Coming Revolution in the Gathering of Information:

Wireless Integrated Microsystems

Kensall D. Wise

Stanford University

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NUMBER OF TRANSISTORS/CHIP, 1970-2010

Heading toward 1 billion transistors in 2007
Typical Sensing-Control Loop

- Interface Circuits
  - Digital-to-Analog Conversion
  - Demultiplex and Drive

- Transducers
  - Sensors
  - Actuators
  - Control Parameters

- MICROSYSTEMS: The Front-End of Distributed Information Gathering Networks

Higher-Level Control

MICROCOMPUTER

Digital Signal Processing
Secondary Parameter Compensation

Analog-to-Digital Conversion
Amplification, Multiplex

TYPICAL SENSING-CONTROL LOOP

Being collapsed toward a single monolithic chip
1966: Micromachining and MEMS is born
Transistors isolated from each other by air and held together by plated gold beams.
Can beam-lead technology be used to create multi-point electrode arrays for studying the central nervous system?
Projects led by Professor James B. Angell

Micromachined Neural Probes, 1966

Single-cell discharge in cat auditory cortex in response to an audible tone burst.
Functional but not manufacturable
Isotropically etched on 50µm-thick wafers
EARLY WORK ON INTEGRATED SENSORS

Micromachined Pressure Sensors

First pressure sensors with a built-in micromachined rim
Catheter-tip Devices for biomedical use
No etch-stop; not producible in volume

1969

Silicon Diaphragm/Beam
Formed from the Wafer Bulk

Silicon

Sensing Elements

On-Chip Circuitry
EARLY WORK ON INTEGRATED SENSORS:
A Single-Wafer Gas Chromatograph, 1970

Good separations but inadequate valve technology
Intended for the Viking Mars Lander

Integrating Microwaves Sampling System

Chromatographic Separation Column

Thermal Conductivity Detector

Signal Processing Electronics

Display

Regulated Temperature and Flow Control

Carrier Gas

Inlet Gas
The Single-Wafer µGC

Heater and MOSFET buffer on a beam-lead chip piggy-backed with a SrBaNO$_3$ pyroelectric crystal.

Eutectic bonded column wafers using 2” wafers and an isotropically etched column.
THE STANFORD "RAT PACK" — 1972
A SOLID STATE OF PROGRESS — 1972-2004

1972 - 1980:
- Bulk micromachining is developed; impurity-based etch-stops and anodic wafer bonding; first high-volume commercial applications.
- Microsystems and microinstruments employing microfluidics, bioMEMS, T-MEMS, optical-MEMS, inertial devices.

1980 - 1990:
- Surface micromachining is born; MicroElectroMechanical Systems (MEMS) become MicroElectromechanical Systems (MEMS); Sensor conferences begin (Transducers, Hilton Head, MEMS); Several startups launched.
- MEMS moves into microsystems; Deep Reactive Ion Etching developed (DRIE); Large-scale funding begins worldwide;

1990 - 2000:
- MEMS moves into microsystems; Deep Reactive Ion Etching developed (DRIE); Large-scale funding begins worldwide;
- Expanding efforts at commercialization; Proliferation of applications in Microsystems, BioMEMS, T-MEMS, optical-MEMS, inertial devices.

2000 - 2004:
- Microsystems and microinstruments employing wafer-level packaging, wireless interfaces, and embedded computing.
Surface Etch (Sacrificial)

- Deposited and Undercut Diaphragm/Beam
- Formed from the Wafer Bulk
- Using a Front Undercut Etch

Bulk Front-Etch

- Formed from the Wafer Bulk
- Sensing Elements

Bulk Back-Etch

- Sensing Elements

On-Chip Circuitry

Capacitive Sense/Drive Elements

MICROMACHINED DEVICE OPTIONS
Leaf-Spring Tether

Produced using Deep Reactive Ion Etching (DRIE)

All-Silicon Ring Gyro

BULK (DRY) MICROMACHINING OF SILICON

Courtesy Lucas NovaSensor

The University of Michigan

Courtesy F. Ayazi and K. Najafi
SURFACE MICROMACHINING

• Undercut polysilicon shuttle mass
• Differential capacitance sensing
• Force-balanced operation
• 1000g survivability
• ±5g operating range

ADXL05 Accelerometer:
- ±5g operating range
- 1000g survivability
- 0.5mg/√Hz noise floor

Photos Courtesy Analog Devices, Inc.
APPLICATION AREAS:

