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Nanosensor Arrays: Integrating Nano-Scale Sensors and VLSI Processing Circuitry

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Motivation

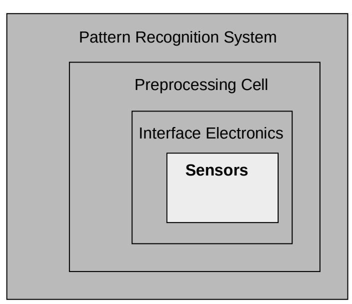
- **Electronic noses:** a chemical sensing system that contains an array of several different types of sensors, where each element measures a different property of the sensed chemical
- **Applications:**
  - detecting hazardous emissions from chemical plants
  - detection and control of automobile emissions
  - odor control in chemical and food processing
  - discrimination of breath alcohol constituents

Outline

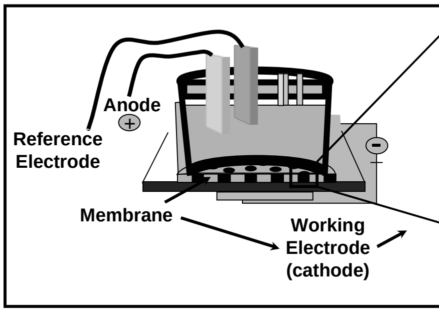
- ◆Nanowire sensor background
- ◆Interface Electronics
- ◆Signal Processing For Gas Detection
- ◆Signal Processing For Gas Classification

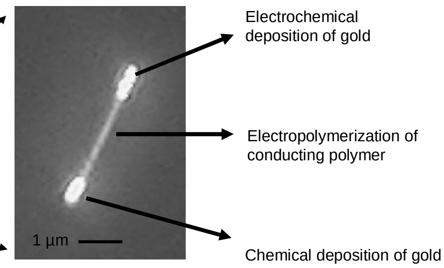
Chemiresistive Sensors

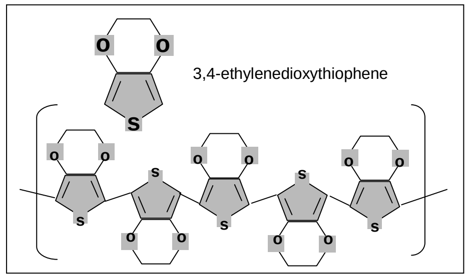
- Convert Chemical Energy to Change in Resistance



Electrochemical Growth of Nanowires

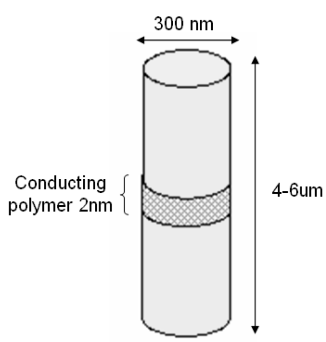






Source: Mallouck et. al.

Chemiresistive sensors



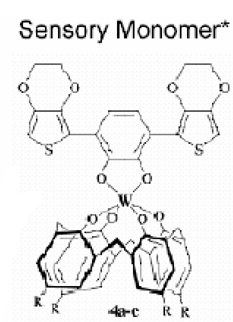
Au-poly-Au nanowire

$$R_s = \frac{1}{AC^{\alpha}}$$

R_s: resistance of the polymer

C: concentration of the gas

A,α: constants that change with type of gas and temperature



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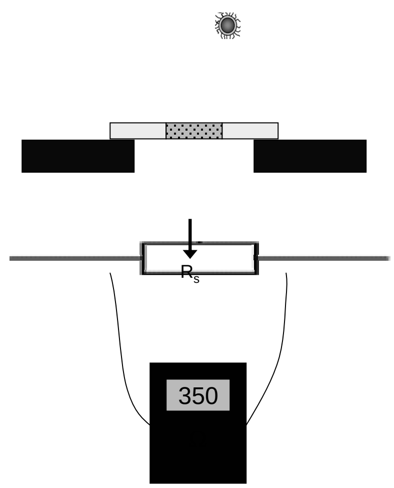

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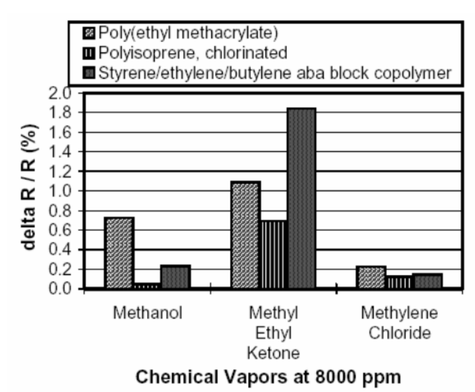
Chemiresistive Sensors



By integrating the responses from different types of sensor array, a distinctive pattern or signature is produced for each chemical gas.

