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

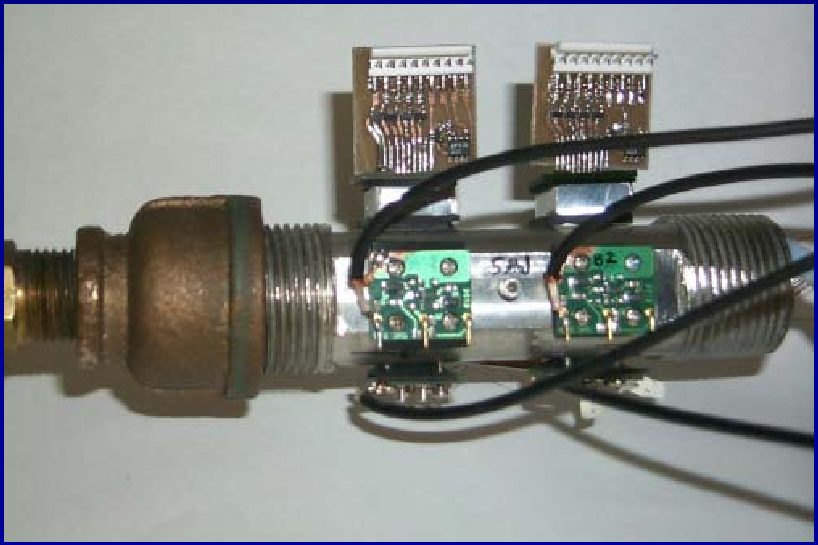
Distributed environmental monitoring

- 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

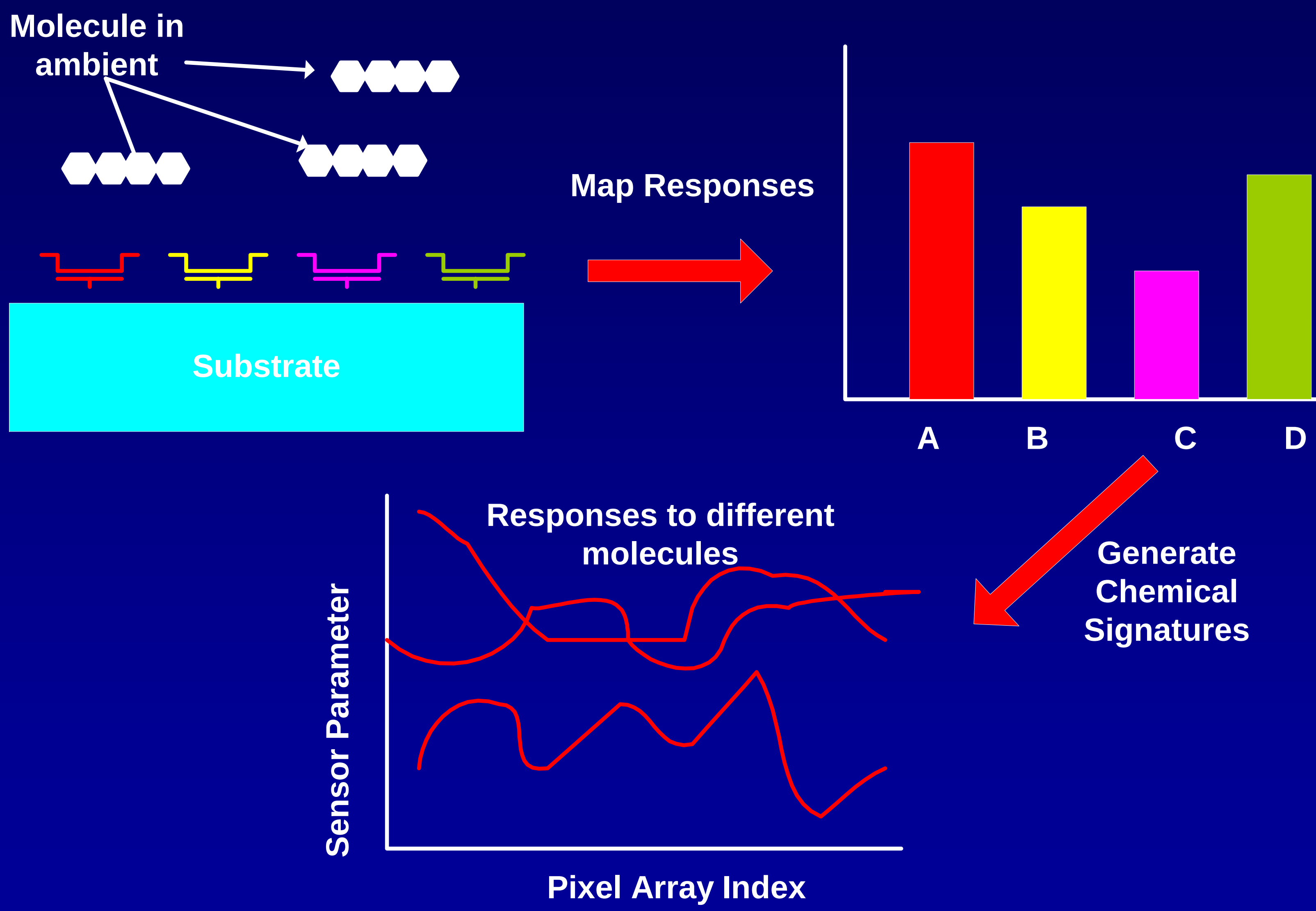


- ppbRAE Plus — $6215
  - For homeland security
  - Detects toxic agents, mildew
- Cyranose — $7995
  - Can be trained to detect a wide range of odors: alcohols, chemicals, oil, food

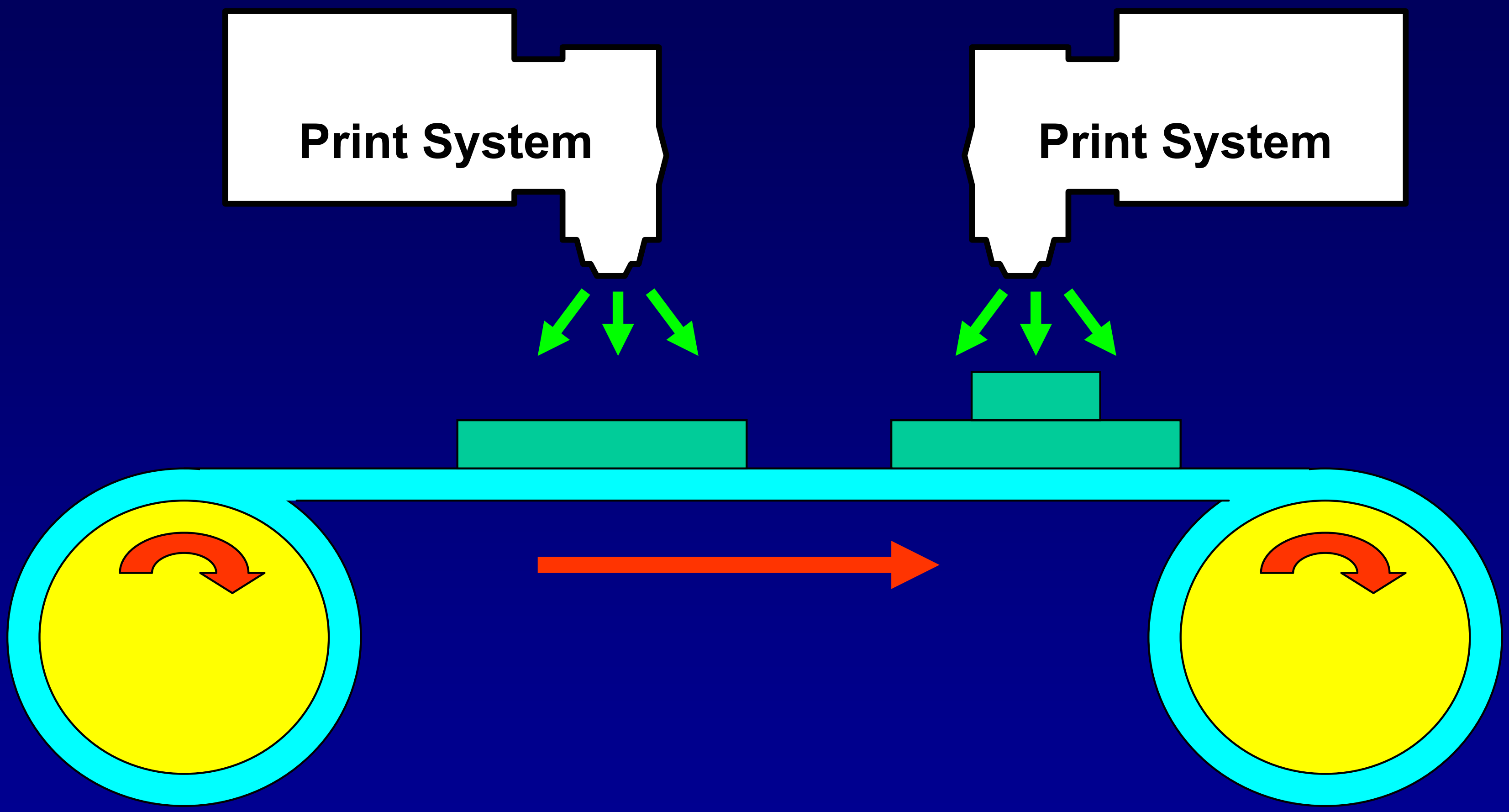
Commercial Gas Sensors

- Vernier O_2 sensor — \$186
- Minimax Pro H_2 sensor— \$199
- Gas Alert Micro 3 H_2S sensor — \$612

