SMART SENSORS

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Expert Lecture delivered at:

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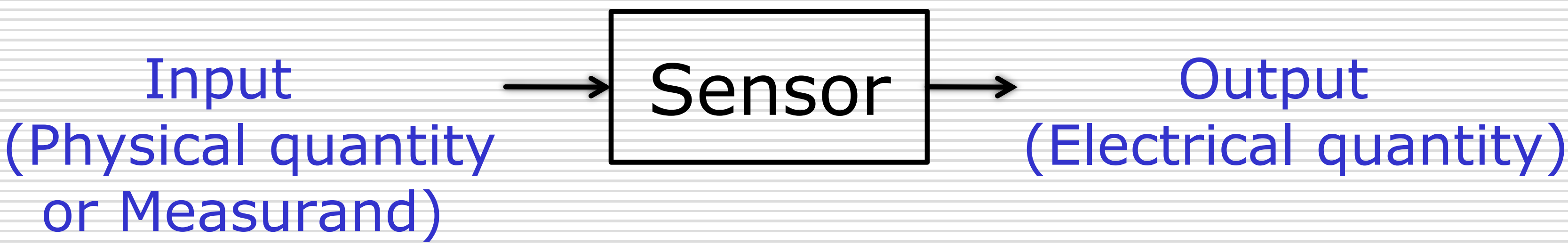
Smart-Sensor Basics

What is a Sensor?

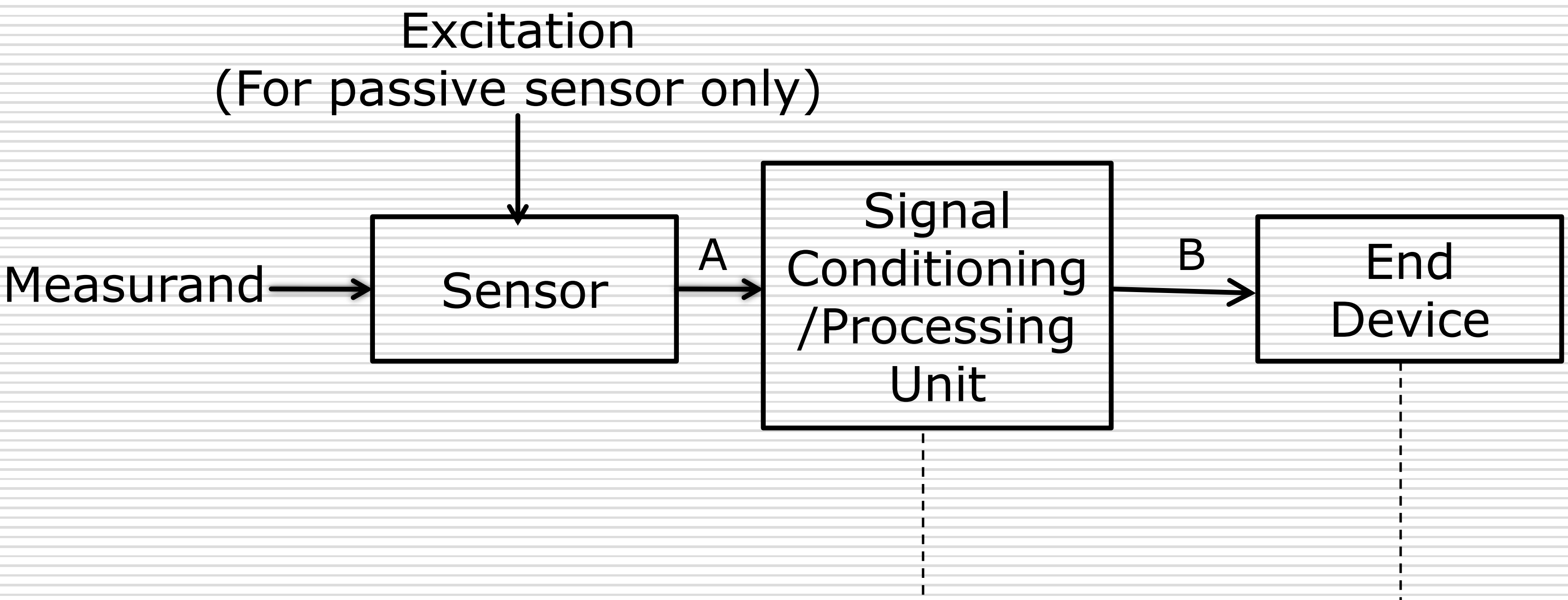
- Device that senses a **physical quantity**
- This physical quantity becomes **input** to the sensor
- **Output** of the sensor is an electrical quantity
- Input is called measured quantity or **“measurand”**



Sensor Output

- The electrical output of a sensor can be one of the two types:
  - ***Variation of an electrical parameter***
  - ***An electrical signal***
- Variation of electrical parameter means
  - Variation of resistance (delta R), or
  - Variation of inductance (delta L), or
  - Variation of capacitance (delta C)
- Electrical signal means
  - Voltage signal, or
  - Current signal

Sensor-Based Measurement System



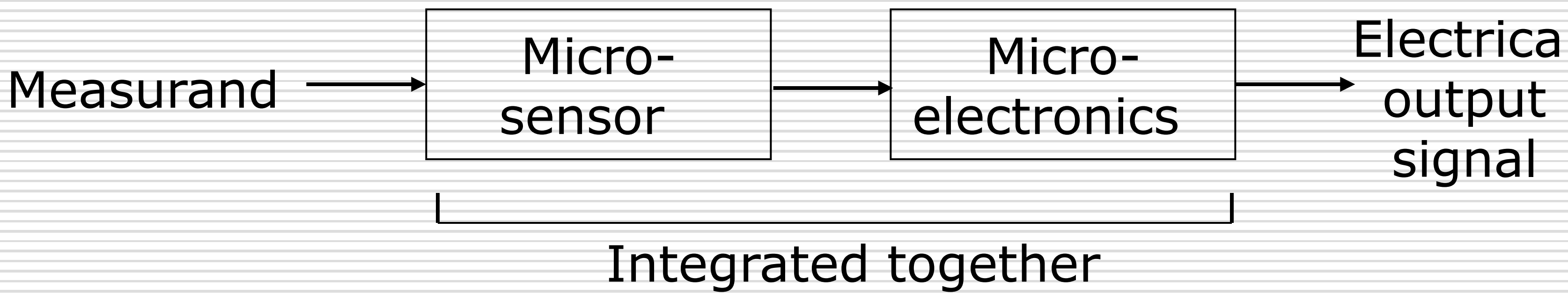
Conditions or processes electrical signal A into signal B to make it compatible with End Device, **both in form and magnitude.**

- Indicating device
- Display device
- Storage device
- Comm. device
- Data processor

What is a Smart Sensor?

- Most of the sensors now *labeled as Smart Sensors* by the manufacturers and *accepted as Smart Sensors* by the users would fit into the following definition:

"Smart Sensor is a micro-sensor suitably integrated with appropriate micro-electronics, such that the final output is fully or easily compatible with the intended end device or devices"