Responses of three polymer sensor films when exposed to three gases

MEMS Chmical Gas Sensor Using a Polymer-based Array, by F. Zee and J. Judy, Transducers '99

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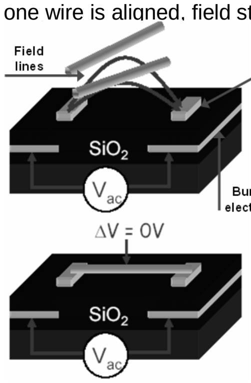
Going from macro to nano scale

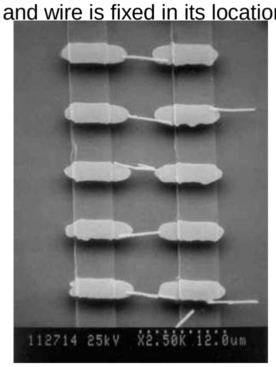
- **Low cost:** batch fabricated
- **Low power consumption:** Individual nanowires will dissipate on the order of tenths of mW; long term battery-powered operation becomes possible for small arrays
- **Massive redundancy :** fault tolerant, high sensitivity

Electric Field-Driven Assembly

- AC field is used to induce long range forces to drive nanowire alignment between pairs of pre-patterned electrodes.
- If nanowire is more polarizable than the medium in which it is suspended, dielectrophoresis force will cause the nanowire to move in the direction of highest field strength.
- Once one wire is aligned, field strength = 0, and wire is fixed in its location



Alignment of 200nm diameter, 5μm long Au nanowires

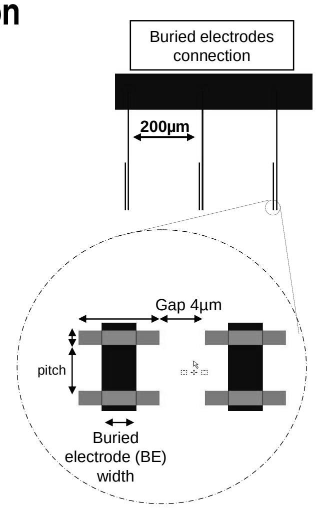


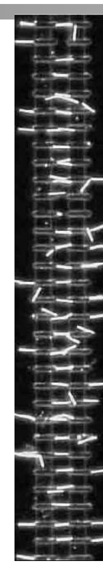
SEM image of nanowire alignment

Source: Mallouck

Factors influencing Alignment Yield

- Local wire concentration
- Effective field area
- Electric field
- AC frequency
- Medium





Source: Mayer

Sensor Area

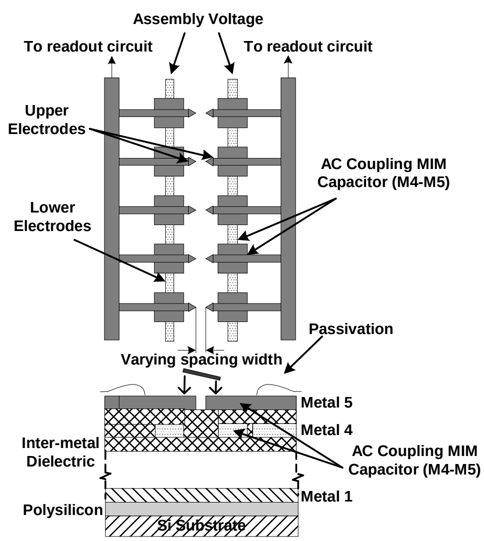
Pitch	BE Width	Area (um²)
1.5um	1.5um	643 x 10.5
6um	3um	655 x 24
10um	1.5um	643 x 36

- 4 x 4 Sensor Array
- Total 4 pairs of electrodes.
- 200μm between 2 pairs of electrodes.

