A Multi-Element Smart Gas Sensor
with IEEE 1451 Protocol

Darold Wobschall

State University of New York at Buffalo
Dept. of Electrical Engineering
and
Eensors, Inc.

May version
Presentation Topics

- Goals and Applications
- Review of gas sensor technologies
- Analog signal conditioners – various technologies
- Smart (digital) sensor configurations
- IEEE 1451 protocol
- Multi-element gas sensor module design
- Networking considerations
- Test data
Goals and Applications

- Measurement of gases for environmental monitoring, industrial safety and homeland security
- Design a sensor pad which allows interchange of sensors for various gases
- Convert gas sensor data to digital form (smart sensor)
- Interface to various networks
- Configure automatically (plug and play)
- Use commercial, off-the-shelf sensor elements
Gas Sensor Technologies

- Semiconductor – resistive*
- Semiconductor – voltage*
- Amperometric*
- Catalytic*
- Infrared
- Photo-ionization
- Fluorescent
- Surface acoustic wave (SAW) & vibrating beam
- Capacitive* and other

* Used in this multi-sensor
Solid State (Semiconductor, Resistive) Characteristics

- Based on Tin Oxide (SnO$_2$) or similar metal oxide semiconductors
- Surface reaction with ambient gases when hot (350-500 °C)
- Heater (e.g. 4 v @ 100 mA) heats substrate
- Adsorbed gas reduces grain-boundary potential barrier and thus increases conductivity (decreases resistance)
- Delta-R is a function (approx. log or square root) of gas concentration (ppm)
- Resistance also decreases with temperature so temperature control needed for zero stability
Solid state sensor construction

CityTech Ltd – Semiconductor Sensor
Solid State – Resistive Responses

![Diagram of sensor setup](image)

**Graph 1:**
- Log(Rs in kohms) vs. Log(conc in ppm)
- Line shows decrease in resistance with increased concentration.

**Graph 2:**
- Resistance (kohms) vs. Conc (ppm)
- Line shows decrease in resistance with increased concentration.
Solid Electrolyte Gas Sensor

- Similar to semiconductor gas sensor but has voltage output
- Heater (5v @ 11.5 ohms)
- Has thermistor for temperature control
- $V_{sen}$ increases 50 mv per factor of 10 change in gas conc (220 to 490 mv at 350 ppm)
- Requires hi-Z amplifier
- Examples: Figaro TGS4160 (CO$_2$) or Oxygen (zerconia)
- Periodic re-zeroing desirable
Amperometric Characteristics

- Chemical reaction involving gas releases electrons at electrode (electrolysis reaction)
- Example: $\frac{1}{2} \text{O}_2 + \text{H}_2\text{O} + 2e^- \rightarrow 2 \text{OH}^-$
- Gas is dissolved in electrolyte (e.g. H$_2$O)
- Reaction is reversible so number of electrons released is proportional to gas concentration (gas conc in electrolyte is proportional to partial pressure of gas in air)
- Reaction occurs at specific applied voltage (e.g. 0.55 volts)
- Sensor current output is proportional to gas conc (ppm)
Amperometric Construction

City Tech Ltd – Toxic Gas Sensors
Infra-red Principle

- Some gases absorb light at particular IR wavelengths
- \( I/I_0 = e^{-Ax} \)
  
  where \( I/I_0 \) is light absorbed during transmission,
  
  \( x \) is path length and \( A \) is absorption coef. at specific wavelength
- Transmission filters select specific wavelength bands
- \( A \) is proportional to gas concentration
- IR sensors reproducible but not sensitive (need high conc or long paths)
Infra-red Construction

**Gilway** Visible/IR Lamps for NDIR Gas Sensors

Acoustical detection an attractive option
Photo-ionization

- High energy UV photons (> 3ev or <300 um) will ionize some gases (e.g. toluene, trichloroethylene) but not others (e.g. air, methane)
- Ions collected by e-field produce a current proportional to gas conc
- Sensitive (< 1 ppm) but not selective
- Special UV lamps costly and have limited life (also high power)
Fluorescent

- UV light impinges on some organics produces a fluorescent light proportional to ambient gas concentration (e.g. oxygen)
- High sensitivity (because photo-detectors are sensitive)
- Applicable only to a few gases (but used with many biological materials where it can be sensitive and selective)
- Few commercial sensors using this technology are available.
SAW and vibrating beam