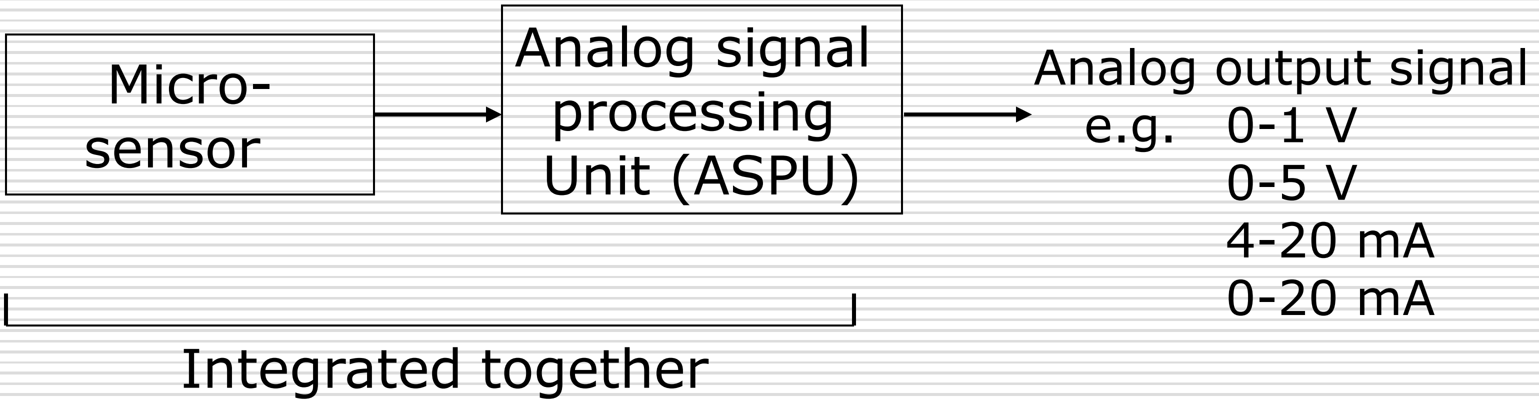


Levels of Integration

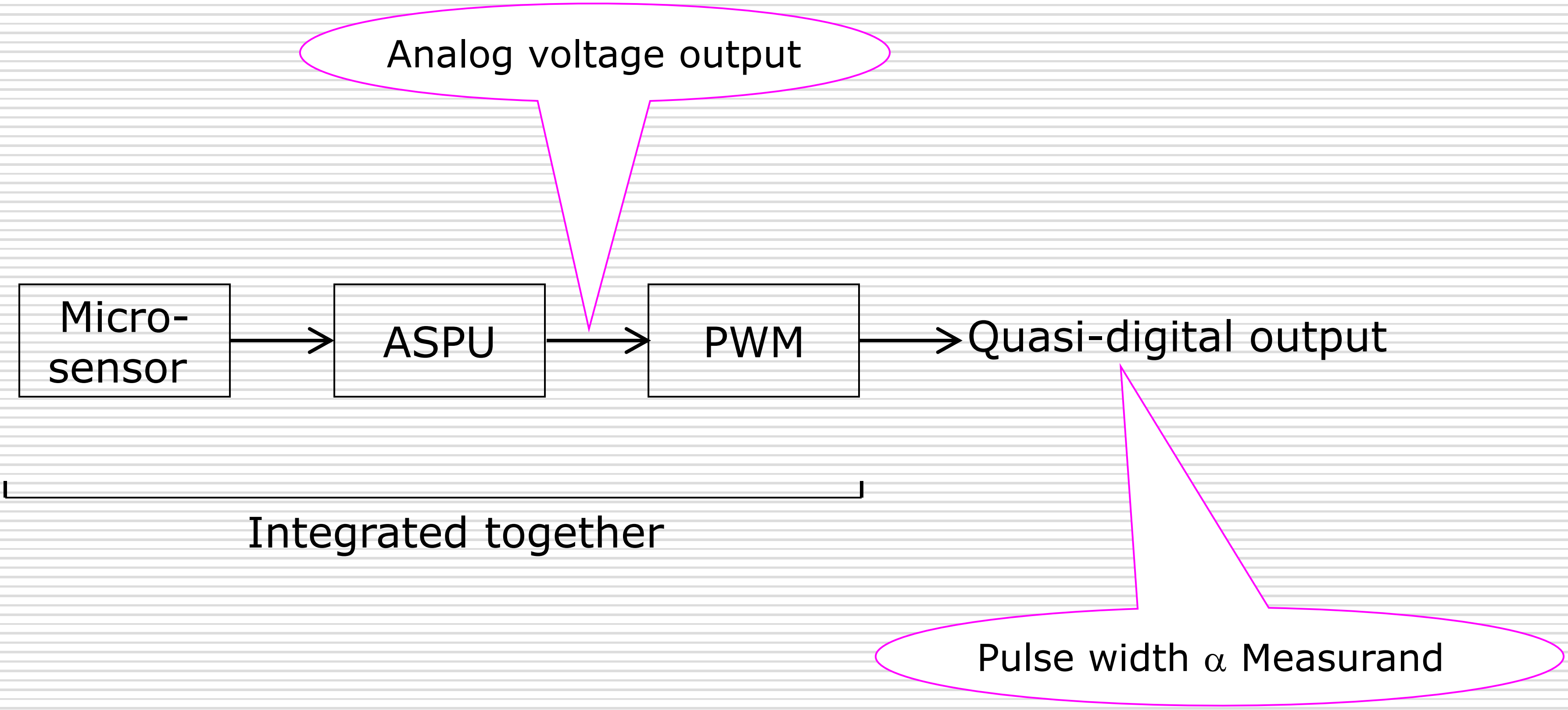
- The output signal of smart sensor can have one of three forms:
  - Analog
  - Digital
  - Quasi-digital (PWM or pulse frequency)

- Extent/ level of integration of electronics with the micro-sensor:
  - Lowest Level: Smart sensor with analog output
  - Low Level: Smart sensor with quasi-digital output
  - High Level: Smart sensor with digital output
  - Higher Level: Smart intelligent sensor
  - Highest Level: Smart network sensor

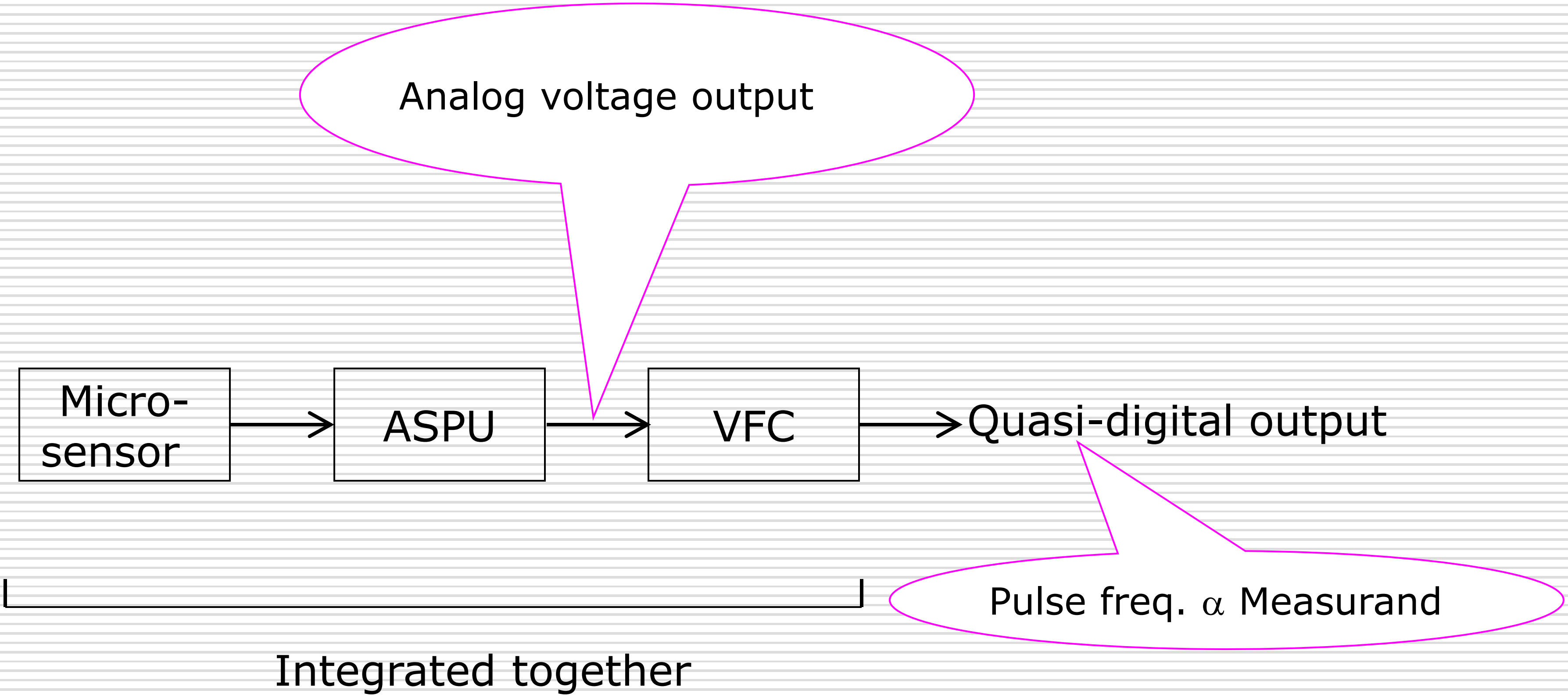
Smart Sensor with Analog Output



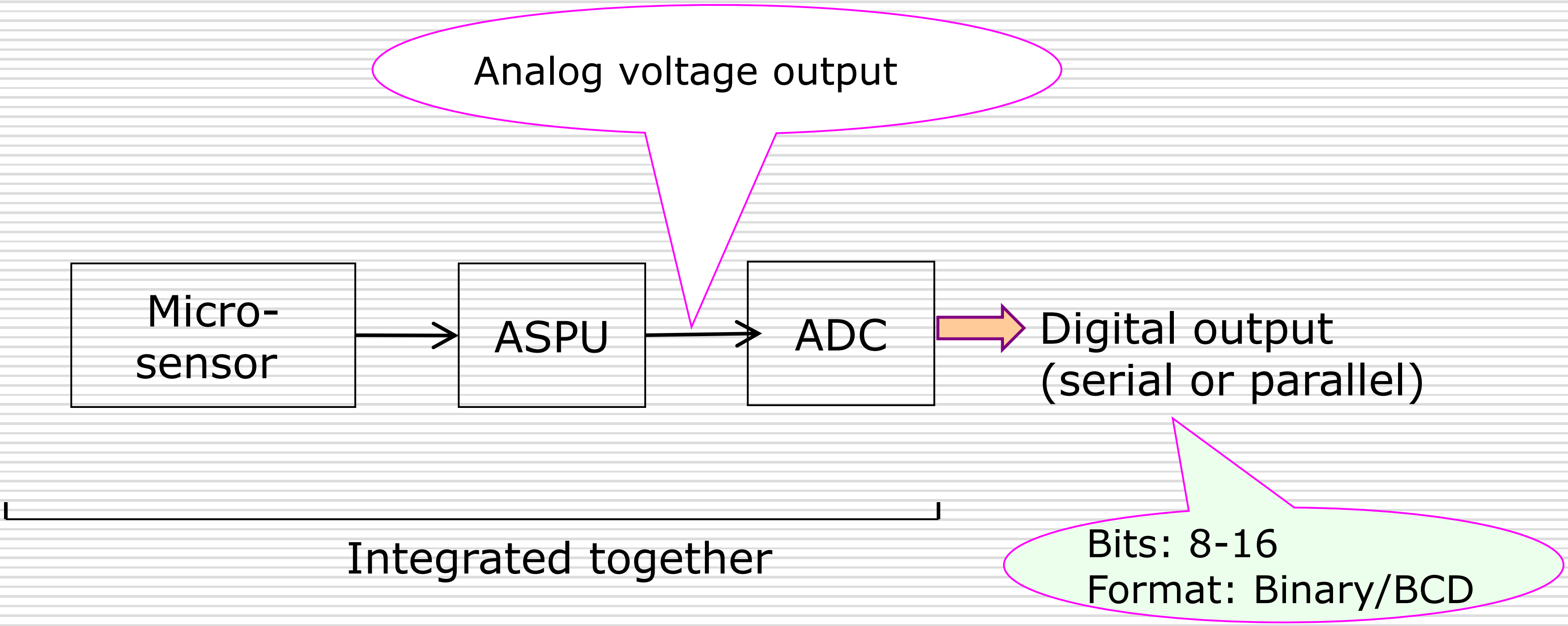
Smart Sensor with PWM Output



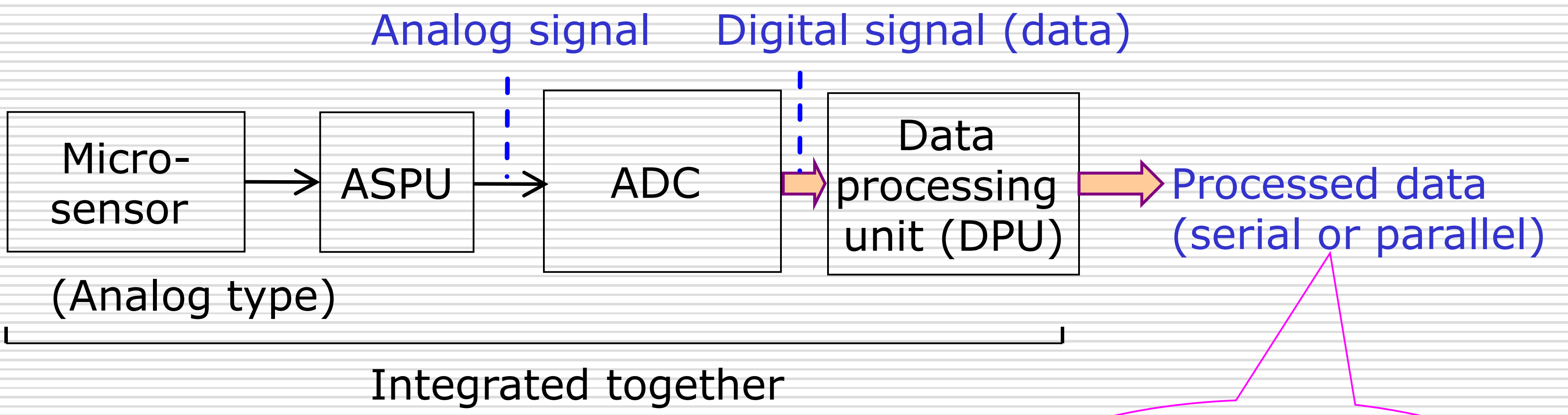
Smart Sensor with Pulse-Frequency Output