Pitch	BE Width	Area (um²)
1.5um	1.5um	1483 x 22.5
6um	3um	1507 x 54
10um	1.5um	1483 x 72

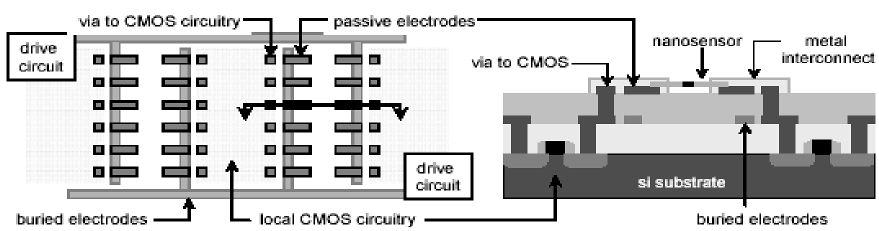
- 8 x 8 Sensor Array
- Total 8 pairs of electrodes.
- 200μm between 2 pairs of electrodes.

Integrating Sensors with VLSI Circuitry



Source: Evoy

Integrate Nanosensor Array with silicon CMOS circuitry

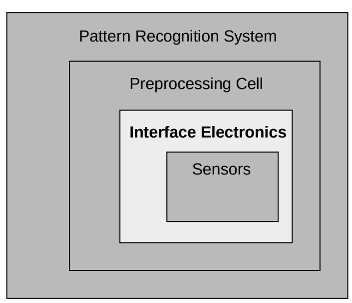


Outline

- Nanowire sensor background
- Interface Electronics
- Signal Processing For Gas Detection
- Signal Processing For Gas Classification

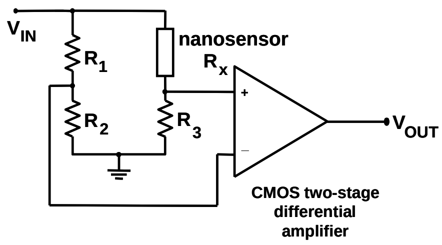
Interface Electronics

- Signal Conditioning
- Analog to Digital Conversion



Interface Electronics

Signal Conditioning (Wheatstone Bridge)



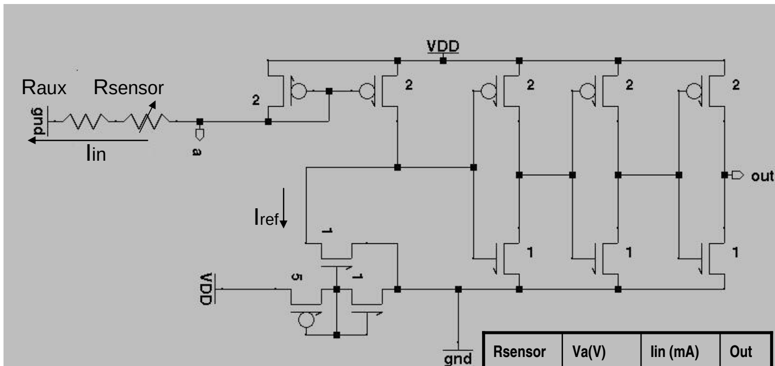
Benefits

- Standard Circuit

Disadvantages

- Errors due to contact resistance
- Difficult to fabricate resistors precisely
- Non-linear response when sensors > 1

Interface Electronics



Rsensor (KΩ)	Va(V)	Iin (mA)	Out
3	1.35	0.321	0
3.1	1.36	0.316	0
3.2	1.38	0.314	0
3.3	1.39	0.308	1
3.5	1.42	0.302	1

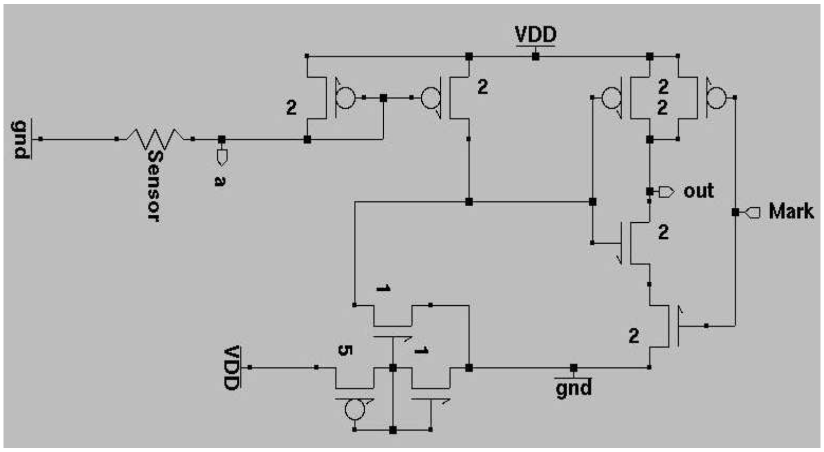
Example:

