Towards a miniaturized micromechanical electronic nose

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e-Nose: advanced sensing in complex environments

Human olfactory system

e-nose: array of non-specific, cross-reactive sensors combined with an information processing system

Literature examples

- Target Agent
- Sensor Array
- Agent Identification

- Data Processing

- Pattern Variable 1
- Pattern Variable 2

- Glowing Cigarette
- Smouldering Cable
- Glowing Cotton
- Air

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Many Applications For e-Noses

<table>
<thead>
<tr>
<th>Industry sector</th>
<th>Application area</th>
<th>Specific use types and examples</th>
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<tbody>
<tr>
<td>Agriculture</td>
<td>crop protection</td>
<td>homeland security, safe food supply</td>
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<td></td>
<td>harvest timing &amp; storage</td>
<td>crop ripeness, preservation treatments</td>
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<td>meat, seafood, &amp; fish products</td>
<td>freshness, contamination, spoilage</td>
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<td>plant production</td>
<td>cultivar selection, variety characteristics</td>
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<td>pre- &amp; post-harvest diseases</td>
<td>plant disease diagnoses, pest identification</td>
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<td>detect non-indigenous pests of food crops</td>
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<td>Airline transportation</td>
<td>public safety &amp; welfare</td>
<td>explosive &amp; flammable materials detection</td>
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<td>passenger &amp; personnel security</td>
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<td>Cosmetics</td>
<td>personal application products</td>
<td>perfume &amp; cologne development</td>
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<td>fragrance additives</td>
<td>product enhancement, consumer appeal</td>
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<td>Environmental</td>
<td>air &amp; water quality monitoring</td>
<td>pollution detection, effluents, toxic spills</td>
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<td>indoor air quality control</td>
<td>malodor emissions, toxic/hazardous gases</td>
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<td>Food &amp; beverage</td>
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<tr>
<td>Manufacturing</td>
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<td>Medical &amp; clinical</td>
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<td>Military</td>
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<td>Pharmaceutical</td>
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<td>Regulatory</td>
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<tr>
<td>Scientific research</td>
<td>botany, ecological studies</td>
<td>chemotaxonomy, ecosystem functions</td>
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<td>engineering, material properties</td>
<td>machine design, chemical processes</td>
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<td>microbiology, pathology</td>
<td>microbes and metabolite identifications</td>
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State of the art commercial e-noses

7100 zNose
Electronic Sensor Technology (California)

- Gas Chromatography + polymer coated SAW
- Response time 10 sec
- Listed price $14,950

Cyrano Science 320
Cyrano Science (Pasadena)

- 32 polymer sensors
- Response time of 10 sec
- Weight ~1 kg (<2 pounds)
- Listed price is $7,995

Miniaturization is needed for truly portable e-noses!!!
## Sensor Grand Challenges

### State-of-the-art of e-Nose Sensors

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Calorimetric or catalytic bead</td>
<td>Fast response and recovery time, high specificity for oxidized compounds</td>
<td>High temperature operation, only sensitive to oxygen-containing compounds</td>
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<tr>
<td>Catalytic field-effect sensors</td>
<td>Small sensor size, inexpensive operating costs</td>
<td>Requires environmental control, baseline drift, low sensitivity to ammonia and carbon dioxide</td>
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<tr>
<td>Conducting polymer sensors</td>
<td>Ambient temperature operation, sensitive to many VOCs, short response time, diverse sensor coatings, inexpensive, resistance to sensor poisoning</td>
<td>Sensitive to humidity and temperature, sensors can be overloaded by certain analytes, sensor life is limited</td>
</tr>
<tr>
<td>Electrochemical sensors (EC)</td>
<td>Ambient temperature operation, low power consumption, very sensitive to diverse VOCs</td>
<td>Bulky size, limited sensitivity to simple or low mol. wt. gases</td>
</tr>
<tr>
<td>Metal oxides semiconducting (MOS)</td>
<td>Very high sensitivity, limited sensing range, rapid response and recovery times for low mol. wt. compounds (not high)</td>
<td>High temperature operation, high power consumption, sulfur &amp; weak acid poisoning, limited sensor coatings, sensitive to humidity, poor precision</td>
</tr>
<tr>
<td>Optical sensors</td>
<td>Very high sensitivity, capable of identifications of individual compounds in mixtures, multi-parameter detection capabilities</td>
<td>Complex sensor-array systems, more expensive to operate, low portability due to delicate optics and electrical components</td>
</tr>
<tr>
<td>Quartz crystal microbalance</td>
<td>Good precision, diverse range of sensor coatings, high sensitivity</td>
<td>Complex circuitry, poor signal-to-noise ratio, sensitive to humidity and temperature</td>
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<tr>
<td>Surface acoustic wave (SAW)</td>
<td>High sensitivity, good response time, diverse sensor coatings, small, inexpensive, sensitive to virtually all gases</td>
<td>Complex circuitry, temperature sensitive, specificity to analyte groups affected by polymeric-film sensor coating</td>
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</tbody>
</table>