Smart Sensor with Digital Output



Smart Intelligent Sensor



Can be readily connected to a host computer or other digital system

DPU = Microcontroller

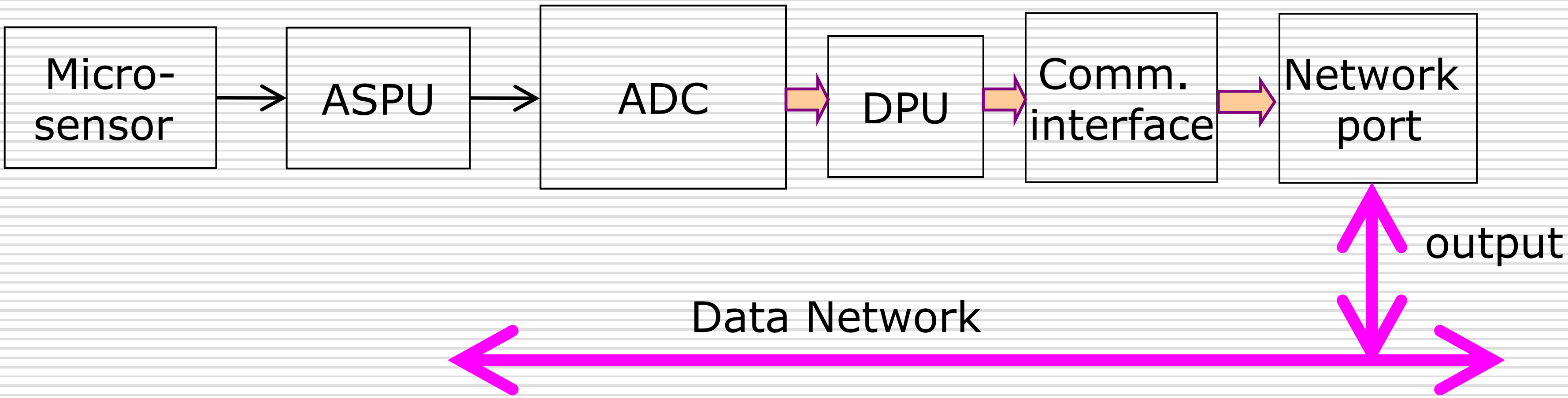
OR

μP + memory + I/O interface

OR

DSP +memory + I/O interface

Smart Network Sensor



Output: *processed data on integrated network port in appropriate format*

Advantages of Smart Sensor (1)

1. User's Convenience because of:
   - No wiring
   - Compact size
   - No headache of selecting SC
   - No headache of designing SC

2. Superior Performance because:
   - Externally-induced noise absent, high SNR
   - Built-in sensor-specific SC circuits perform better
   - Built-in negative feedback reduces nonlinearity
   - Built-in compensating circuits reduce sensitivity to temperature/ excitation changes

Advantages of Smart Sensor (2)

3. High Reliability because of:
   - Reduced component count
   - Reduced wiring

4. Cost Reduction because of:
   - Concurrent production of electronics and sensor
   - Mass production techniques

Additional Advantages of Smart Intelligent Sensor

- Performance Improvement because of:
  - Linearization of response using software
  - Reduction of cross-sensitivity using software
  - Automatic self calibration
- Simpler Interfacing because:
  - Data formatting can be done as per need
- Internal Data Logging because of:
  - On-chip EEPROM or flash-RAM
- Higher flexibility because:
  - Most of functions are software-based.

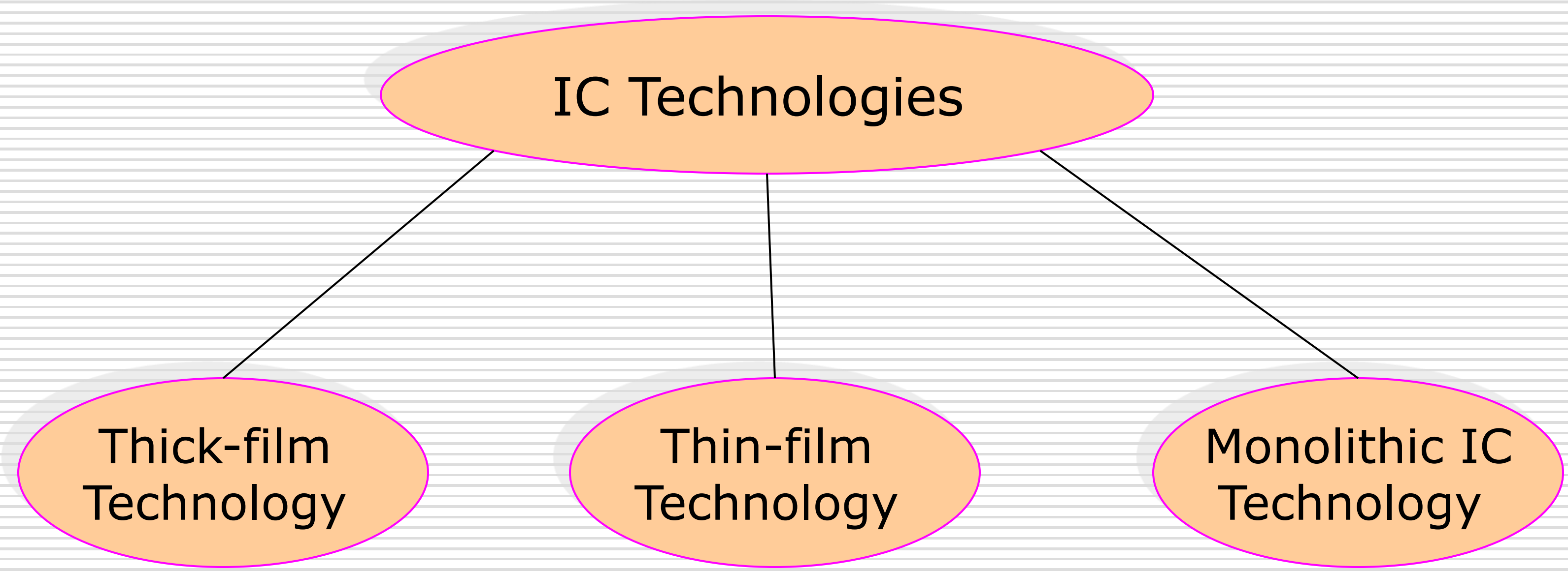
Smart-Sensor Technologies

Smart Sensor Technologies

Two types of technologies used:

- IC Technologies
- Micromachining Technologies

IC Technologies & Capabilities



Thick-film Technology

- R, C & L
- Conductors
- Sensor elements
- Sensor supports

Thin-film Technology

- R & C
- Conductors
- Sensor elements

Monolithic IC Technology

- R & C
- Diodes & transistors
- Conductors
- Sensor elements

Thick-Film Sensor Elements

- Temperature Sensors: Film RTD
  Film thermistor
  Film thermocouple
- Pressure Sensors: Film diaphragms
  Film capacitors
  Piezo-electric pastes
  Piezo-resistive pastes
- Light Sensors: Photo-conductive pastes
- Magnetic Sensors: Magneto-resistive pastes
- Humidity Sensors: Organic polymer based pastes
- Gas Sensors: Metal-oxide pastes

Advantages of Thick Film Technology

- Components can withstand high temperatures
- Large voltage / current excitation can be used
- Heaters can be integrated
- Economical for low-volume production

Thin-Film Deposition Techniques

- Sputtering or cathodic deposition
- Vacuum evaporation
- Spin casting
- Reactive growth
- Chemical vapour deposition
- Plasma deposition

Thin-Film Materials

- For conductors: Aluminium or gold
- For resistors: Nichrome
- For dielectrics: Silicon dioxide
- For sensors (examples)
  - Strain gauge: Nichrome, polycrystalline silicon
  - RTD: Platinum
  - Gas sensor: Zinc oxide
  - Piezo-resistive pressure sensor: Nichrome, polycrystalline silicon
  - Thermo-anemometric flow sensor: Gold

Advantages of Thin-Film Technology

- Almost any metal can be deposited to produce thin-film sensors

- Add resistances, capacitances and sensors to monolithic IC.

- Miniaturization (smaller dimensions than thick-film devices).

- Economical for high-volume production.

