Low-cost Printed Electronic Nose Gas Sensors for Distributed Environmental Monitoring

Vivek Subramanian

Department of Electrical Engineering and Computer Sciences
University of California, Berkeley

This research is funded by U.S. EPA - Science To Achieve Results (STAR) Program
Grant #RD83089901
Distributed environmental monitoring

• **Need for distributed monitoring**
  - Identification of environmental hazards
  - Triggering of proactive action
  - Development of accurate environmental models

• **Sensor Requirements**
  - Ultra-low-cost
  - Ease of dispersal
  - Trainability / adaptability

• **Our Approach: Arrayed organic FETs**
  - Easily arrayed at low-cost via printing
  - Flexible for easy dispersal
  - Trainable via electronic nose architecture
Commercial E-noses

- ppbRAE Plus — $6215
  - For homeland security
  - Detects toxic agents, mildew

- Cyranose — $7995
  - Can be trained to detect a wide range of odors: alcohols, chemicals, oil, food
Commercial Gas Sensors

- Vernier O₂ sensor — $186
- Minimax Pro H₂ sensor— $199
- Gas Alert Micro 3 H₂S sensor — $612
Arrayed Gas Sensors

Molecule in ambient

Substrate

Map Responses

Responses to different molecules

Generate Chemical Signatures

Sensor Parameter

Pixel Array Index

A      B  C  D
Printing: a pathway to low-cost

- No lithography
- No vacuum processing (CVD, PVD, Etch)
- Reduced abatement costs
- Cheap substrate handling
- Reduced packaging costs
Organic Gas Sensors

Gas sensing with OTFTs is a good match

- Good sensitivity
- Synthetic richness
- Easy array integration
- Low performance requirements
- Short-term applications available

OTFT Gas Sensing

Absorbed through grain boundaries and reactive molecular sites

Film expands

Odors

Analyte donates carriers or activates existing donors

Analyte introduces traps and scattering sites

Analyte changes hopping barrier height

valence band edge

$E_B$
Low-cost Fabrication

- Inkjet deposition of organic material allows integration of sensor array
- Ultra-low cost requires integration of supporting circuitry
Printed Transistors

Gate electrode is printed using gold nanocrystals

Polymer dielectric is deposited via inkjet

Low-temperature anneal forms gate stripe to edge of array (out of page)

Source / Drain contacts are printed using gold nanocrystals

Low-temperature anneal forms S/D stripes and connections (in plane of page)

Various active layers are deposited via inkjet
Materials are characterized using a substrate-gated architecture (easy fabrication for rapid screening).

A silicon substrate enables easy I/O via an edge connector.

The channel is exposed to the analyte, resulting in performance changes.
Sensor Characterization

Switching between individual sensors is performed via a switch matrix PCB.

To ensure accuracy, measurements are performed with a calibrated precision semiconductor parameter analyzer.

Agilent 4156
Experimental Setup

- **N₂**
- Mass Flow Controller
- Analyte Delivery
- Valve
- Sensor Chamber
- Bubbler
- Mass Flow Meter
- Exhaust
- Agilent 4156 Mass Flow Meter
- Valve
- Valve
- Valve
Sensor Repeatability

Multiple cycles can be performed with full regeneration
Multi-parameter sensing

**Transconductance**

- Baseline 60 sccm: gm = 1.00E-08
- Regen 100 sccm: gm = 2.00E-09

**Mobility**

- Baseline 60 sccm: $u = 4.50E-04$
- Regen 100 sccm: $u = 5.00E-04$

**Threshold Voltage**

- Baseline 60 sccm: $V = -1.00E+01$
- Regen 100 sccm: $V = 0.00E+00$

**Drain Current**

- Baseline 60 sccm: $I_d = -1.60E-07$
- Regen 100 sccm: $I_d = 0.00E+00$
Sensor response can be very slow, due to slow analyte absorption. Speed can be increased by reducing film thickness.
Interaction Mechanisms

- Sensors show a wide range of interactions, complicating analysis. Interactions include:
  - Polar group interactions
  - Chain / bulk interactions
  - Swelling
Differential sensitivity – pathway to an electronic nose?

Nose Response to Water (Pentacene)

Nose Response to Water (P3HT)

Nose Response to Water (P3OT)
Demonstration of basic electronic nose functionality

Nose Response to Water and Milk

- Water
- Milk

Percentage of Baseline Current

Time (Minutes)

- Pentacene
- P3OT
- P3HT
Implication: We must either improve dielectric interface or use $V_T$-insensitive differential sensing method.
Sensing Circuits

• Amplify sensor response
• Desensitize against operational drift
• Integration of encapsulated and unencapsulated OTFTs
• Integration of sensing OTFTs with supporting OTFT or silicon CMOS circuitry
Sensing Circuits

Conclusions & Future Work

• Organic FET-based sensors show promising responses, including transient behavior and cycle life

• Work remains to optimize structure and process flow, particularly in terms of stability and reliability

• Future Work:
  - Integration of latest sensing materials into printed device architecture
  - Deployment in testing of environmentally-relevant analytes
  - Enhancement of specificity through functionalization / doping