Examples of Emerging Microsystems

Many Additional Consumer Products

• Fully-Integrated, Low-Power MEMS-Based Wireless Transceivers

• Implantable Diagnostic and Prosthetic Devices

• Portable Hand-Held Mass Spectrometry and Gas Chromatography

• DNA Analyses and Sequencers on a Chip

Low-Power, Hand-Held Personal Navigation Systems

• Micromechanical Optical Systems on a Chip

• High-Definition Display Systems Based on Micromirror Arrays

• Accelerometers and Gyros for Inertial Measurements

• Pressure Sensors for Medical Diagnostics and Process Control

• Visible and Infrared Imagers (Camcorders, Digital Cameras)

• Ultra-High-Density Data Storage Systems (Hard Disk Heads)

• Inkjet Print Heads
All of these have become microsystems

- The Gas Chromatograph
- Neural Probes
- Pressure Sensors

Looking at Three Devices

... TRACING SILICON SENSOR TECHNOLOGY:
THE EVOLUTION OF SILICON PRESSURE SENSORS

First-Generation Pressure Sensor

- Simple Thinned Piezoresistive Structure
- Difficult Mounting, High Cost
- Large Package-Induced Stresses
- Poor Diaphragm Thickness Control
- Simple Thin Film Piezoresistive Structure
- High Cost

Define a Figure of Merit:

\[ I = \frac{p}{S} \]

where

- \( p \) is the pressure sensitivity
- \( S \) is the pressure sensitivity
- \( D \) is the device cost
- \( t_D \) is the readout speed
- \( P \) is the power dissipation
- \( T_d \) is the uncompensated temperature drift

Applied Pressure

First-Generation Pressure Sensor

where

\[ \frac{P}{T} \times \frac{d}{d} \times \frac{D}{P} = \frac{I}{S} \]

Applied Pressure

Glide

PRESSURE SENSORS

THE EVOLUTION OF SILICON
IMPURITY-BASED ETCH-STOPS

Batch-Fabricated and High Yield
Built-in Micromachined Rim
Etch-stopped Diaphragm

$Fm = 20^\circ$ F

12.5mW, 10µs; 0.2; 80ppm/°C
80ppm/mmHg: 500mmHg

MICROMACHINED ETCH-STOPS

Etch-Stop
Diaphragm
Sensing Resistors
(Full Bridge)
Rim

Si Diaphragm
$$F_m = \frac{\mu}{5,000}$$

50ppm/°C

1 mW; 5 sec; 0.2

250mmHg:

1000ppm/mmHg:

the same die.

than 10^6:1 is possible on

A dynamic range of more

Requires In-Module Circuity

More Complex Process

Sensitive to Parasitics

Low Temperature Sensitivity

High Pressure Sensitivity

CAPACITIVE PRESSURE SENSORS
DIGITAL COMPENSATION

By allowing fits to nonlinear Pressure and Temperature Responses, Digital Compensation in an Embedded Microcontroller improves Accuracy ~10X.

$F_m = 40,000 \text{ ppm/mmHg}$; $100\mu \text{sec}; 5\text{ppm/°C}$;

1mW; 100ppm/mmHg; 1000mmHg; 10,000ppm/mmHg;

Putting Precision Trims in Software

Present Discrete Trimming Approach
These barometric pressure sensors were the first to achieve a vacuum-sealed reference cavity at wafer-level using polysilicon leads. The devices resolve one part in 32,000.
Typifying many microsystems to come, this barometric pressure sensor combined micromachining with high-performance bus interface circuitry and wafer-level vacuum packaging.
This capacitive barometric pressure sensor realizes a wide range of MEMS devices. Achieving an accuracy of 25mTorr in the field and opening a closed-loop vacuum-control system in the reference cavity, water-level packaging to a wide range of MEMS devices.
Two pressure sensors combined with an integrated antenna and circuitry allow the realization of a wireless active stent for reading out intra-arterial pressure on demand.
The original Stanford design, improved using a bulk boron etch-stop, has been supplied in volume to the neuroscience community, forming the first practical high-density interface to the cellular world.
THE "MICHIGAN PROBES"

• Over 6000 devices distributed to over 180 external investigators.
• Over 120 different designs.
• Over 200 publications and presentations in the neuroscience literature
Changing Research Directions in Neuroscience
The probes perform well for more than one year in-vivo.

- Various methods are being examined to further extend in-vivo recording life.
- Protein encapsulation of small sites can lead to loss of recorded signals.
- The probes perform well for more than one year in-vivo.