Arrayed Gas Sensors



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

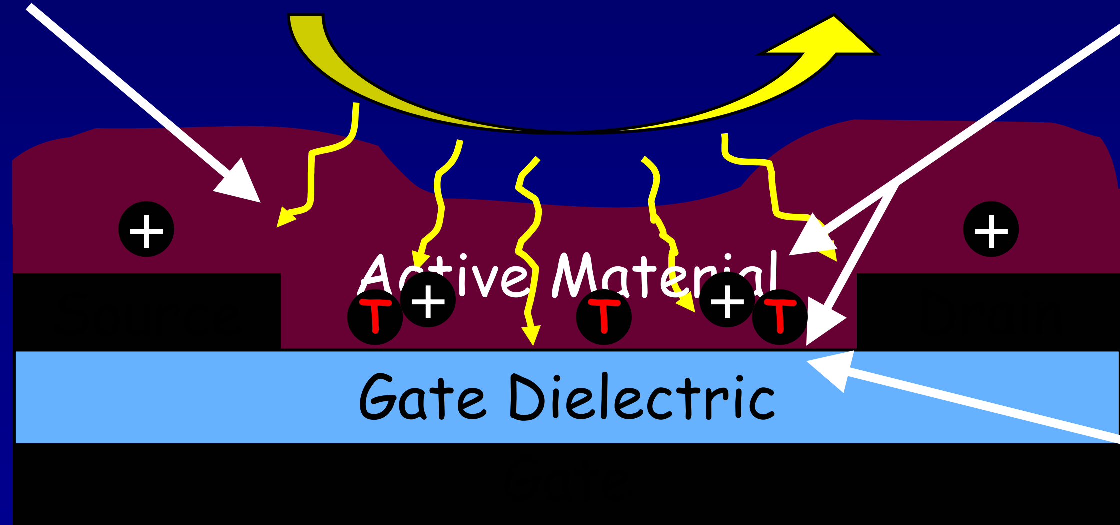
- Good sensitivity
- Synthetic richness
- Easy array integration
- Low performance requirements
- Short-term applications available