- Surface acoustic wave (SAW) travel from transmitter to receiver on substrate surface.
- Velocity depends on surface mass which is affected by adsorbed gases.
- Positive feedback produces oscillation at frequency which depends on sound velocity and thus gas concentration.
SAW and vibrating beam continued

- Usually used in pairs (one not exposed to gas) and difference (beat frequency) measured
- Moderate sensitivity and selectivity
- Vibrating beam type (usually quartz) resonance frequency varies with mass loading and thus gas concentration.
- Can be small and low cost
- Few commercial products available.
Capacitive

- Dielectric constant of polymer increase with absorbed gas such as water vapor (K is 80 for water, 2-3 for polymer)
- Typically C increase by 10-30% as relative humidity (RH) varies from 0 to 100%.
Other Gas Sensor Technologies

These techniques have few commercial product available

- Polymer resistance
- Fiber optic
- ChemFET
- Miniaturized versions of mass spectrometers
MEMS Sensors

- Micro Electronic Mechanical Systems (MEMS) type sensors are miniaturized versions of types already described
- Promise much smaller size, lower power and lower cost than conventional gas sensors
- Many under development but few commercially available.
Linearization by shunt resistors

Rs has log response vs T (thermistor)

[Diagram of a circuit with Rs and Rm connected in series, Rs' connected in parallel with the thermistor]

[Graph showing resistance ratio vs temperature with curves for 'No shunt' and 'With shunt']
Linearization by load resistors

![Diagram of sensor circuit with load resistors](image)

**Semiconductor sensor response**

- Resistance (kohm) vs. Conc (ppm)

**Sensor Response with Load Resistor**

- Vout vs. Conc (ppm)
Signal Conditioner for Voltage Type Sensors
Signal Conditioner for Amperometric Type Sensors
Generic Smart Sensor Block Diagram

- SENSOR ELEMENT
- ANALOG SIGNAL CONDITIONER
- A/D
- MICRO-CONTROLLER
- DATA LOGGER (optional)
- CALIBRATION / ID MEMORY
- BUS/NETWORK INTERFACE
- COMPUTER (READOUT, DATA STORE)
- BUS/NETWORK INTERFACE

Sensors Expo -- June 2004
Need for Network Standards

- Smart sensors require a digital network
- Over 50 sensor networks and busses in common use
- Users and manufactures would like one standard to reduce manufacturing/installation costs and for plug&play capability
- No single local network is likely to dominate in near future due to divergent needs
- The Internet via Ethernet will likely be one of the dominate networks (but cost and complexity are problems)
- The IEEE 1451 standard for sensor interfacing overcomes many of the complications of multiple networks
IEEE 1451 Parts

- IEEE 1451.0 Protocols/formats (approval process underway)
- IEEE 1451.1 Object model (approved 1999)
- IEEE 1451.2 Interface (approved 1997)*
- IEEE 1451.3 Local network (approved 2003)
- IEEE 1451.4 Analog & TEDS (just approved)
- IEEE 1451.5 Wireless (early approval process)
- IEEE 1451.6 Canbus (just started)

* Enhancement /revision working group in process
Present (1997) IEEE 1451.2 System Block Diagram
IEEE p1451.2 TEDS Blocks
-- Transducer Electronic Data Sheet --

**Machine Readable**
- Meta-TEDS (mandatory)
- Channel TEDS (mandatory)
- Calibration
- Physical Layer Meta (proposed)
- Physical Layer Channel (proposed)
  Note: One TEDS per channel for Channel and Calibration

**Human Readable**
- Meta-ID TEDS
- Channel-ID TEDS
- Calibration-ID TEDS
- Application Specific
  End Users’ Application-Specific TEDS
- Future Extensions
  Industry Extension TEDS

*New Tuples format TEDS approved by Dot 2 working group*

Dot2
Advantages of the IEEE 1451 Standard

- Continuing network interface and microcontroller cost reductions have made interface more attractive.
- The sensor industry is closer to recognizing the necessity for a sensor network standard.
- The general concept of the IEEE 1451 approach, especially TEDS, is supported by many.
- Working groups are addressing the dot2 problems and expanding the standard via dot3, dot4, and dot5.
TEDS Memory Types