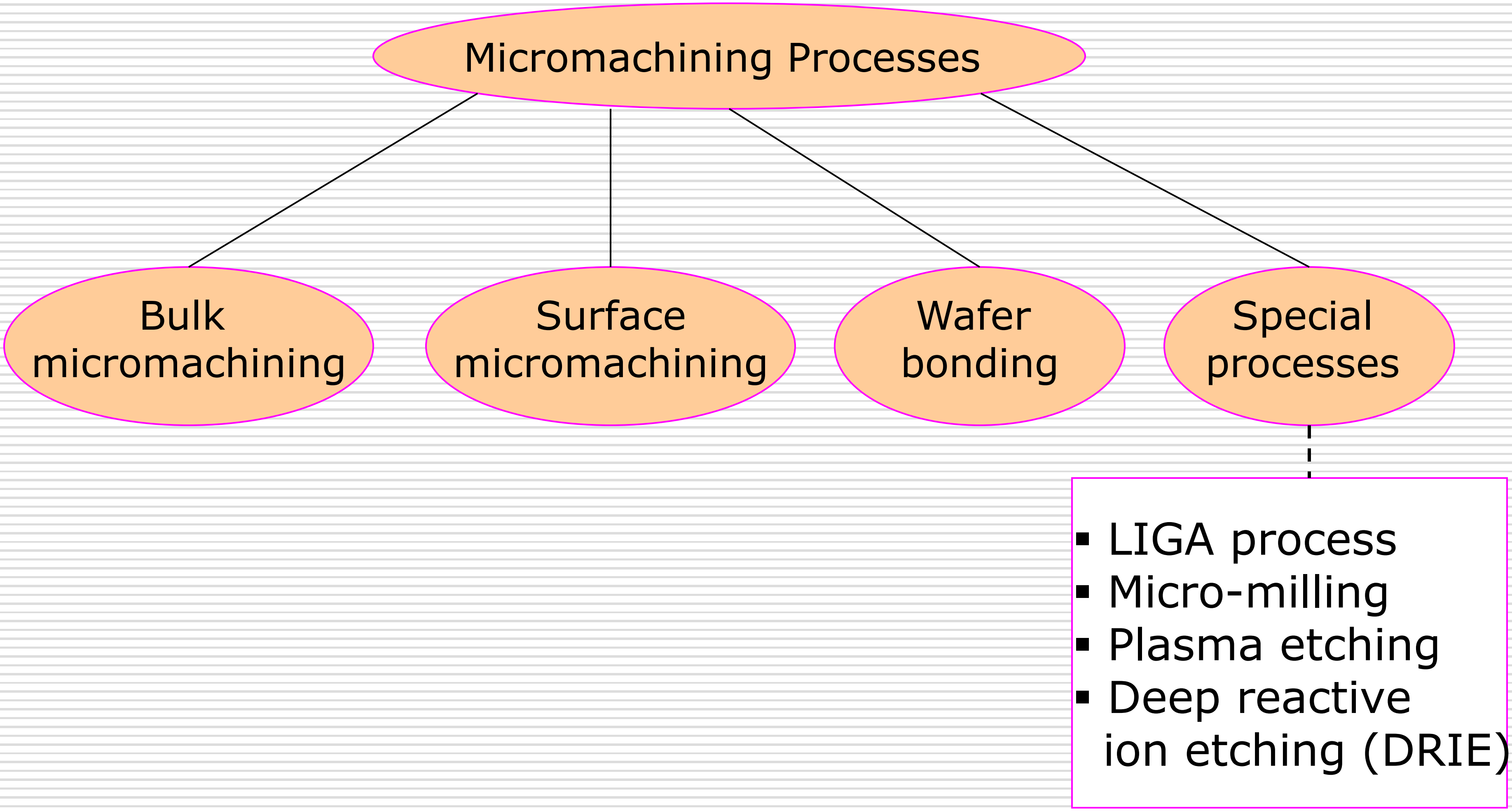
Monolithic IC Technology: Advantages

- Both active and passive devices
- Very high density of devices

Monolithic IC Technology: Limitations

- A few types of sensors only
- Resistances in medium-range only
- Capacitances of small values only

Micromachining Technologies



Bulk Micromachining

- Si wafer is etched on both sides
- Etching done with masks and etchants
- Pattern defined by photo-lithographic technique
- Etching processes:
  - Isotropic etching
  - Anisotropic etching

Isotropic Etching

- Etchants used have same etching rate for all crystallographic orientations of silicon wafer (crystal)

- Common Etchants (examples)
  - Sulfur hexaflouride (SF6)
  - Hydrogen flouride (HF)

- Structures Produced (examples)
  - Semi-spherical cavity
  - Rim-cantilever

Anisotropic Etching

- Etchants used have **different** etching rates for different crystallographic orientations of silicon wafer (crystal)

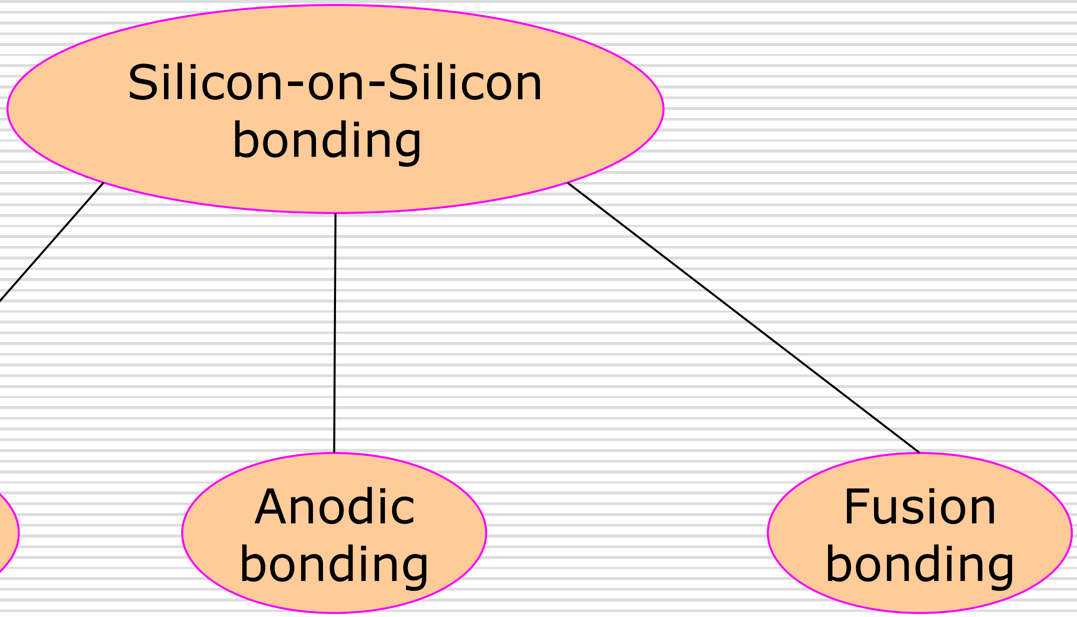
- Common Etchants (examples)
  - Ethylene-diamine pyrocatechol (EDP)
  - Potassium hydroxide (KOH)

- Structures Produced (example)
  - Diaphragm

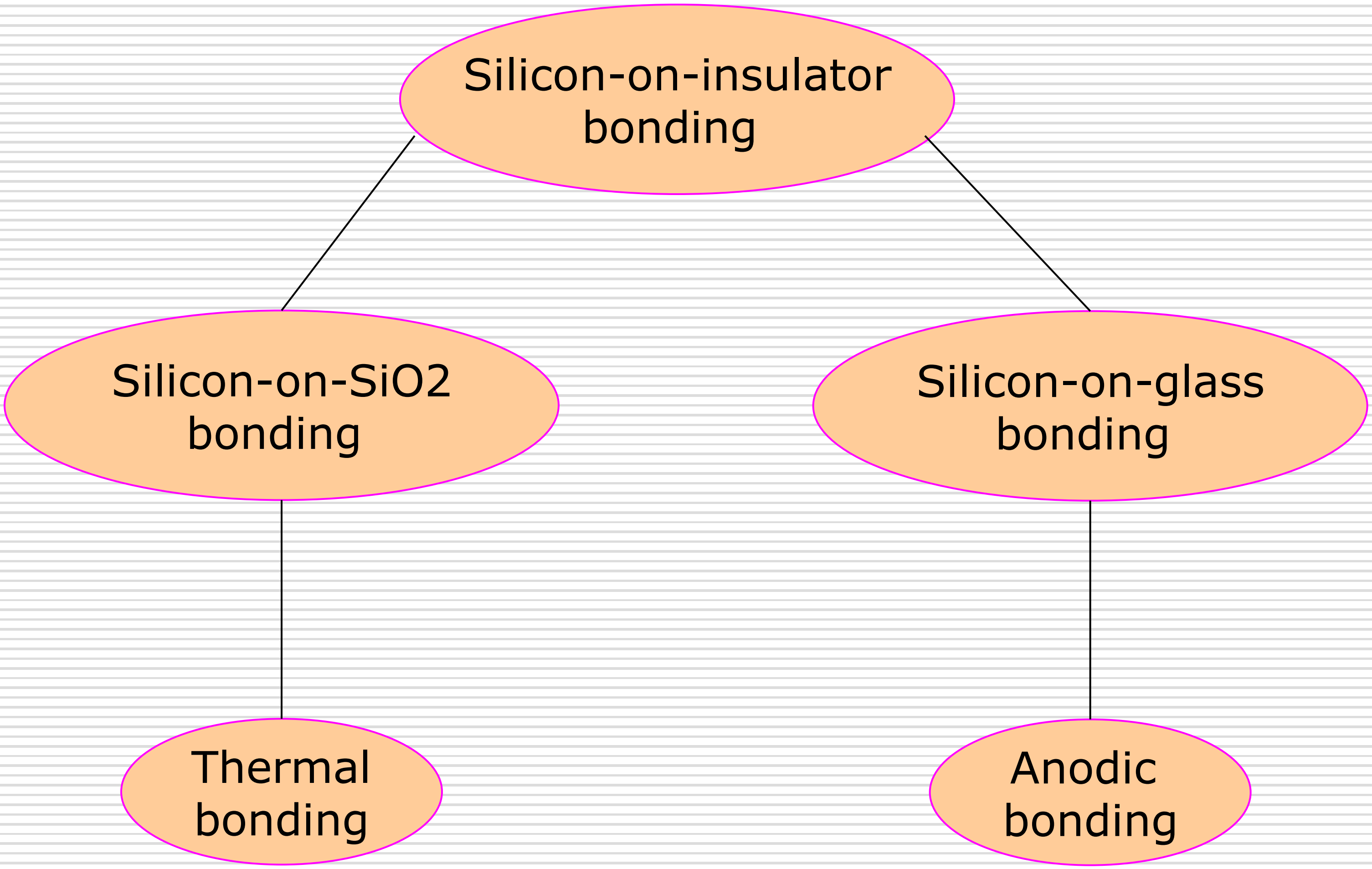
Surface Micromachining

- Etching and deposition processes from one surface
- 3-dimensional structure built by stacking layers
- Sacrificial and structural layers used
- Substrate is usually Si; glass also used
- SiO_2 and SiN for masking