The New York Times, April 4, 2002, illustration by Mary Ann Smith

OTFT Gas Sensing

Absorbed through grain boundaries and reactive molecular sites

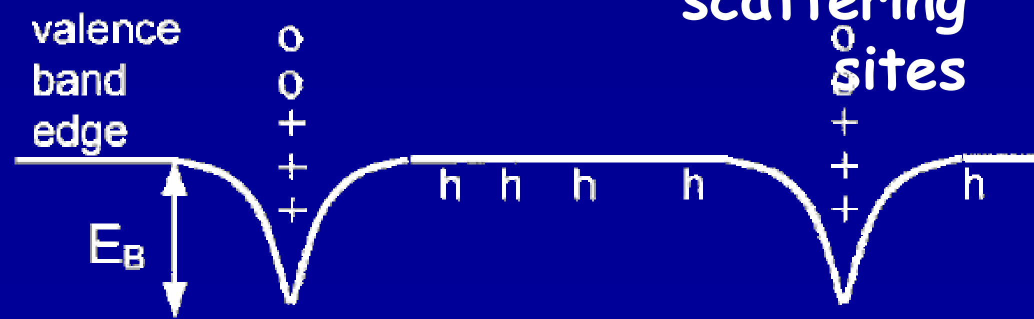
Odors



Analyte donates carriers or activates existing donors

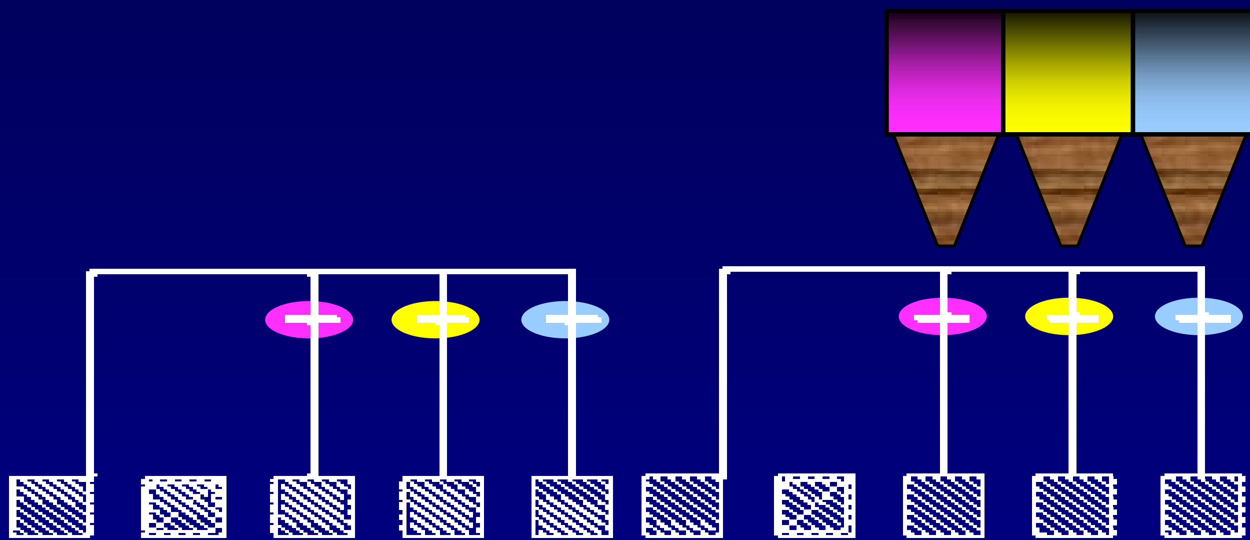
Film expands

Analyte introduces traps and scattering sites



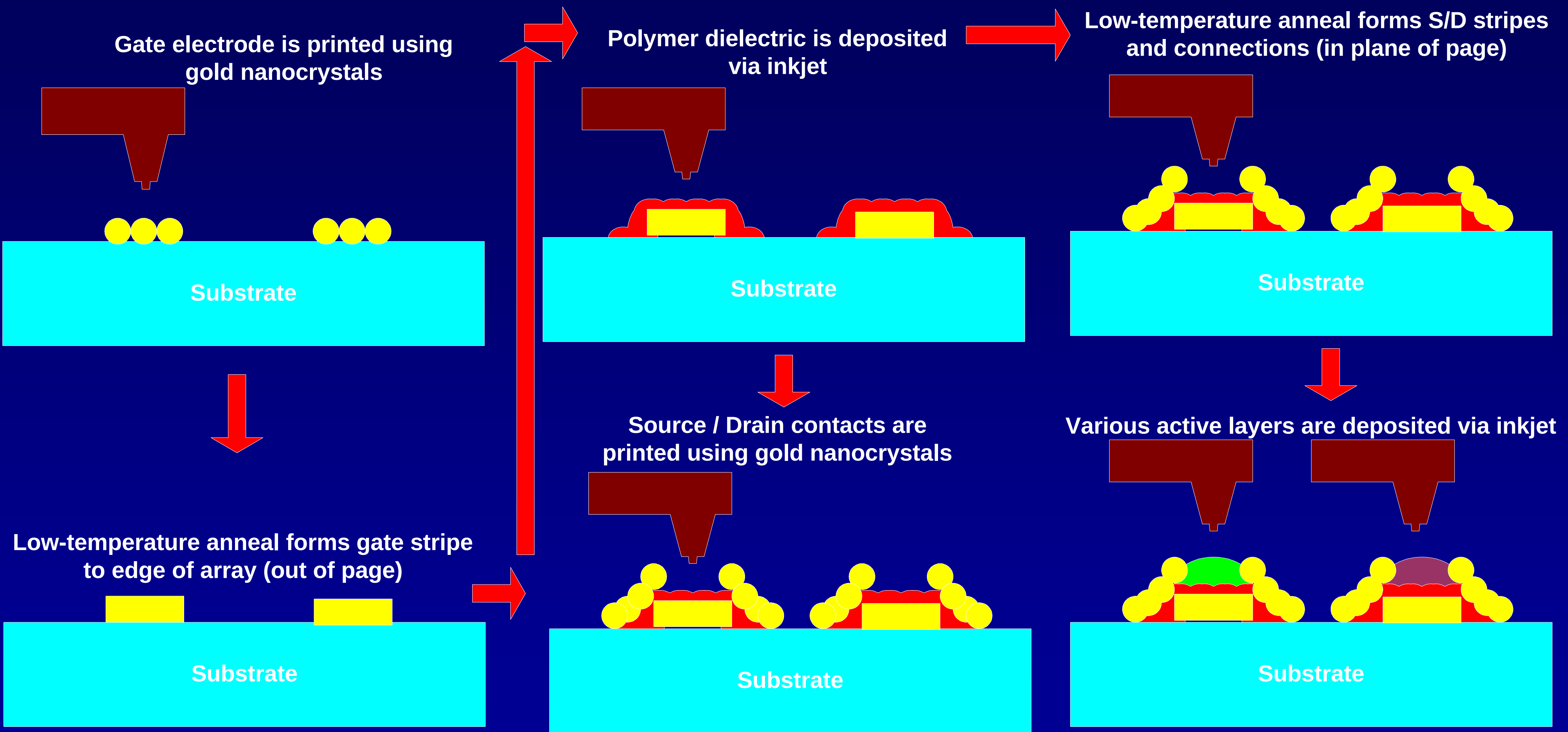
Analyte changes hopping barrier height

Low-cost Fabrication



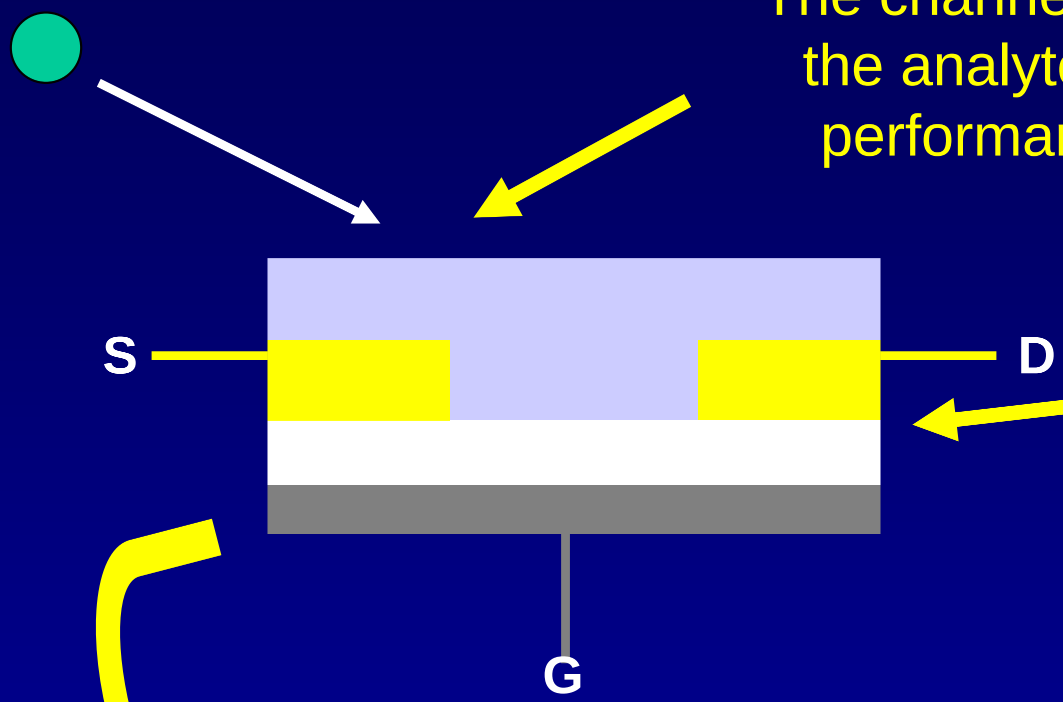
- Inkjet deposition of organic material allows integration of sensor array
- Ultra-low cost requires integration of supporting circuitry

Printed Transistors

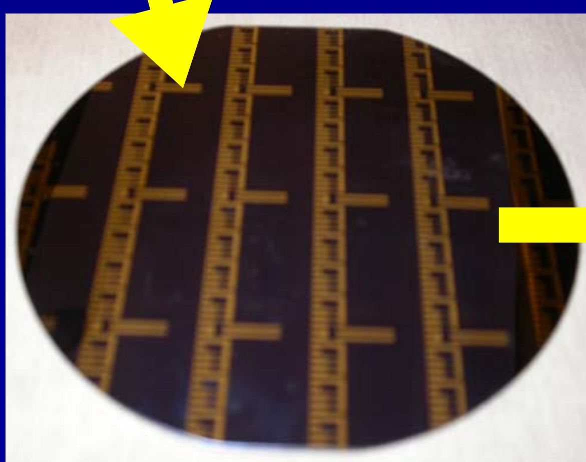


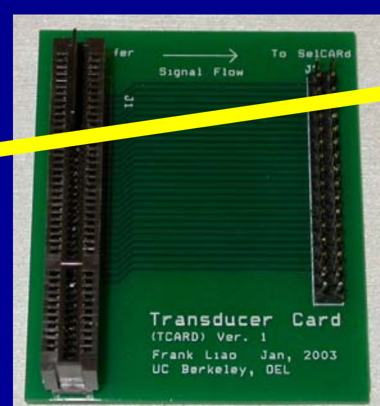
Baseline sensor screening process

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



Materials are characterized using a substrate-gated architecture (easy fabrication for rapid screening)