R_{aux}=1.2K Ω, VDD=3.7V, I_{ref}=0.31mA

Assume R_{sensor}=3K Ω (no gas)

ΔR=0.3K Ω (gas exists)

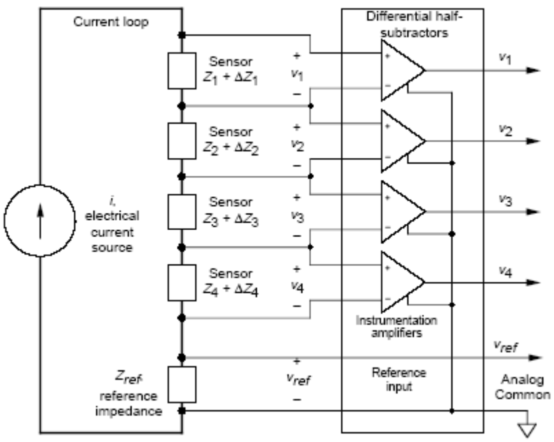
Interface Electronics



Size of ADC: 8.71*7.23= 63 µm^2 , 0.25 µm Technology

Interface Electronics

Signal Conditioning (Anderson Loop)



Benefits

- Insensitive to contact voltage losses
- 2x gain compared to Wheatstone
- Necessarily linear output for N sensors
- Only one reference resistor for each loop

Disadvantages

- Slightly more complex circuit

Outline

- ◆Nanowire sensor background
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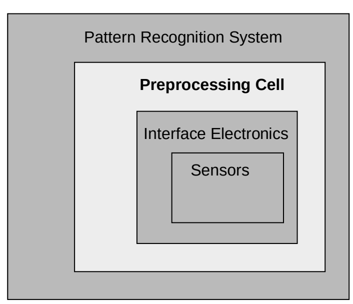
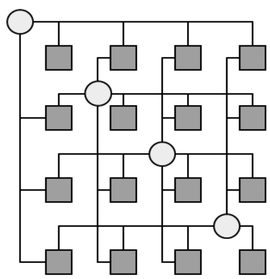
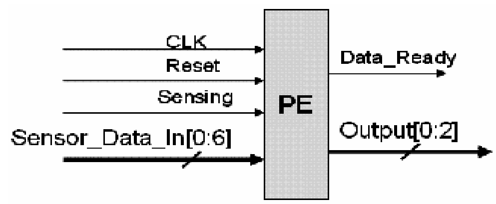
Preprocessing Circuit

- Sensor Array Control
- Calibration
- Power Management
- Data Preprocessing



NANSEA Architecture—basic module





■ Sensor ○ Processing Element

PE_i counts the number of 1s in the i^{th} row and i^{th} column

Adapted from *"Processor time Optimal Parallel Algorithms for Digitized Images on Mesh Connected Processor Arrays"* by H. M. Alnuweiri and V. K. Prasanna

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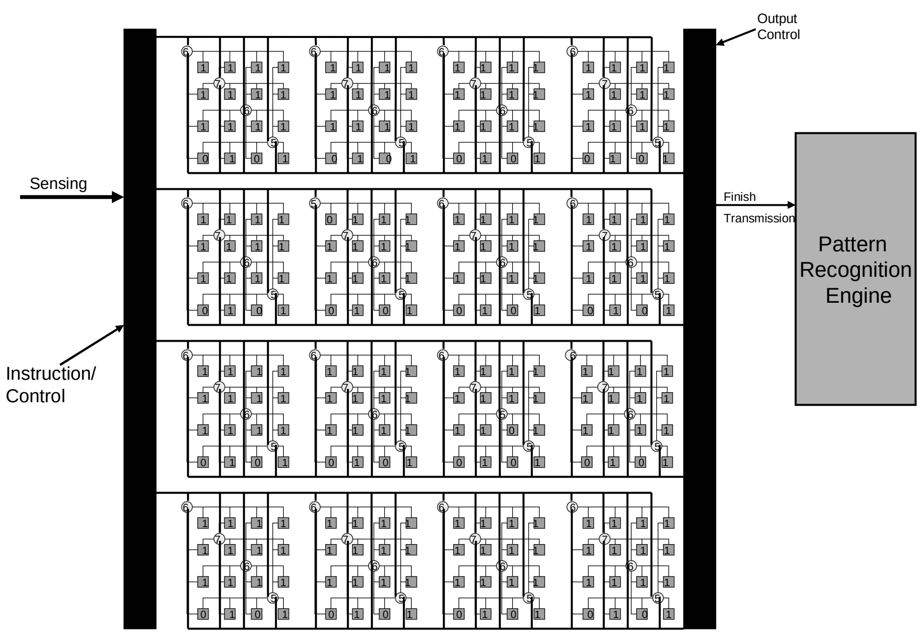