Wafer Bonding (1)



Wafer Bonding (2)



Smart-Sensor Case Studies

Case Study # 1

Smart Three-Terminal Temperature Sensor

or

Three-Terminal IC Temperature Sensor

or

Voltage-Output IC Temperature Sensor

LM35/LM34

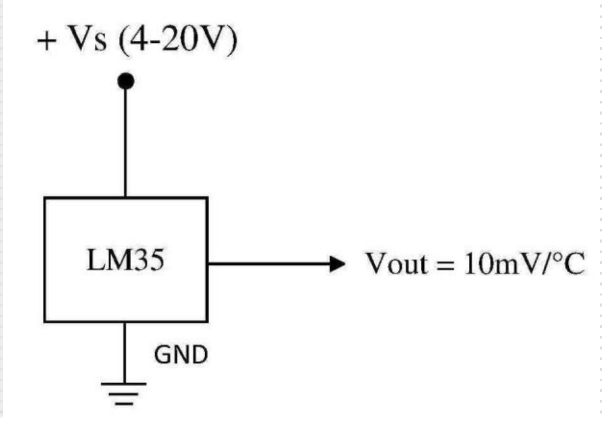
Manufacturer: National Semiconductor Corporation

Website: www.national.com

Major Specifications

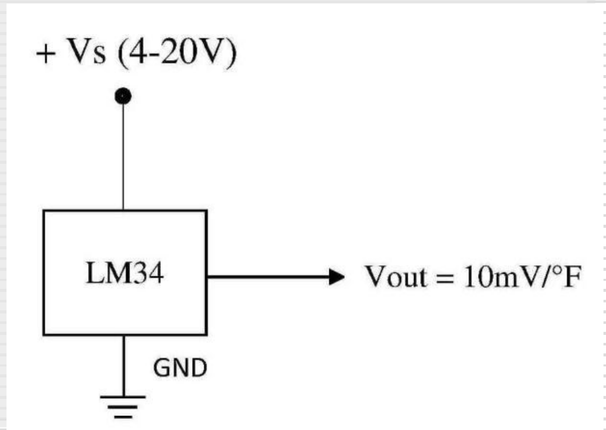
❑ LM35: Centigrade (or Celcius) Temperature Sensor

- Range: -55 to +150 °C
- Output (Sensitivity): 10 mV/°C
- Accuracy: ±0.2 °C (typical)
- Linearity: ±0.2 °C (typical)
- Current Drain: 65 μA (typical)



❑ LM34: Fahrenheit Temperature Sensor

- Range: -50 to + 300 °F
- Output (Sensitivity): 10 mV/°F
- Accuracy: ±0.4 °F (typical)
- Linearity: ±0.3 °F (typical)
- Current Drain: 75 μA (typical)

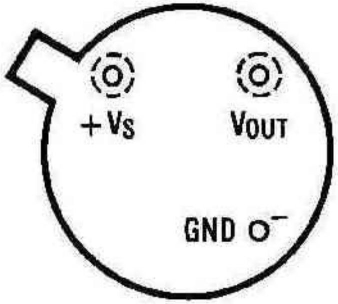


Principle of LM35/LM34

- These sensors are based on temperature sensitivity of band gap voltage of silicon junction.
- Band gap (or energy gap) is the energy range in a solid where no free electron states can exist.
- Band gap in a semiconductor will decrease as its temperature is raised.
- This property (temperature sensitivity) of semiconductors forms the basis of all silicon temperature sensors.

Packages and Pins of LM35

TO-46
Metal Can Package*

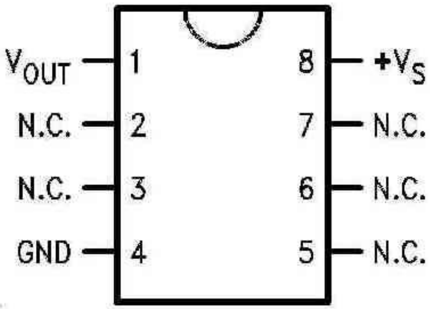


BOTTOM VIEW

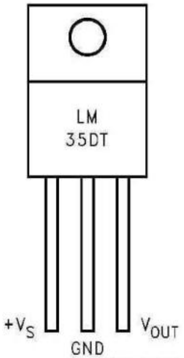
TO-92
Plastic Package

BOTTOM VIEW

SO-8
Small Outline Molded Package



TO-220
Plastic Package*



Case Study # 2

Smart Humidity and Temperature Sensor

SHT7x / SHT1x

Manufacturer: Sensirion Corporation

Website: www.sensirion.com

Salient Features

- Senses relative humidity and temperature
- Single chip sensor-cum-transmitter
- Capacitive polymer sensing element for relative humidity
- Band-gap for temperature sensing
- CMOS & micromachining technologies combined
- Patented as “CMOS Sens” Technology
- Serial digital output
- Self calibration

Devices in SHTxx Series

Pin-Type Package

SHT 71

SHT 75

SMD Package

SHT 10

SHT 11

SHT 15

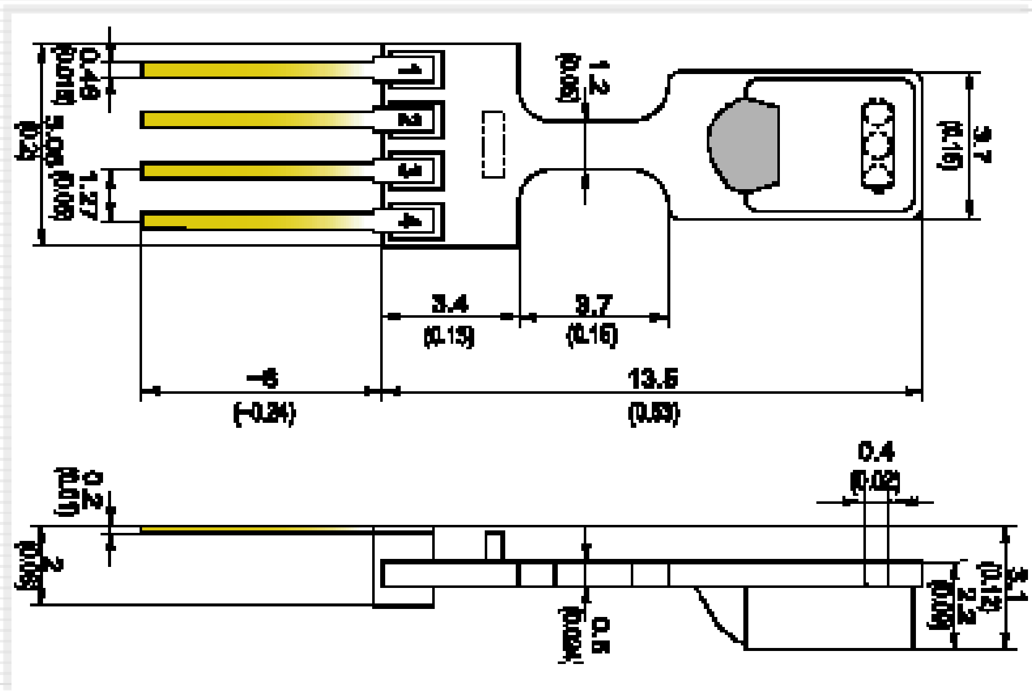
SHTxx ....

Technical Data

Feature	SHT 71	SHT 75	SHT 10	SHT 11	SHT 15
RH Accuracy	± 3%	± 1.8%	± 4.5%	± 3%	± 2%
RH Range	0-100%			0-100%	
RH Stability	<0.5% per year		<0.5% per year		
Temp. Accuracy @ 25^{0}C	0.4^{0}C	± 0.3^{0}C	±0.5^{0}C	±0.4^{0}C	0.3^{0}C
Temp. Range	-40 to + 120^{0}C		-40 to + 120^{0}C		
Power Consumption	**30μW**	**20μW**	**30μW**	**30μW**	**30μW**
Response Time	4s		4s		
Package	4-Pin SIL		SMD (LCC)*		

**Surface mounting device (leadless chip carrier)*

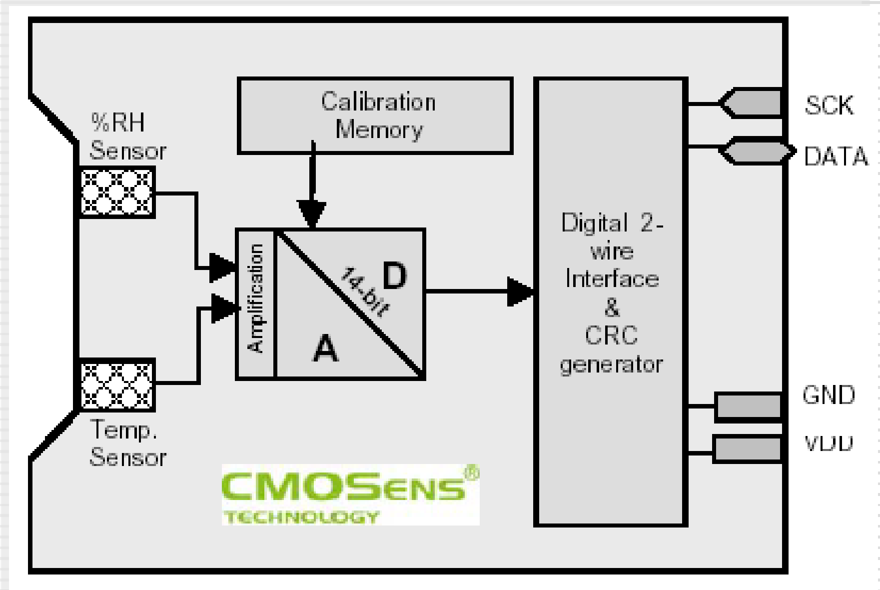
Dimensions of SHT7x



(Source: Data sheet of SHTxx)

Block Diagram

Pin No.	Pin Name	Description
1	SCK	Serial clock input
2	VDD	Supply 2.4 – 5.5 V
3	GND	Ground
4	DATA	Serial data bidirectional



Serial interface of SHTxx is not compatible with I²C interfaces.