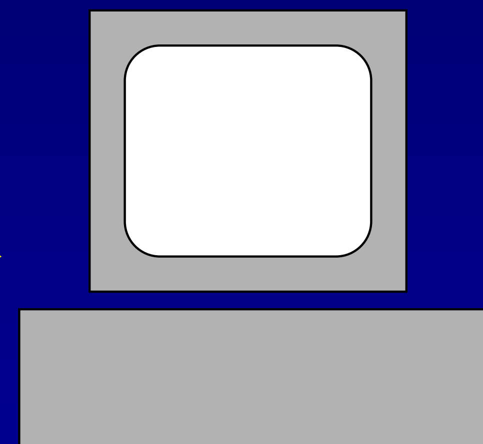




A silicon substrate enables easy I/O via an edge connector

Sensor Characterization

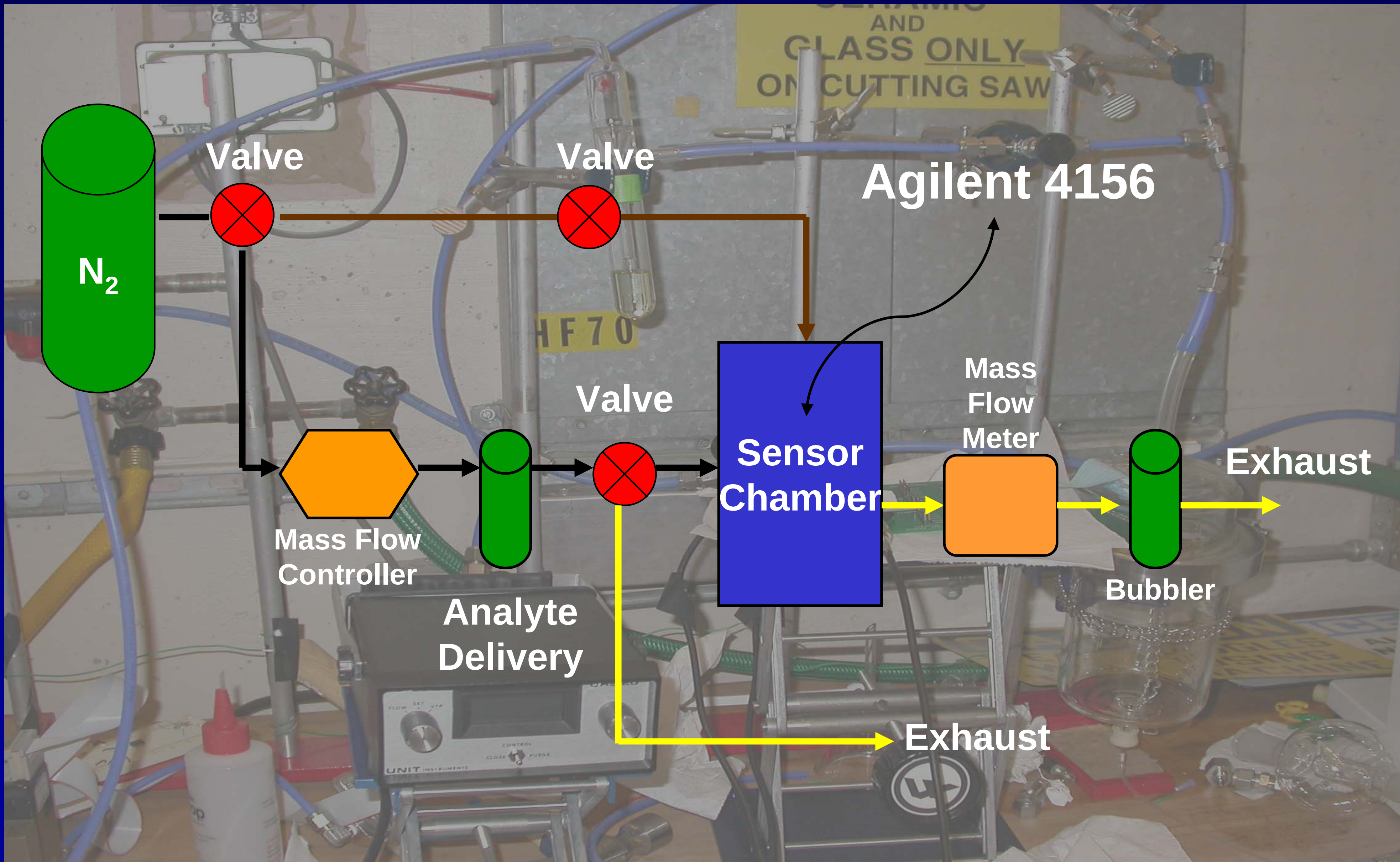
Switching between individual sensors is performed via a switch matrix PCB