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Gas Detection – Operating Phases

Step 1: Training --> mark all the “bad” sensors

Step 2: Computing signature feature vector

Step 3: Processing data, get feature vector

Step 4: Final gas detection (compare feature vector with signature feature vector), using Least Square Estimation

Step 1: Training

Sensor Input

No Gas

0	1	0	0
0	0	0	0
0	0	1	0
1	0	0	0

Expose to Gas

0	1	1	0
1	1	1	0
1	1	1	1
1	1	1	1

No Gas

0	1	0	0
0	0	0	0
0	0	1	0
1	0	0	1

Mask matrix

1	0	1	1
1	1	1	1
1	1	0	1
0	1	1	1

0	0	1	0
1	1	1	0
1	1	0	1
0	1	1	1

0	0	1	0
1	1	1	0
1	1	0	1
0	1	1	0

Step 2: Signature feature vector

Mask Matrix

0	0	1	0
1	1	1	0
1	1	0	1
0	1	1	0

PE signature feature vector

Gas Exists

3			
	5		
		6	
			3

No Gas

0			
	0		
		0	
			0

Step 3: Sensing

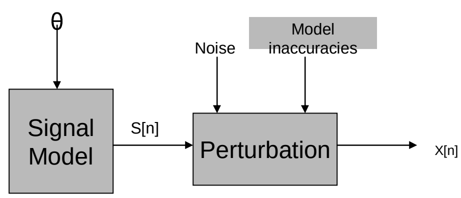
Sensor Array Output

X	X	0	X
0	1	1	X
1	0	X	1
X	1	1	X

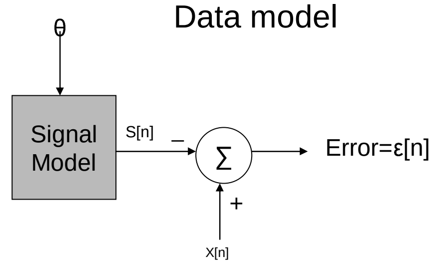
Feature Vector

1			
	3		
		4	
			3

Step 4: Pattern recognition-Least Squares Approach



Data model



Least squares error

LS error criterion

$J(\theta)= \sum_{n=0}^{N-1} (X[n]-S_{\theta}[n])$

The value of θ that minimizes J(θ) is the LSE

Apply LSE to our problem

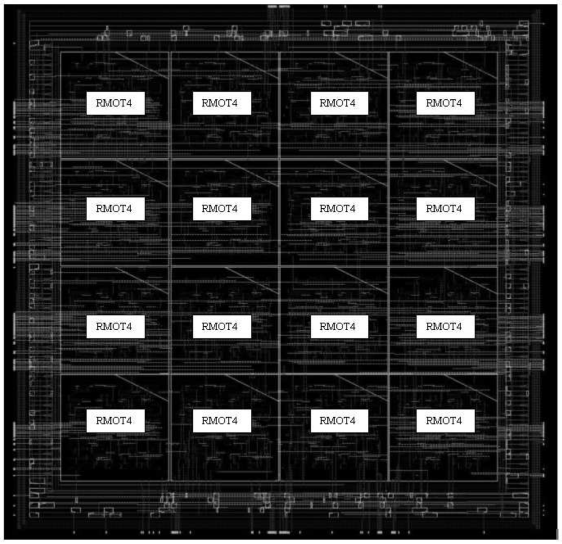
S_0={0,0,0,0 | θ= No Gas}

S_1={3,5,6,3 | θ= Gas Detected}

X={1,3,4,3}

- **$J(0)= \sum_{n=0}^{N-1} (X[n]-S_0[n])= (1-0)^2+(3-0)^2+(4-0)^2+(3-0)^2=35$**
- **$J(1)= \sum_{n=0}^{N-1} (X[n]-S_1[n])= (1-3)^2+(3-5)^2+(4-6)^2+(3-3)^2=12$**
- **J(1) < J(0) → Gas Detected**