Case Study # 3

Smart Acceleration Sensor

or

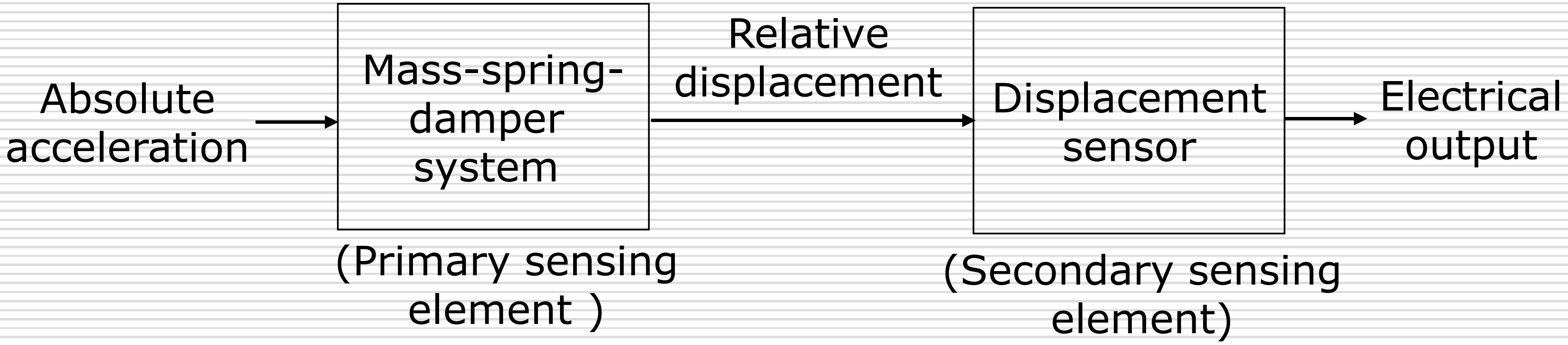
iMEMS Accelerometer

ADXL 150/250/210/311

Manufacturer: Analog Devices

Website: www.analog.com

Basic Principle of Acceleration Sensors



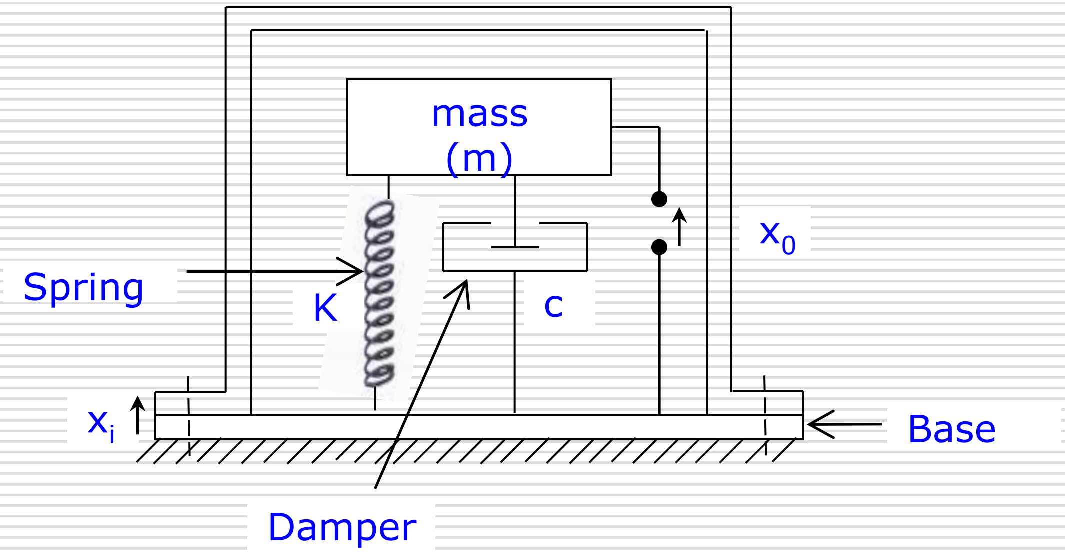
Displacement Sensor Options

(a) Strain gauge: Output is change in resistance

(b) Capacitive displacement sensor: Output is change in capacitance

(c) Piezoelectric transducer: Output is electric charge

Mass-Spring-Damper (MSD) System



m = mass in kg

c = damping constant in Ns/m

k = spring stiffness in N/m

Frequency Response of MSD System

$$G(j\omega) = \frac{1/\omega_n^2}{1 + \left(j\omega/\omega_n \right)^2 + 2j\,\xi\,(\omega/\omega_n)}$$

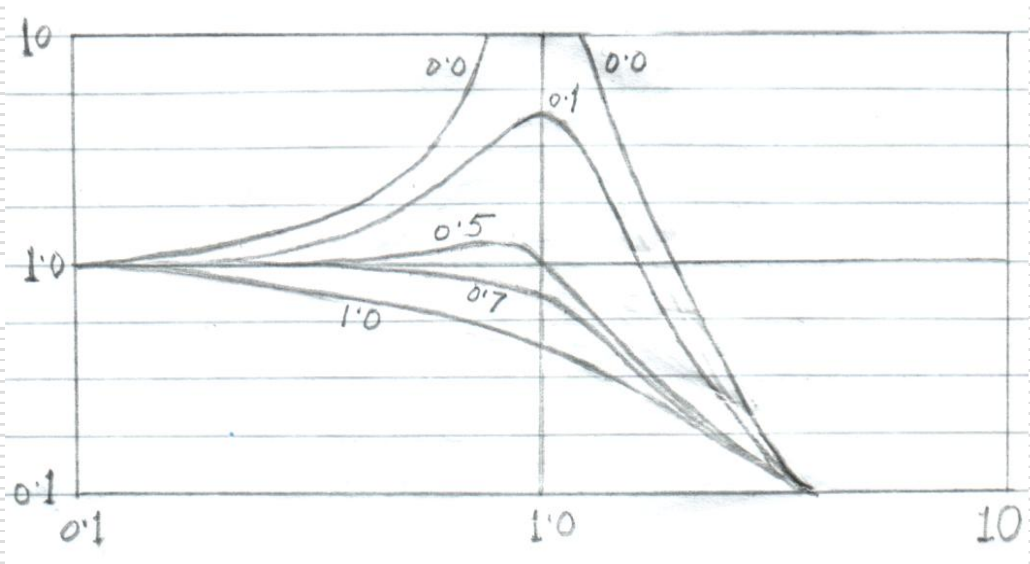
where G is the ratio of relative displacement (output), x_0 to the absolute acceleration (input), x_i,

ω_n is the natural frequency , and

ξ is the damping ratio.

Frequency Response Plot of MSD System

Gain |G|



Frequency ratio ω / ω_n

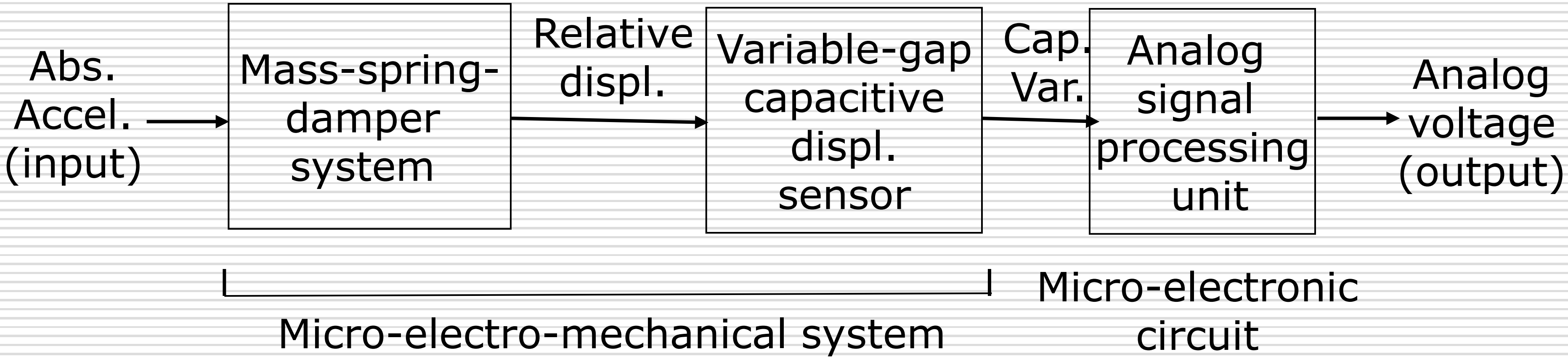
Smart Acceleration Sensors: ADXL Series

- ADXL 150: **Single-axis**
  14-Pin dual-in-line (DIL) package
  DC output
- ADXL 250: **Dual-axis**
  14-Pin dual-in-line (DIL) package
  DC output
- ADXL 210: Dual-axis
  8-Terminal leadless chip carrier (LLC) package
  PWM output
- ADXL 311: Dual-axis
  8-Terminal leadless chip carrier (LLC) package
  DC output

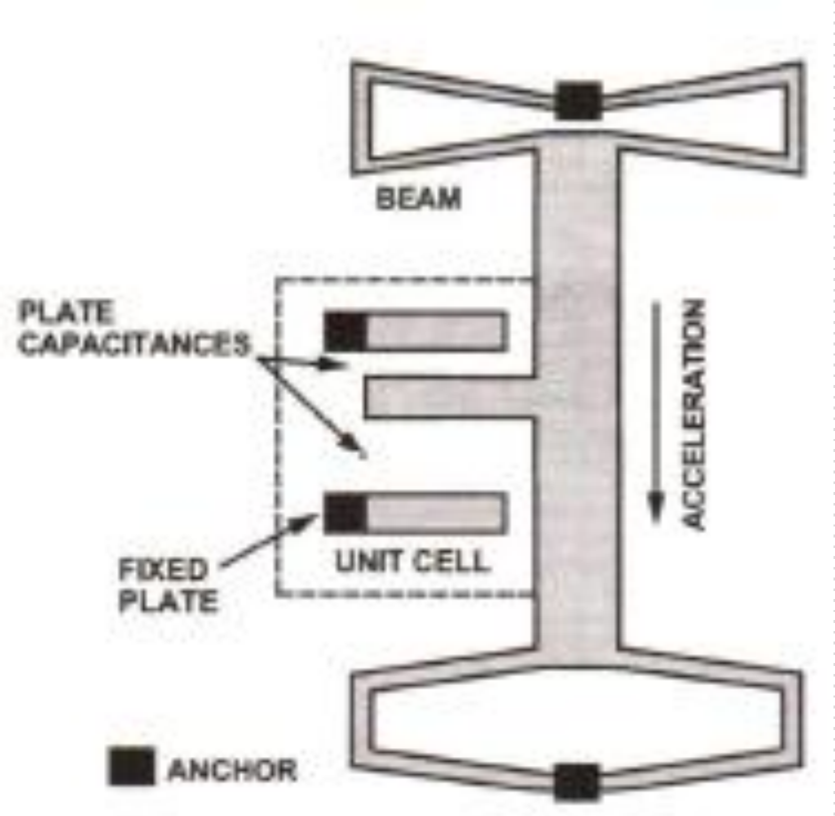
Common Features of ADXL Series

- Can measure dynamic acceleration (vibrations) as well as static acceleration (gravity)
- Ultra-small package
- Ultra-low weight (<1 gram)
- Low power (<0.5 mA @ Vs)
- Output is ratiometric to supply voltage
- Self test feature
- 1000 g shock survival
- Sensing element fabricated using proprietary surface micromachining process.