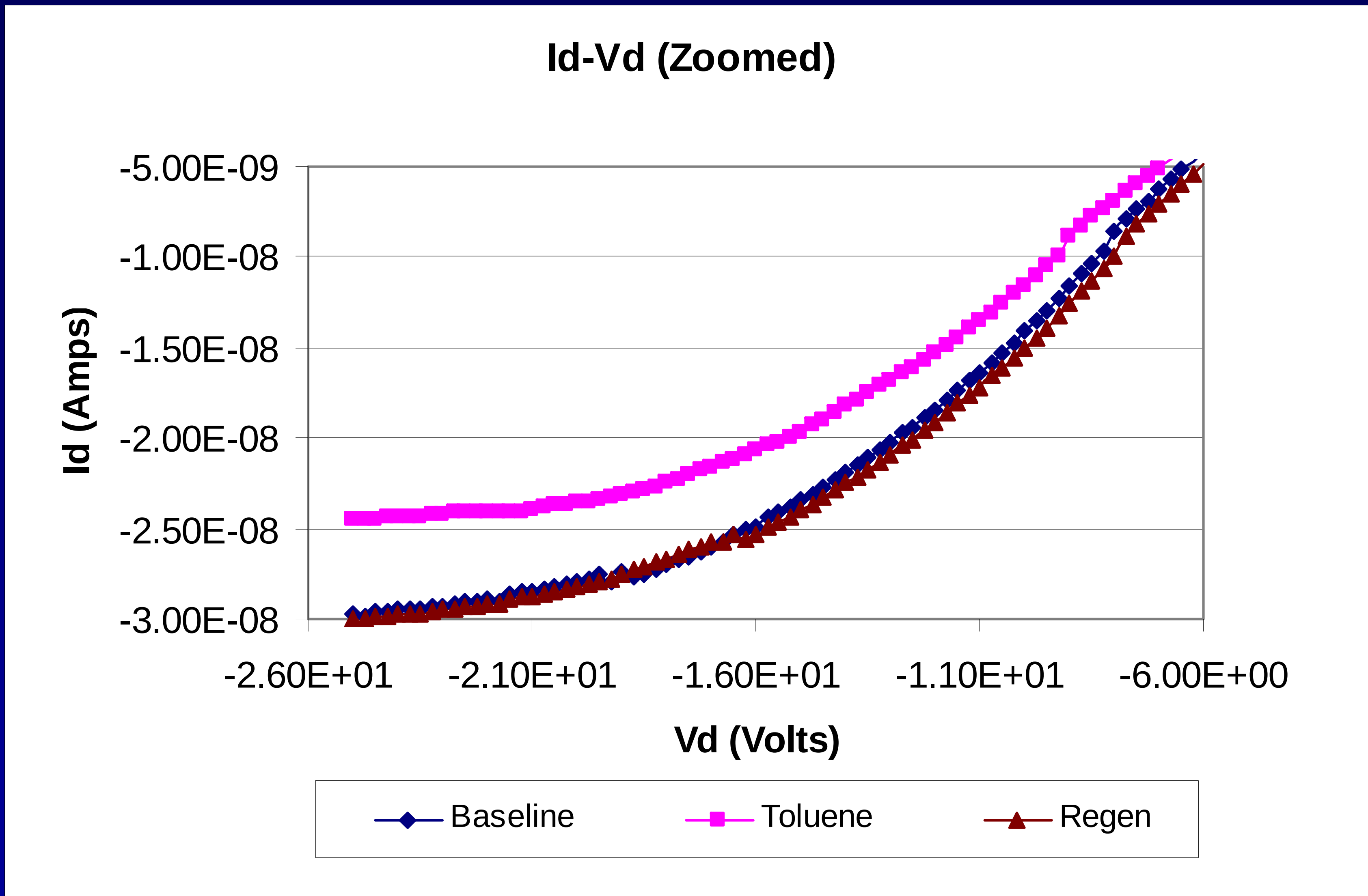
Agilent 4156

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

Experimental Setup

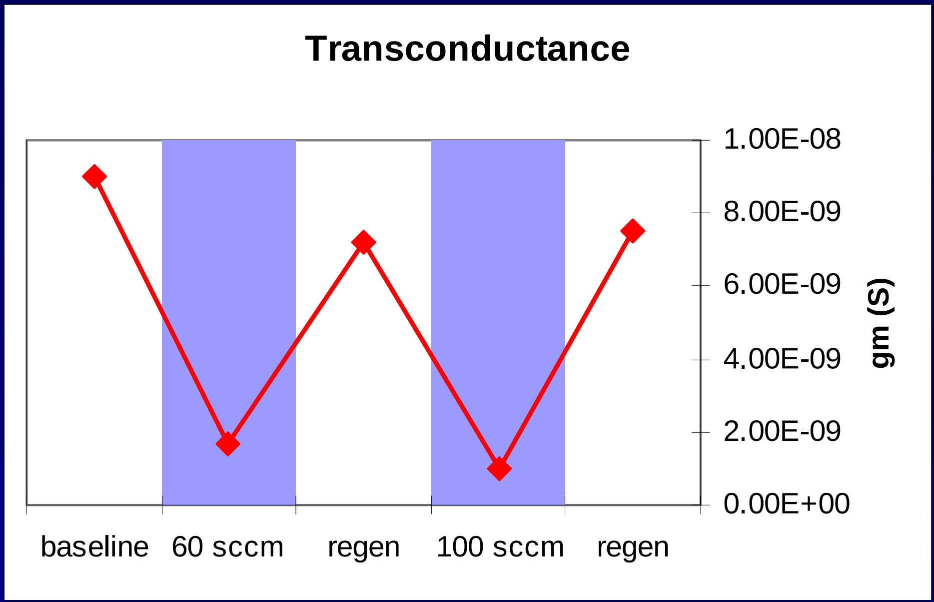


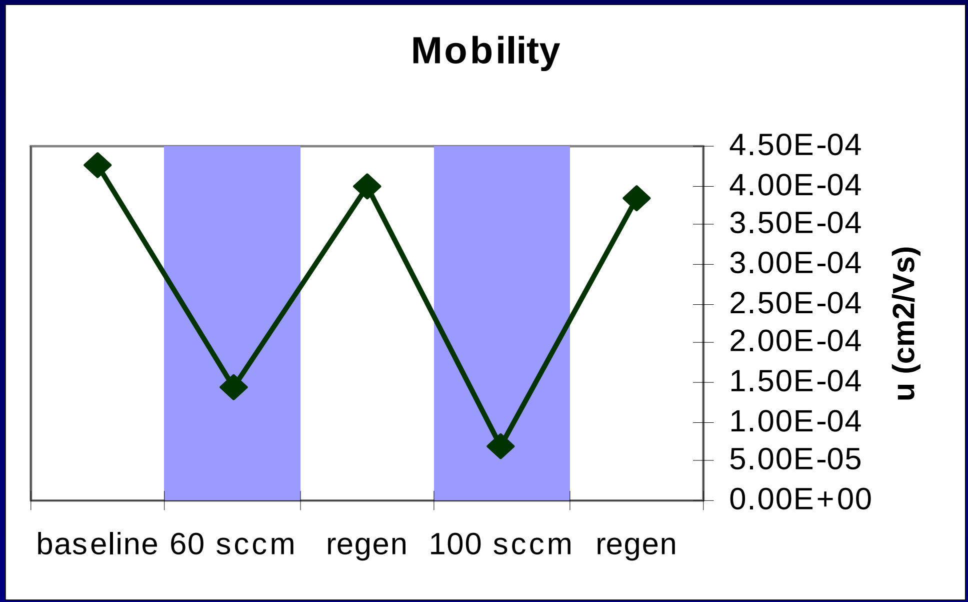
Sensor Repeatability

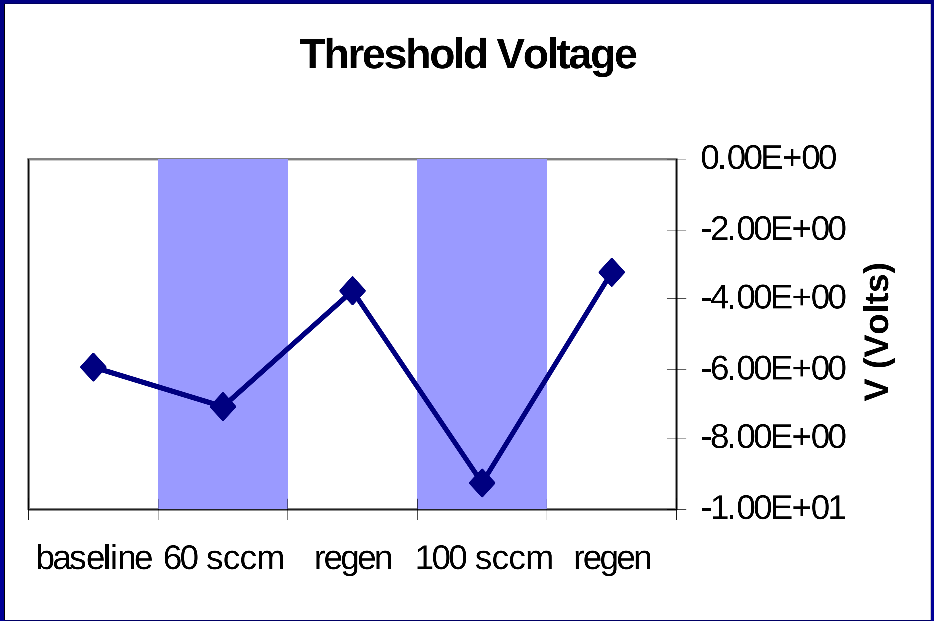


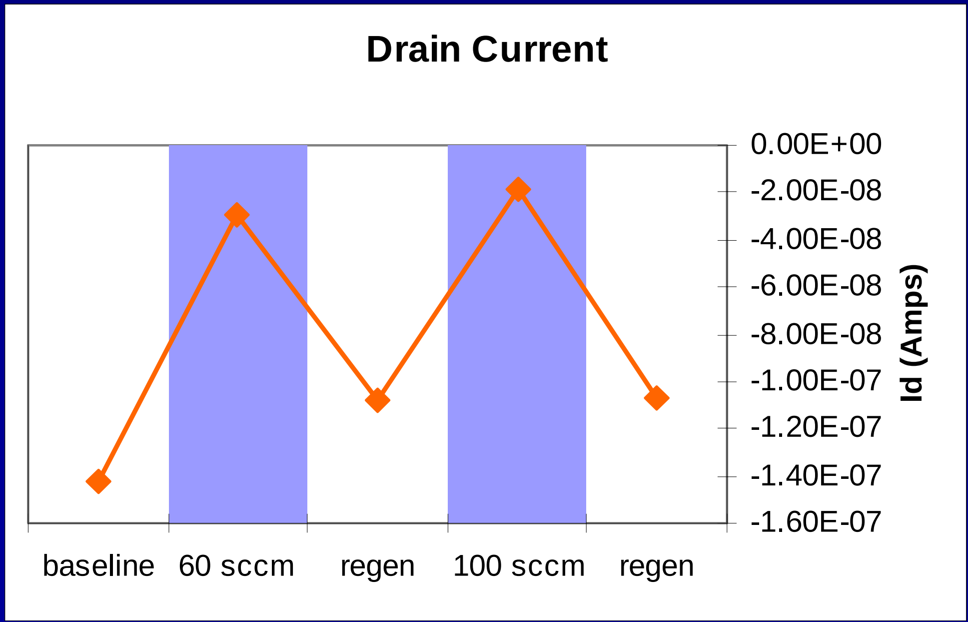
Multiple cycles can be performed with full regeneration