- Option #1 – Standard dot2 TEDS
  * Meta-TEDS (binary/machine readable)
    [Meta is all channel]
  * Meta-ID-TEDS (ASCII)
  * Channel-TEDS (binary)

Option #2 – Modified dot4
* Basic TEDS (8 bytes, binary)
* ID TEDS (user provided 24 bytes ASCII)
* Standard templates available but special used here
IEEE 1451.4 (Dot4) Interface
Basic TEDS

- Basic TEDS (8 bytes)
  - Manufacturer ID (14 bits)
  - Model Number (15 bits)
  - Version Letter (5 bits, A-Z)
  - Version Number (6 bits)
  - Serial Number (24 bits)

Dot4
Dot 2 to Dot 4 TEDS Conversion

- Dot4 TEDS read over 1-wire (specific sensor head)
- Contains standard TEDS and special (manufacturer specific) TEDS
- Special head configuration data used for signal conditioner setup
- A/D data read in and converted to floating point (Dot2 option)
- Calibration data from Dot4 TEDS used to convert to engineering units
- Data from Dot4 standard TEDS used to prepare tuples style Dot2 (Dot0) TEDS (Meta, Channel, Meta-ID, and Channel ID)
- Parameters (fields) not in Dot4 TEDS inserted into Dot2 TEDS
- UUID or Universal Unique Identification (10 bytes) consists of 6-byte Dot4 TEDS as the least significant + 4 bytes (FFFF0000h), which will not occur using the specified Dot2 formula
Multi-Element Gas Sensor Design Challenges

- Sensor elements for different gasses use different technologies, and thus signal conditioners, making sensor head/element interchange difficult.
- Many reliable off-the-shelf sensor elements require large amounts of power (heaters) thus reducing battery life.
- Multiple communications channels (Wireless, Internet via Ethernet) may be needed.
- Auto configuration (plug and play)
- Should be easy to use
- Moderate cost desirable
System Block Diagram
Sensor Pod Board Organization

SIDE VIEW

TOP VIEW

Sensors Expo -- June 2004
Sensor Pod Block Diagram
* Technologies Accommodated

Semiconductor with Heater (e.g. CO) – 3 Types
Amperometric (e.g. O₂) – 2 Types
Catalytic (e.g. Methane) – 2 Types
Gas Sensor List

**HVAC/Environmental**
- Carbon dioxide
- Humidity /Temperature
- Smoke

**Decontamination/Industrial gases**
- VOC/Methyl bromide
- Ozone
- Hydrogen peroxide
- Oxygen
- Combustible gases
- Carbon monoxide

**Toxic gas sensors**
- Hydrogen sulfide
- Sulfur dioxide
- Chlorine (chlorine dioxide)
- Hydrogen cyanide
- Nitric oxide
- Nitrogen dioxide
- Hydrogen chloride
Sensor Signal Conditioner
- Semiconductor type -
Sensor Signal Conditioner
- Amperometric type -
Sensor Signal Conditioner
- Microcomputer section -
Humidity/Temperature Sensor with digital output
Communication Options

- Internet via Ethernet
  TCP/IP protocol similar to websensor
- RF Point-to-point – initial wireless version
  900 MHz spread spectrum (Chipcom)
- Full-feature wireless network (IEEE 802.15.4/Zigbee)
  Scheduled transmissions for power reduction, node-to-node hopping, collision recovery, error handling
NCAP Block Diagram
Test data

- VOC response to ethanol measured (100 to 3000 ppm)
- Method: small volume solvent injections into closed container
- Solid state VOC sensor resistance change converted to ppm and transmitted digitally
- Date from computer plotted

Printout line here

Not final data
References

- www.eesensors.com/IEEE1451

*Experimental Dot2 TIM and NCAP demo at IEEE 1451 booth*
Summary

- Interchangeable gas sensor elements/heads of varied technology requires adaptable signal conditioners
- A microcomputer-based smart sensor with the required signal conditioners was developed for this purpose.
- Transmission of sensor data over a network was demonstrated
- IEEE p1451 protocol was used for simplified signal readout and plug and play capability.

Further information: designer@eesensors.com