Chip Layout - Signal Processing Circuitry



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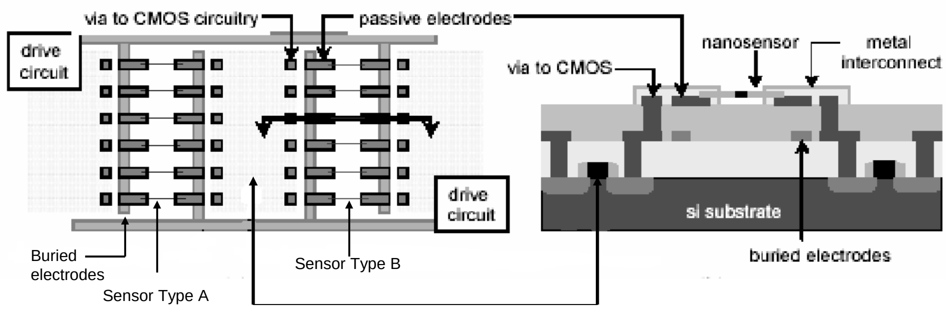
Cross Reactive Sensor Arrays



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System Operation

- System consists of 32x32 pairs of sensors, each sensor connected to an ADC, and a 32x32 cell array
- *Training Phase:* each cell corresponding to a 2-D space location is assigned a gas label by exposing it to known gases
- *Detection Phase:* system is exposed to unknown gases

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Training Phase

- ***feature extraction step:*** **sample points that correspond to responses of "known" gases are labeled and presented to the classifier to form its knowledge base**
- ***cell expansion step:*** **the nearest neighbors of these sample points are identified in successive time periods and source labels are populated in the 2-D space.**

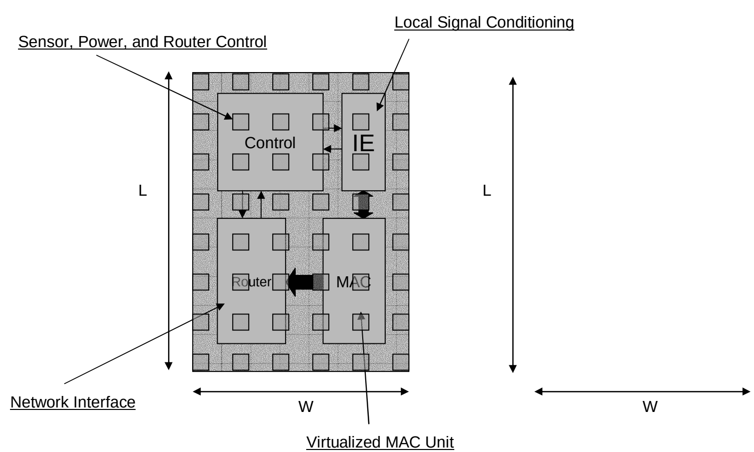
Cell Expansion—boundary formation

						S		
					S	S	S	
		L		S	S	S	S	S
	L	L	X	S	S	S	S	S
L	L	L	L	X	S	S	S	S
L	L	L	L	L	X	S	S	
L	L	L	L	L		S		
	L	L	L					
		L						

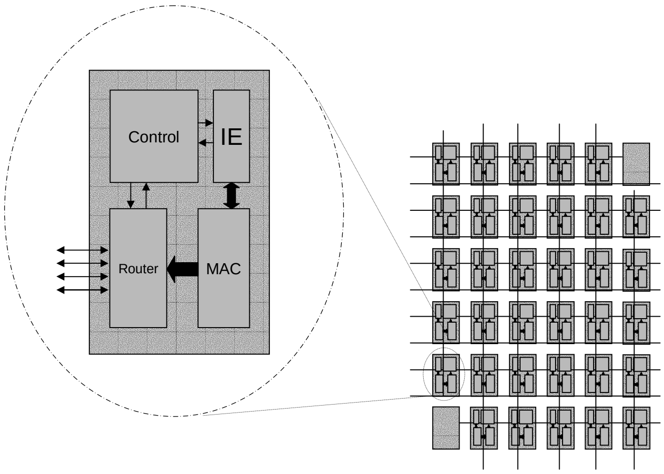
Detection Phase

- ***feature extraction step:*** the feature for the unknown gas is extracted
- ***identification step:*** the gas label of the unknown gas is read from the appropriate cell using the feature coordinates

Evolving towards a Network on Chip Design



Evolving Towards a NoC Implementation



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  - Prof. Irwin for input on signal processing architecture
- Graduate Students: Kevin Irick and Wei Xu

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