Multi-parameter sensing

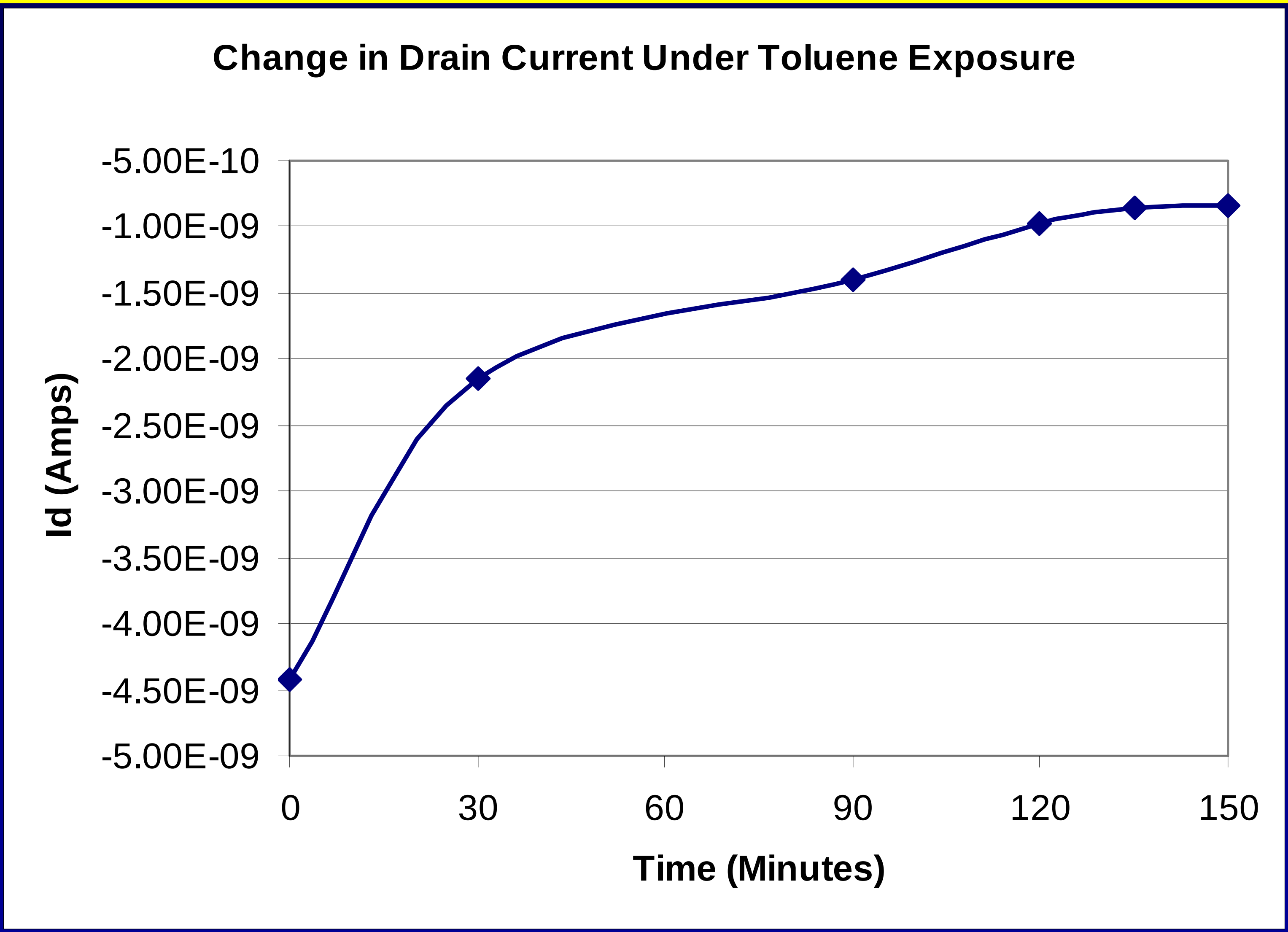








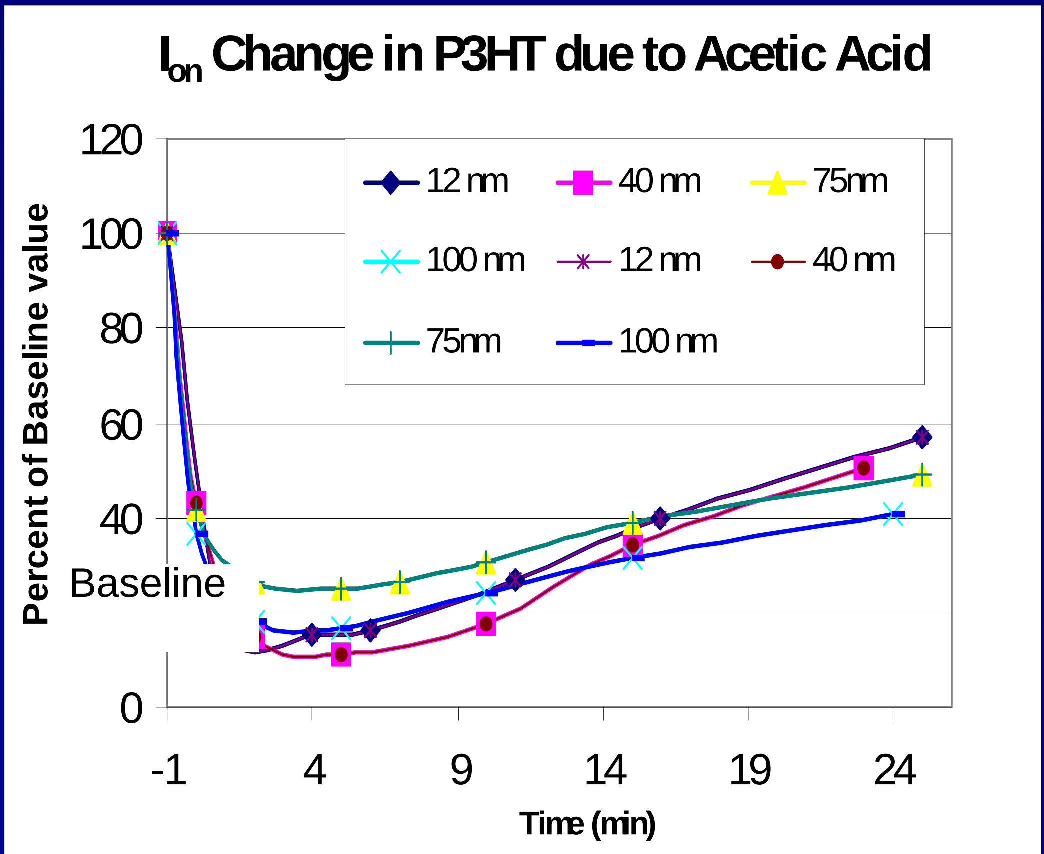
Sensor dynamics – transient response

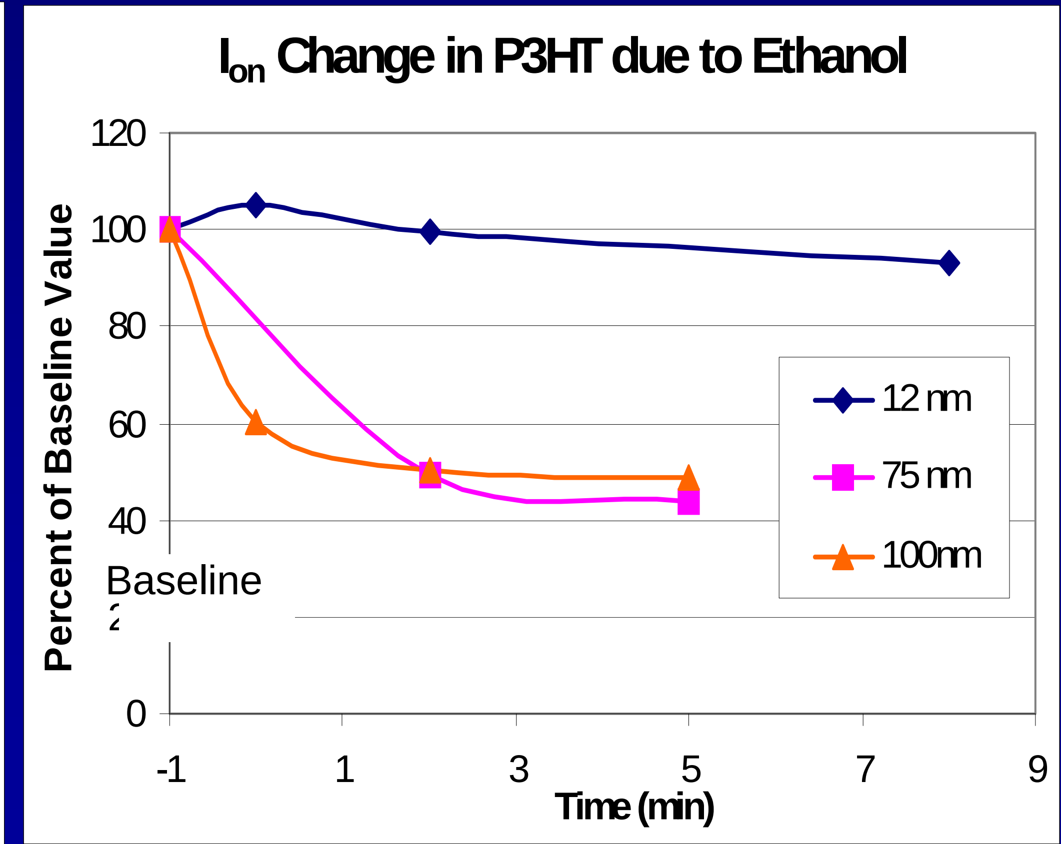


Sensor response can be very slow, due to slow analyte absorption.
Speed can be increased by reducing film thickness