Neurons
Probe Shanks
Capillary

LONG-TERM RECORDING LIFE
neural processes
site encapsulation or attract
filled with gels seeded to prevent
"wells" behind the sites can be
Sites are double-sided
with integrated silicon cable
Four-shank 16-site chronic probe

POLYMER INCORPORATION AT THE SITES...
ACTIVE CMOS RECORDING AND STIMULATING PROBES

- 3-µm p-well CMOS
- 16 masks overall
64-SITE PROBES FOR THE CNS

- Fully self-testing
- Circuitry and achieve low profile
- Gold cables allow folded amplifiers
- Per-channel on-chip recording
- ±1µA
- ±128µA stimulation range: ±128µA
- Acute and chronic, 2D and 3D
Mapping activity in the hippocampus — and understanding the mechanisms of short and long-term memory formation (with Gyorgy Buzsáki, Center for Molecular and Behavioral Neuroscience, Rutgers University).
With 1024 sites on 400µm centers, this micro-assembled probe array is a partial prototype of the front-end required for a neural prosthesis. Still needed: a complete microfluidic drug delivery system, in-module signal processing, and a wireless link.
Moving toward probes having full duality of function between electrical and chemical modes.

**INTEGRATED DRUG-DELIVERY PROBES**
A BUTTON-SIZE WIRELESS HIGH-DENSITY NEUROELECTRONIC MICROSYSTEM

Applications:
- Parkinson's Disease
- Severe Epilepsy
- Paralysis
- Blindness
- Deafness

Required:
- A High-Yield Probe Technology
- Practical 3D Technology
- Integrated Circuits allowing Access to many Sites
- Platform Electronics
- Microlithics
- Hermetic Packaging
- Wireless Interface
- Biocompatible Coatings

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- Deafness
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- Paralysis
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Wireless Communications

Micropower Microelectronics

Integrated Sensors and Microactuators (MEMS)

….. Bringing Together …..

Fabriicated monolithically. Integrated communications on a common substrate, sometimes micropower signal processing electronics and wireless microsystems merged with integrated sensors and microactuators

WIRELESS INTEGRATED MICROSYSTEMS (WIMS)
Key Components:

- Power Source
- Micropower Microcontroller with Power Management and Data Compensation
- Software
- Integrated Programmable Transducers
- Wireless I/O
- Hermetic Packaging

WIMS Architecture:

- Intramodule Sensor Bus
- Analog Mux/Amp/ADC
- Power Management
- EPROM
- RAM
- Instruction Set
- Actuators
- Sensors
- Microcontroller
- Bus Interface
- Data Compensation
- Wireless Interface
THE WIMS VISION

- Micropower Operation (0.1-1 mW) → Low Cost and Permeative
- Customized in Software and by Transducer Selection
- Rapidly Configurable and Reconfigurable
- Reelable Hermetic Water-Level Packaging
- Standardized Internal/External Protocols
- Bi-Directional Wireless Interface (0.1-1 km)
- Self-Testing, Programmable, and Digitally-Compensated
- High-Accuracy (to 16b) Multi-Parameter Sensing/Actuation
- Small Size (1-5cc) and Modular
- Micropower Operation (0.1-1 mW) → Long Operating Life

Featuring:
- Communicating into larger networks and
- Small modular information-gathering and control nodes

Common Generic Platform

Low Cost and Permeative

Customized in Software and by Transducer Selection

Rapidly Configurable and Reconfigurable

Reelable Hermetic Water-Level Packaging

Standardized Internal/External Protocols

Bi-Directional Wireless Interface (0.1-1 km)

Self-Testing, Programmable, and Digitally-Compensated

High-Accuracy (to 16b) Multi-Parameter Sensing/Actuation

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Micropower Operation (0.1-1 mW) → Long Operating Life

FEATURES:
- Communicating into larger networks and
- Small modular information-gathering and control nodes

THE WIMS VISION
A MICROPOWER ENVIRONMENTAL MONITOR

- Addresses General Remote Data Gathering, including Applications in Monitoring Environmental Gas Purity
- Direct Application to Homeland Security
- Blueprint for a Generic Microsystem

Pushes Power, Technology, Sensing, Packaging, Self-Test
Beam and disk resonators can achieve frequencies above 1 GHz and Qs of 10,000 or higher. They could result in a paradigm shift for communications transceivers.
Versatile Microanalytical System for Trace Analysis of Complex Mixtures of Atmospheric Pollutants