Block Schematic of ADXL-150

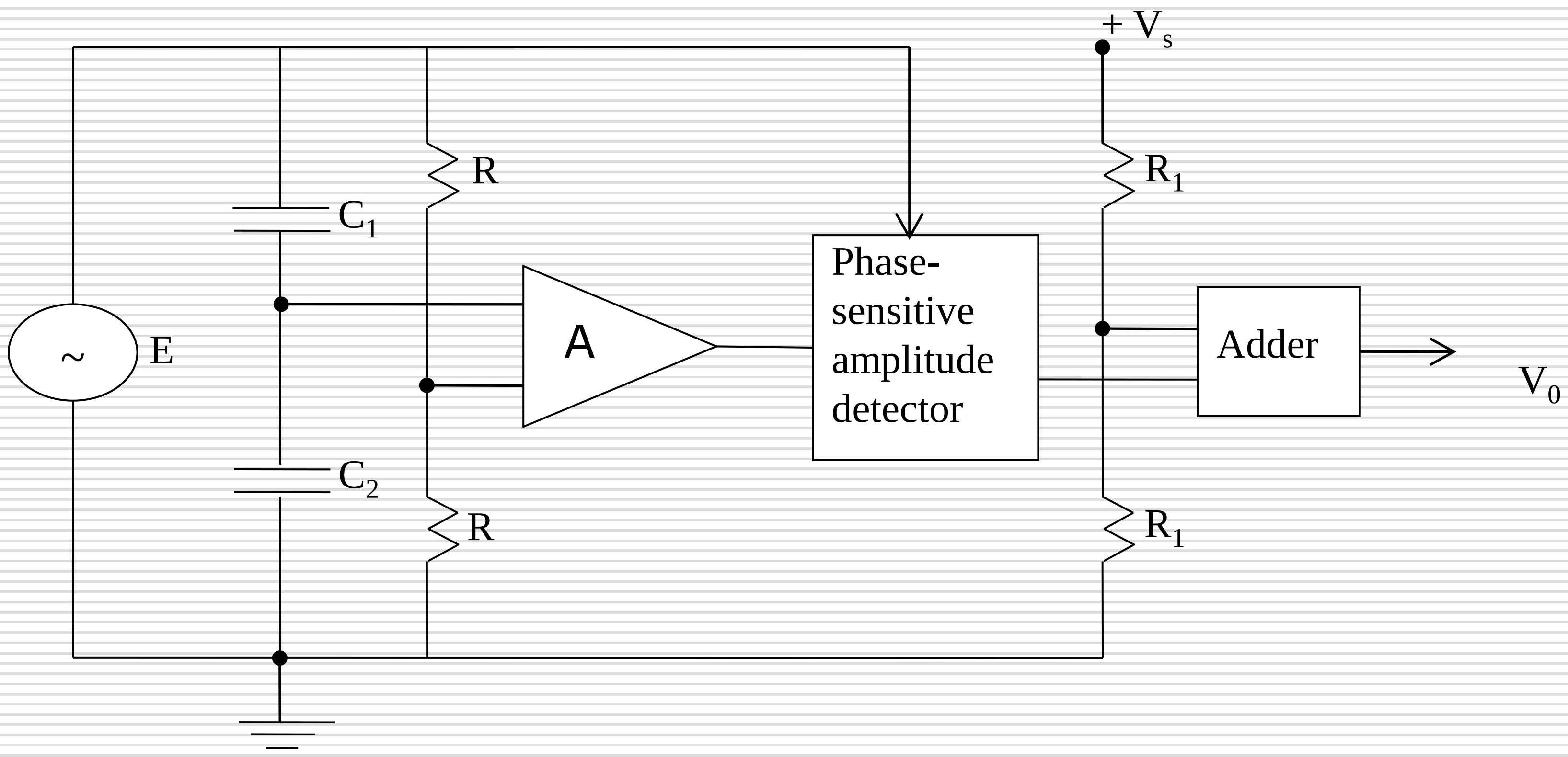


Sensor (MEMS) of ADXL



(Source: Data sheets of ADXL-150)

ASPU of ADXL-150



For acceleration = 0, $C_1 = C_2 = C$

For acceleration = a, $C_1 = C + \triangle C$ & $C_2 = C - \triangle C$

For acceleration = -a, $C_1 = C - \triangle C$ & $C_2 = C + \triangle C$

Output of ADXL-150

- The output of signal processing circuit is a d.c. voltage
- It is ratiometric and given by

$$V_0 = \frac{V_s}{2} + S.a.\frac{V_s}{5}$$

- Here

  V_0 = output voltage
  V_s = supply voltage (actual)
  S = sensitivity of the smart sensor in V/g @ 5V
  a = acceleration in g

- The maximum value of $S.a.\frac{V_s}{5}$ is less than $\pm V_s/2$.
- Therefore, the sensor output V_0 is always positive.

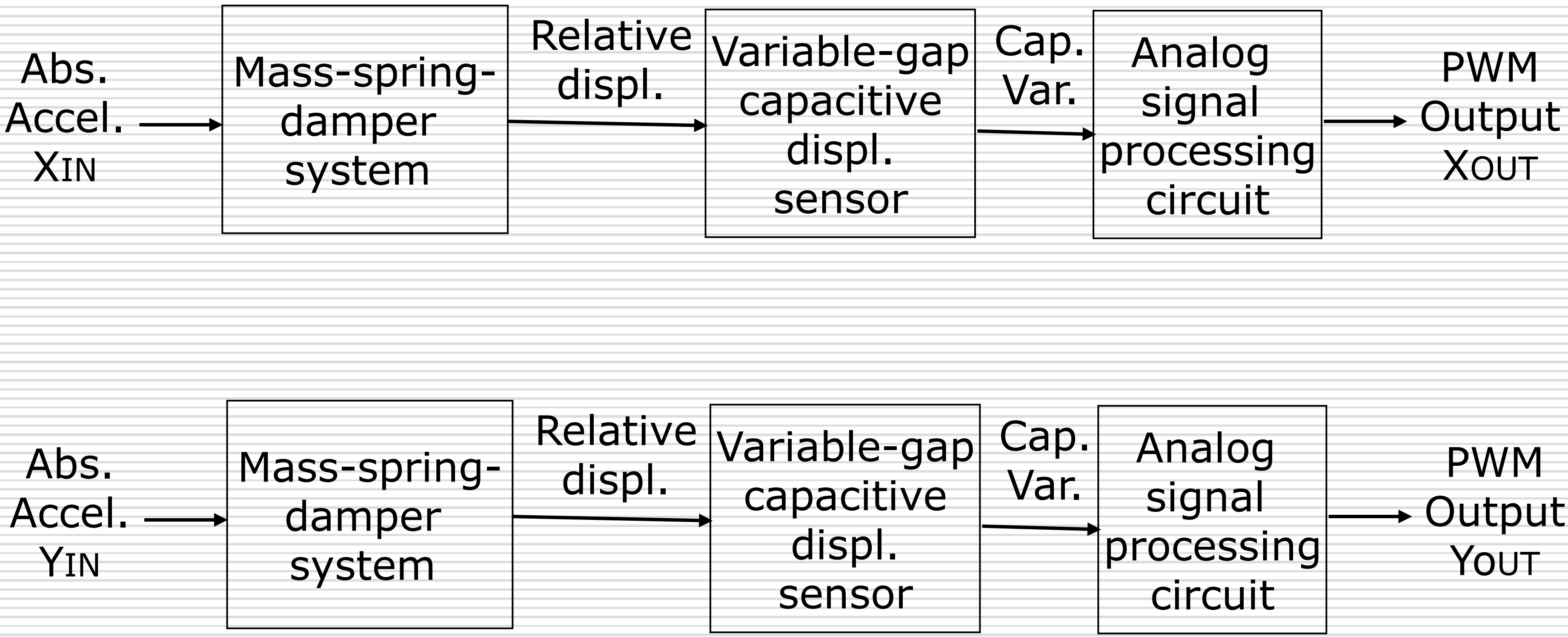
Specifications of ADXL-150

Input Range	:	± 50 g
Power Supply (V_s)	:	4.0 V to 6.0 V
Sensitivity @ V_s = 5V	:	38 mV/g
Transverse Sensitivity	:	± 2%
Zero-g offset	:	0.5 V_s
Output Swing	:	0.25 V to V_s-0.25 V
Sensor Resonant Freq.	**:**	**24 kHz**
3dB Bandwidth	**:**	**1 kHz**
Output change on Self Test	:	0.25 to 0.60 V
Operating Temperature	:	0 to 70^0C

Important Features of ADXL-210E

- **Dual-axis sensor** on a single IC chip
- Ultra-small chip (5x5x2 mm)
- **PWM output**, allowing direct interface to low-cost microcontrollers
- Adjustable duty cycle period (0.5 – 1.0 ms)
- Wide operating voltage range (3V - 5.25V)