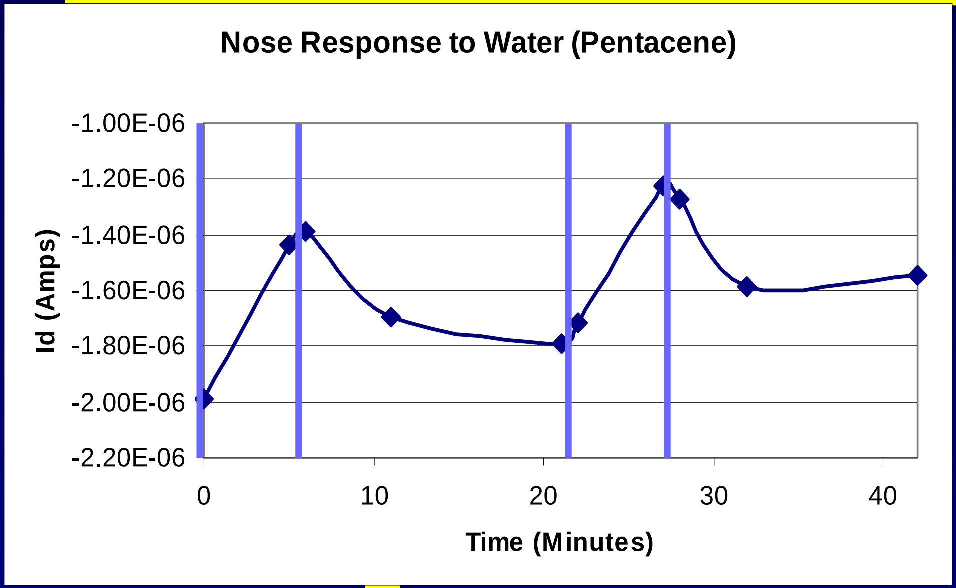
Interaction Mechanisms

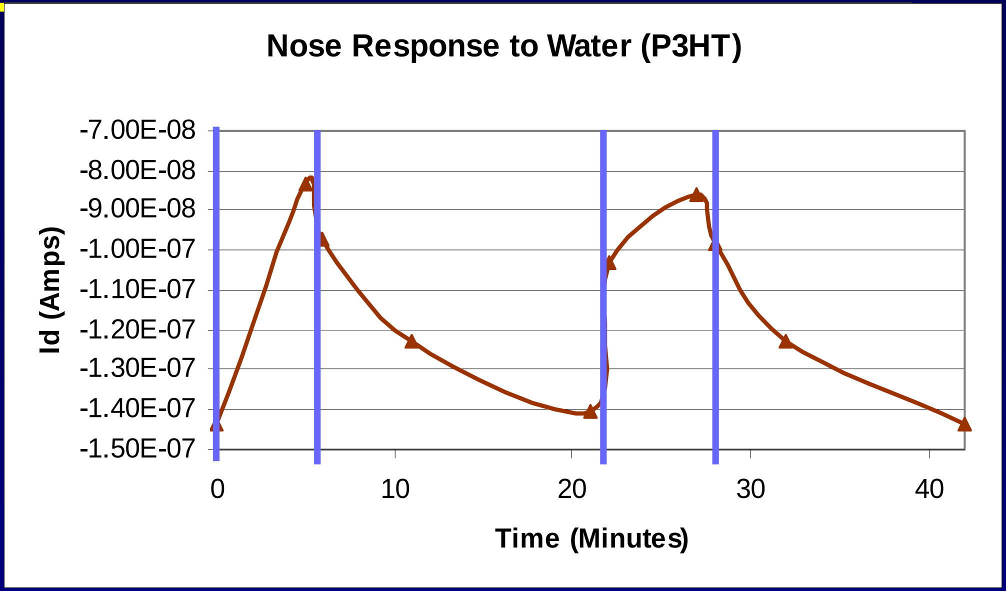
- Sensors show a wide range of interactions, complicating analysis. Interactions include:
  - Polar group interactions
  - Chain / bulk interactions
  - Swelling

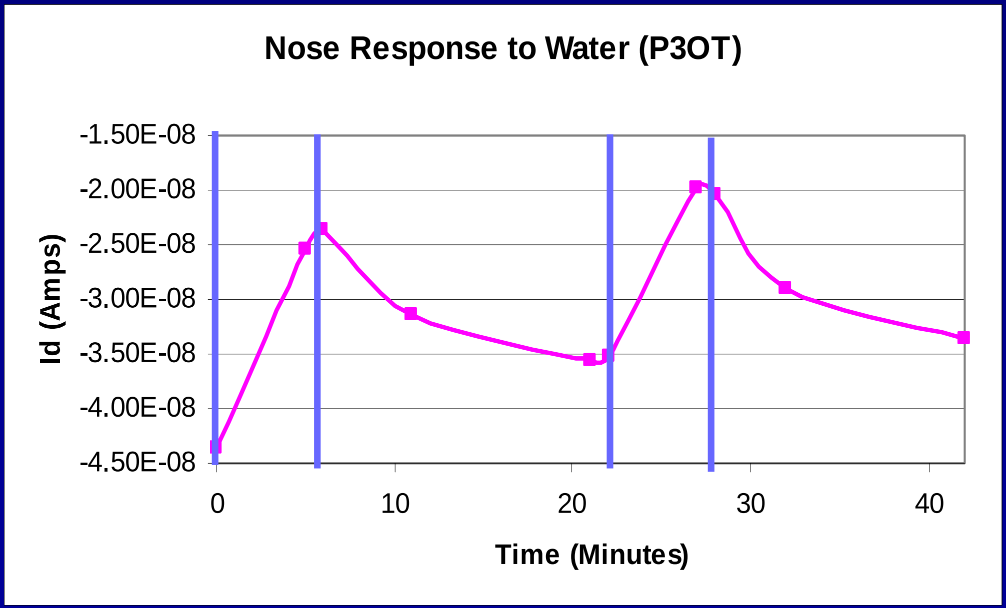




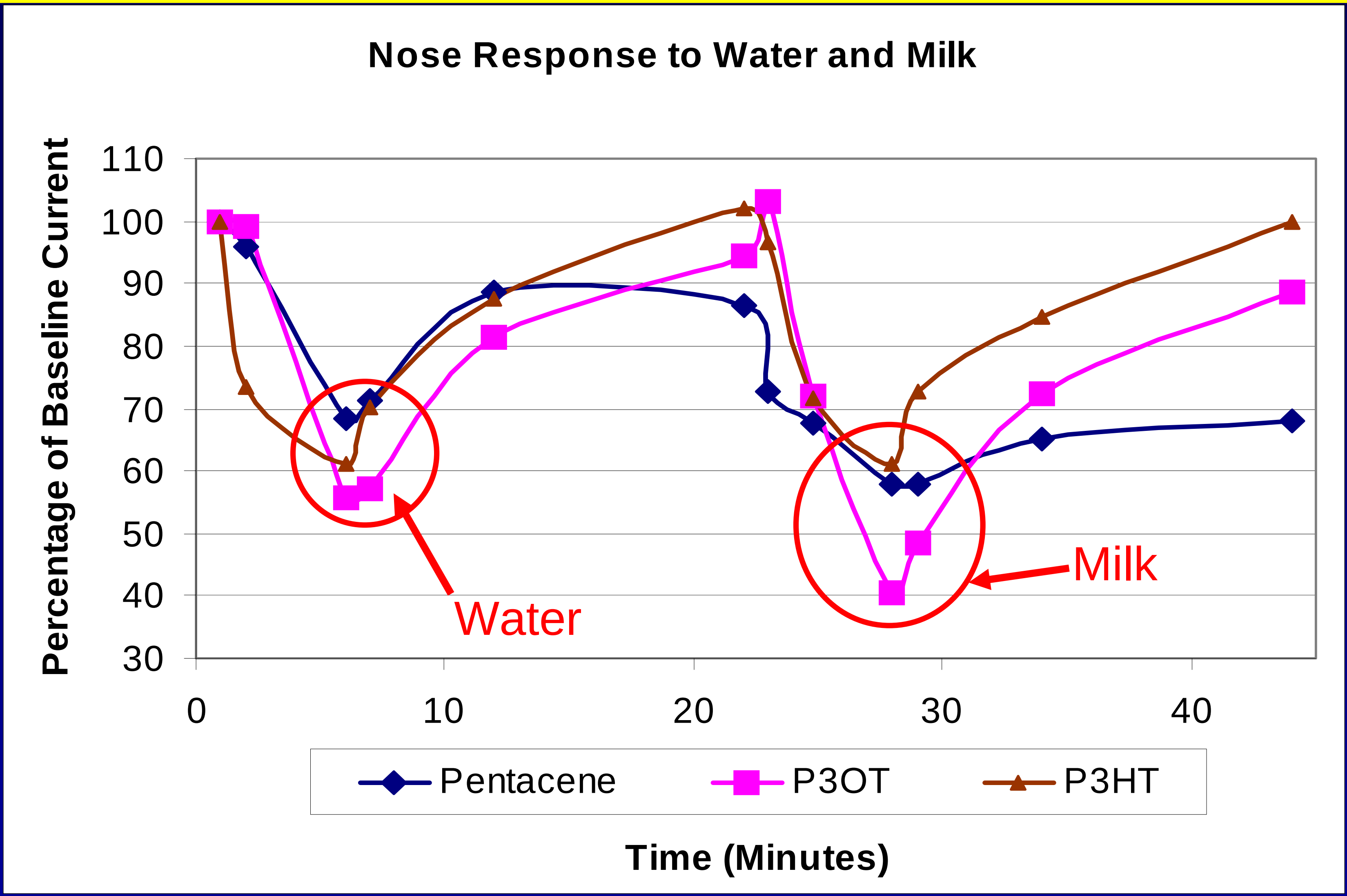
Differential sensitivity – pathway to an electronic nose?



