node

- 250nm
- 180nm
- 130nm
- 90nm
- 65nm
- 45nm
- 32nm

Integration technology to create new services

Market size (# of products)

Time

1
100
10K
1M
100M

More-Moore Integration

Agile micro-electronics systems platform

New platform

MAKERS
THE NEW INDUSTRIAL REVOLUTION
CHRIS ANDERSON
Author of the bestseller The Long Tail

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Electronic system platform example

Arduino (+ Shield)
>100mW, > 5 x 5 x 5cm³

- Non-experts make systems
- Non-experts use software
- Issue is not on digital nor IC’s

http://www.tabroid.jp/news/2014/04/google-ara-project.html
http://www.moff.mobi/
http://www.microfan.jp/booster/clcd-booster

Edison (Intel)
Arduino

Experiment of student: Months → A couple of days
Arduino support package from Simulink

Programming without coding

http://www.mathworks.com/hardware-support/arduino-matlab.html  T.Sakurai
Platform to deliver technologies to services

Components easily combinable to stimulate user’s creativity
Difficult technologies are made transparent to users

- Micro chips
- Application / Contents
- Electronic systems
  - CMOS Foundary
  - iPhone iPad...
  - Arduino

T.Sakurai
Summary

- Organic-transistor based systems are good for:
  - Large-area electronics
  - Bio-compatible applications
- New nano-technologies will be coming in.
- Agile micro-electronics system platform is needed for emerging technologies to be delivered to people’s life.