- High Resolution Pollutant Mapping
- Auto/Stack Emissions
- Ozone Depletion & Global Climate
- Indoor Air Quality
- Workplace Health and Safety
- Emergency Response
- Homeland Security
- Risk/Exposure assessment
- Personal alarms
- Smart homes
- Green manufacturing
- Smart highways
- Flux
- Fate/transport Mapping
- Soil, water, air

THE WIMS MICRO GAS CHROMATOGRAPH (µGC)

Screening/surveillance

ECOLOGICAL SURVEILLANCE

FATE/TRANSPORT

FATE/TRANSPORT

FATE/TRANSPORT
Unprecedented size, power, versatility
Analysis time of 5 minutes (general) to >1 minute (targeted)
Detection limits of <10 ppb per analyte
30-50 Organic-Vapor Pollutants per Analysis

Sensor Array
Vacuum Pump
Preconcentrator/Filter
Internal Standard
Inlet Filter

IGC SYSTEM LAYOUT
THE WIMS MICRO GAS CHROMATOGRAPH

- Filtered inlet
- Multi-stage preconcentrator
- Multi-sensor array
- Distributed vacuum pump
- Stacked polar/nonpolar columns
- Calibraton source
THERMALLY-ISOLATED STACKED \( \mu \)COLUMNS

- Vacuum cavity
- Sealing rim
- \( \sigma \) suspended heated column
- Stationary phase
- Oxide
- Spiral (~1 m)
- P+ tubes
- Vacuum cavity
- Sealing cap
- Suspended heated column
Dry etching of column, followed by boron doping of the walls, and subsequent etching away of the substrate to a supporting glass substrate, and subsequent etching away of the substrate to realize single-crystal silicon channel walls of low thermal mass supported on glass.

µGC COLUMN FABRICATION
3m NON-POLAR COLUMN PERFORMANCE

Rapid injection: 15-vapor mixture
Photoionization detector (100 µL)
Make-up gas
Pump
6 psi

Polymer-embedded non-polar stationary phase:
Polydimethylsiloxane
(Restek, Inc.)

Temperature program:
25 - 100 °C, 1 °C/sec

Wall-bonded non-polar

6,000 theoretical plates (~35% of ideal)

5.5
1.5
1

100 120 140 160
Time (sec)
GAS SENSORS USING MONOLAYER ENCAPSULATED METAL (MnM) NANOCLUSTERS

Vapor Recognition

Resistance Increase/Decrease

Film Swelling/Shrinking

Desorption/Sorption

Vapor
### Limits of Detection (ppb)

**Chemiresistors vs. SAW Detectors**

<table>
<thead>
<tr>
<th>No.</th>
<th>Vapor</th>
<th>Chemiresistor</th>
<th>SAW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>m-Xylene</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>Chloroform</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>Benzene</td>
<td>1.9</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>Ethanol</td>
<td>4.9</td>
<td>0.6</td>
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<tr>
<td>5</td>
<td>Propanone</td>
<td>3.4</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>Butane</td>
<td>2.8</td>
<td>0.3</td>
</tr>
<tr>
<td>7</td>
<td>Isobutane</td>
<td>2.7</td>
<td>1.1</td>
</tr>
<tr>
<td>8</td>
<td>Chloroform</td>
<td>3.5</td>
<td>1.2</td>
</tr>
<tr>
<td>9</td>
<td>1,4-Dioxane</td>
<td>3.5</td>
<td>0.6</td>
</tr>
<tr>
<td>10</td>
<td>Chloroform</td>
<td>6.8</td>
<td>15</td>
</tr>
</tbody>
</table>

**Chemiresistors vs. SAW Detectors**

- Up to 10x lower LODs than "best” SAW sensor
INTEGRATED GAS ANALYSIS

Analysis of 11-component gaseous mixtures in 90 seconds, with a calibration source, preconcentrator, 3m separation column, and chemiresistor detection array having detection limits as low as 100ppt, all integrated in less than 0.9cc.

Chemiresistor Array Outputs

INTEGRATED GAS ANALYSIS
CONCLUSIONS

Over the past thirty years, sensors have evolved to micro-systems, merging sensors, embedded computing, and wireless interfaces. Microsystems will become pervasive in nearly all aspects of society, as problems from global warming and homeland security to health care.

...we seek to interface electronics to the non-electronic world, tackling a rich array of tools, supplementing integrated-circuit technology with bulk and surface micromachining, and wireless packaging. But just as there is no one sensing structure, there is no common sensor process. This is not CMOS.

Microsystems are best suited to high-volume batch processing. Achieving high volume in emerging markets can be difficult but may come through a common microsystem platform that is adaptable to many different applications.

The technology of integrated sensors is not CMOS.