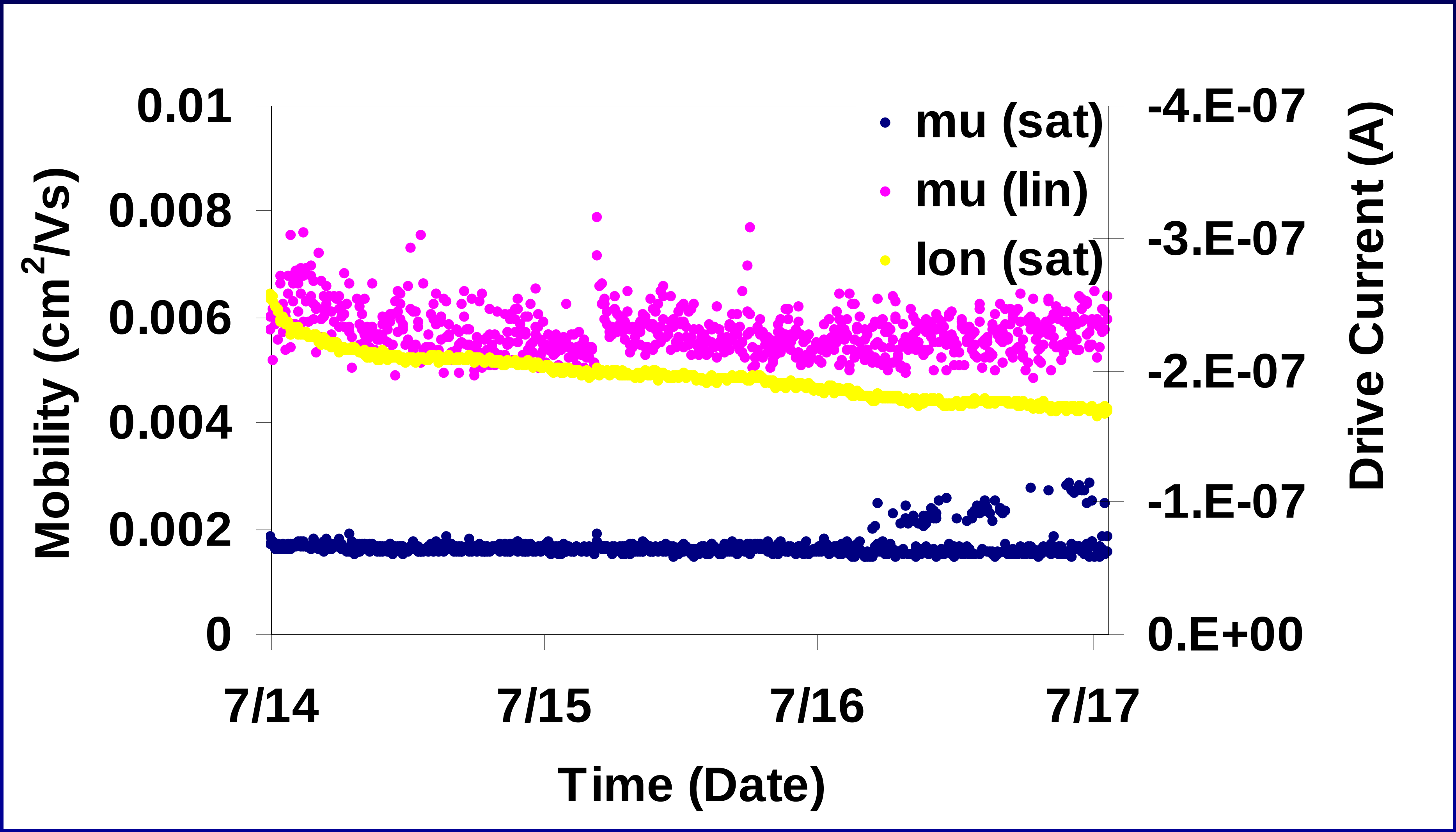




Demonstration of basic electronic nose functionality



Organic Transistor Stability

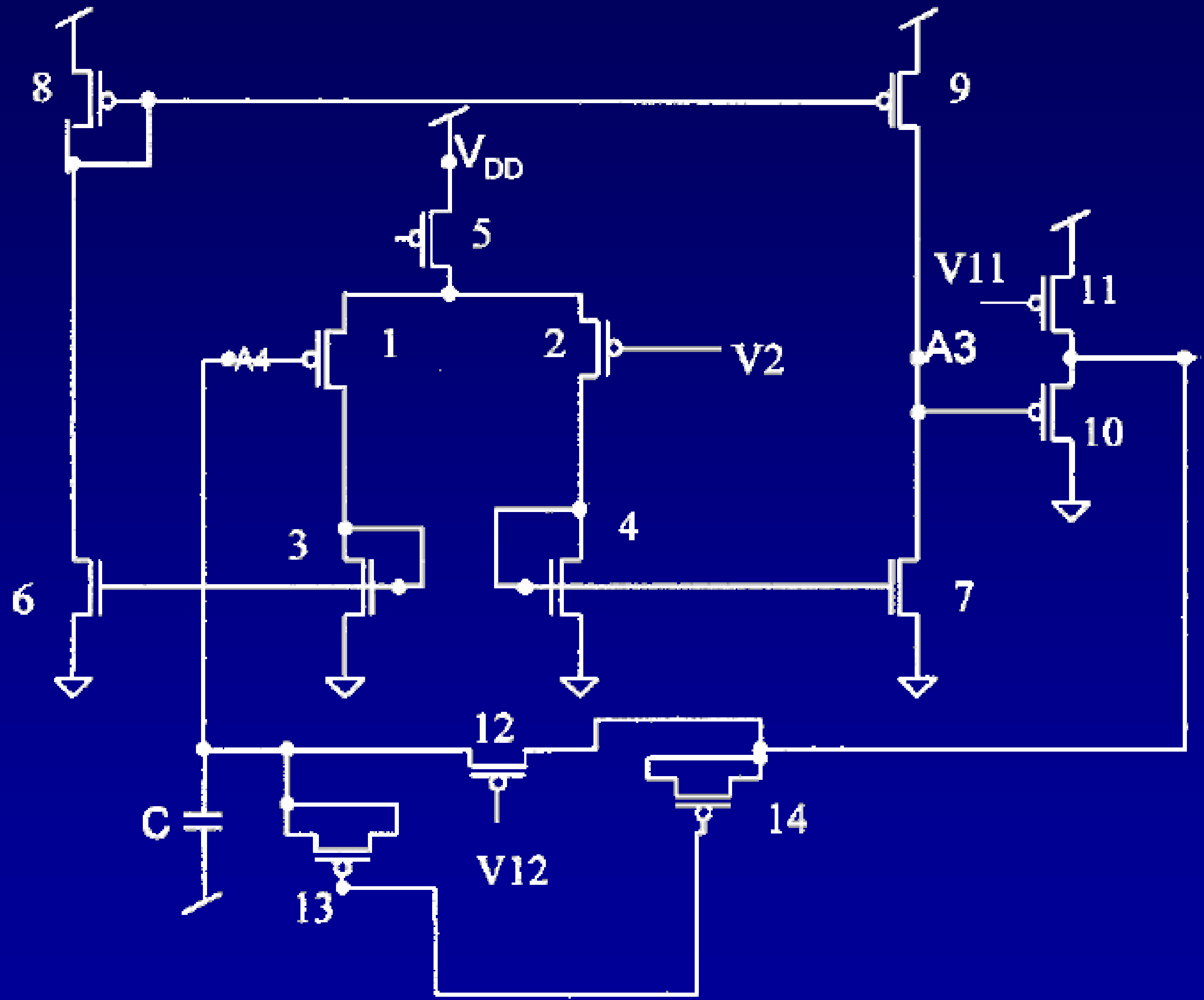


Implication: We must either improve dielectric interface or use V_T-insensitive differential sensing method

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



Crone *et al*, J. Appl. Phys, vol 91, pp. 1014-10146, 2002

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