*Most Disadvantages Rule These Sensors Out for Handheld e-Nose Applications*
**MEMS-based e-Nose For Organic Vapor Analysis**

**Vision**
- Low-power electronic nose for organic vapors and metabolites

**Advantages compared to state-of-the-art**
- Small molecule detection possible
  - Not only heavy bio-molecules → also smaller vapors and gas molecules
  - Enabled by combining well known mass effect with novel stress effect
- Low-power sensing
  - No power consuming optical read-out required (piezo-electrics)
- Easily scalable
  - No bulky optical instrumentation
  - imec CMORE compatible fabrication
- Easy fabrication of sensor arrays
  - Solves the intrinsic lack of selectivity in vapor detection
  - Small form factor
  - Multiple coatings using cheap mature inkjet printing
- Single technology
  - Cheap

\[
\begin{align*}
L/h_{Si} & \geq 100 \\
h_{Poly} & \approx 2h_{Si} \\
L \sim 100 \mu m & \quad w \sim 6-10 \mu m
\end{align*}
\]
The working principle

Adsorption $\rightarrow$ Extra mass

Swelling $\rightarrow$ Stress

Lower Frequency

$$\frac{\Delta f_n}{f_n} = \frac{1}{2} \left( -\frac{\Delta m}{m} + \frac{\Delta k}{k} + \frac{\alpha_n \Delta \sigma}{1 + \alpha_n \sigma} \right)$$
From vision to reality

Die = 8.8 mm x 8.8 mm, 160 resonators
Resonators Array Chip

Die = 8.8 mm x 8.8 mm, 160 resonators
Ink Jet Printing Of Polymers On Suspended Beams

Backside printing
- Using commercial printer
- Custom prepared “ink” containing the specific polymer
Benchmarking

$w = 100 \, \mu m \quad L = 500 \, \mu m \quad h = 8 \, \mu m$

Coating: PMMA
Detection: Optical Beam
Power = 2 mW

$w = 65 \, \mu m \quad L = 750 \, \mu m \quad h = 500 \, nm$

Coating: PMMA
Transduction: Piezoelectric actuation/detection
Power = 0.00017 mW (170 nW)

10,000 times more power efficient

Ethanol sensing

100 ml/min flow in 6 ml chamber

10^{-5} \text{ frequency shift / \%EtOH}

260 times responsivity increase

2.6 \times 10^{-3} \text{ frequency shift / \%EtOH}
Co-optimization MEMS and IC Design

First results

Co-optimized
First demonstrator

Resonators with integrated transducers

Oscillator based read-out

Integrated transduction
Enhanced sensitivity by 200x
→ ~ 7 Hz/ppm
ppm detection capability

Testing the demonstrator

Resonance mode tracking
SELECTIVITY BY COATING CHEMISTRY

Separation of alcohol and water vapors

Response to Ethanol

Response to Humidity

Identical resonators and operation modes

PMMA-coated
PVA-coated
SENSITIVITY & SELECTIVITY TESTING

Automated testing setup now operational
- Multi-device
- Multi-mode
- Multi-flow conditions

Allows for a lot measurements
TRANSFER AND IMPLEMENTATION

Business case

Cost calculations

Packaging

Total MEMS area: 1.8 mm²
Oscillator circuit area: 2.6 mm²

Transferability of fabrication concept

Failure mechanisms analysis
e-Nose Applications Scenarios in Mobile Phones

- Air quality monitoring and indoor air quality control (pollution, malodor emission, toxic gasses..)
- CO₂ high levels
- Consumer fraud prevention (ingredient confirmation, content standards..)
- Ripeness, Food contamination (spoilage, self live..)
- Taste, smell characteristics (off flavors, product variety assessment..)
- Pathogen identification (patient treatment selection, prognosis..)
- Physiological condition (nutritional status, organ failure..)
- Personnel and population security (biological and chemical weapons..)
The future is coming

NASA adapt *iPhone* to smell chemicals (Nov 17, 2009)

*NTT DoCoMo* A Cell Phone that spots Bad Breath

**Nokia EcoSensor** Concept
Wearable sensor unit to sense (environment, health..), and a dedicated mobile phone (not an e-nose yet)

**Nokia Scentsory** Concept
e-nose samples the odor of caller environment and transmit to recipient electronically

Other concepts:
*Health conscious phone* that *smells* food properties

**Future: Year 2020?**
HUMAN++
Pioneering efficient healthcare