Block Schematic of ADXL-210E



Case Study # 4

Smart Pressure Sensor

or

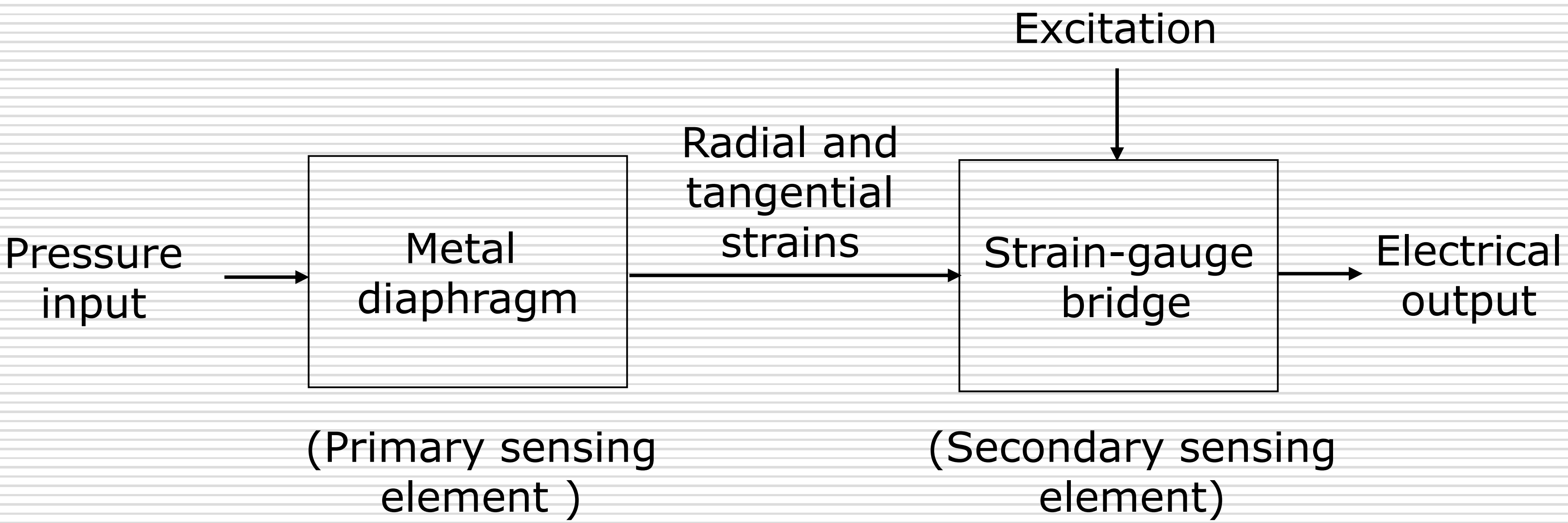
Integrated Silicon Pressure Sensor

MPX5700 Series

Manufacturer: Freescale Semiconductor Inc.

Website: www.freescale.com

Principle of Conventional Pressure Sensor of Diaphragm Type using Strain Gauges



Salient Features of MPX5700

- Monolithic silicon pressure sensor
- Diaphragm based piezo-resistive sensor
- High-level analog output signal
- **Combines micromachining, bipolar IC and thin-film metallization techniques**
- **Available for absolute, differential and gauge pressure measurements**

Variants of MPX5700

- MPX5700A
  - Smart ***absolute*** pressure sensor
  - Has single pressure port

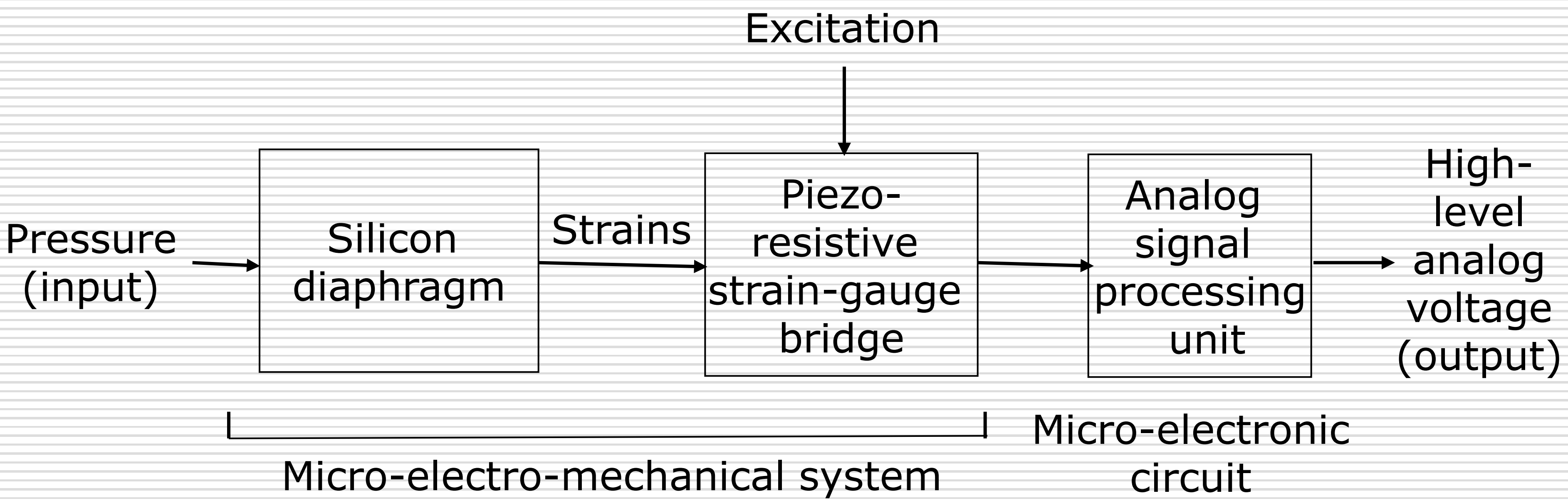
- MPX5700D
  - Smart ***differential*** pressure sensor
  - Has two pressure ports

- MPX5700G
  - Smart ***gauge*** pressure sensor
  - Has single pressure port

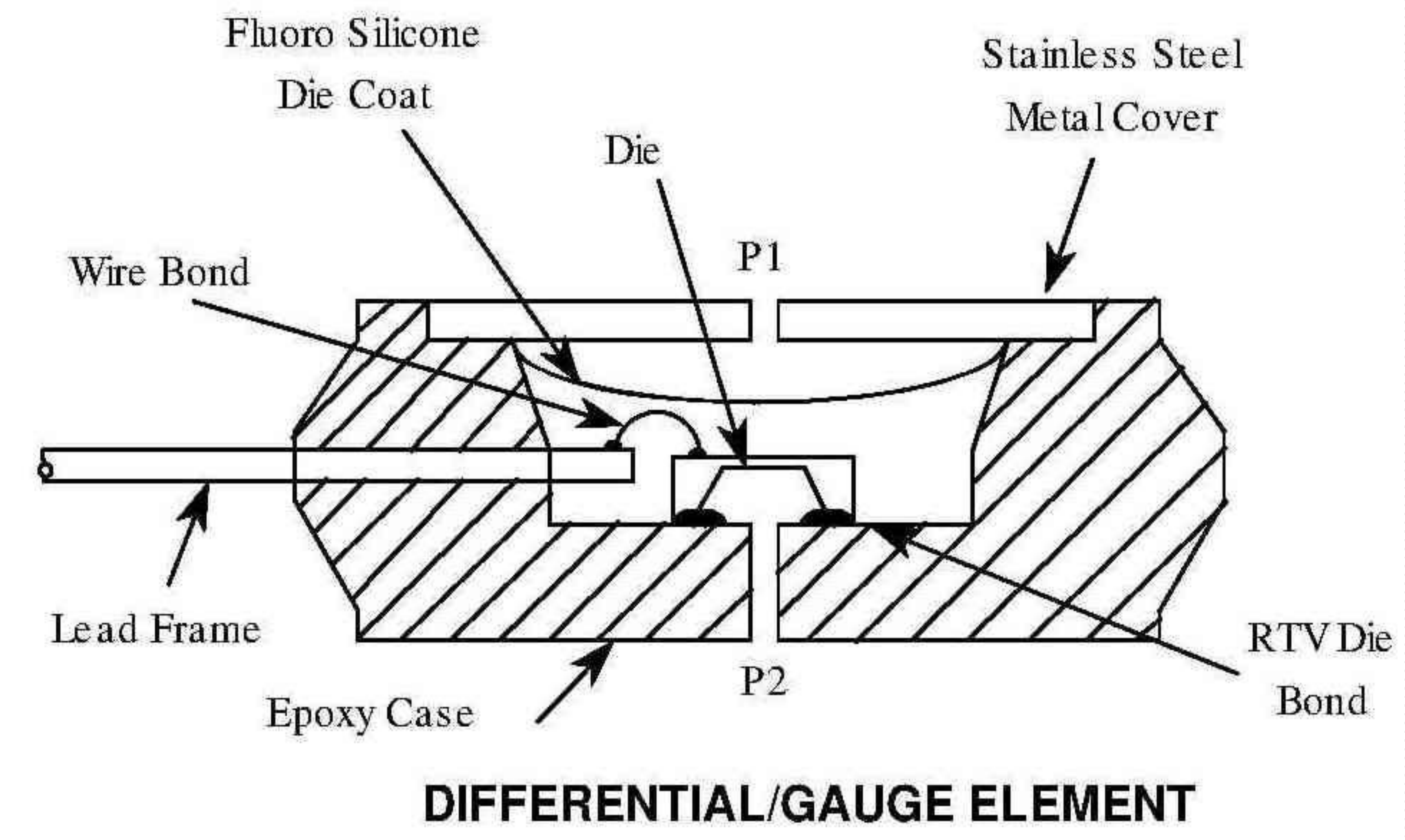
Operating Characteristics of MPX5700

S. No.	Characteristic	Value
1	Pressure Range for Gauge/Differential sensors	0 – 700 kPa
2	Pressure Range for Absolute pressure sensors	15 – 700 kPa
3	Supply Voltage	5.0 ± 0.25V Vdc
4	Full Scale Output	4.7 Vdc
5	Accuracy	±2.5 %V_{FSS}
6	Sensitivity	6.4 mV/kPa
7	**Response Time for 10% to 90% change**	**1.0 ms**
8	Warm-Up Time	20 ms

Block Schematic of MPX5700

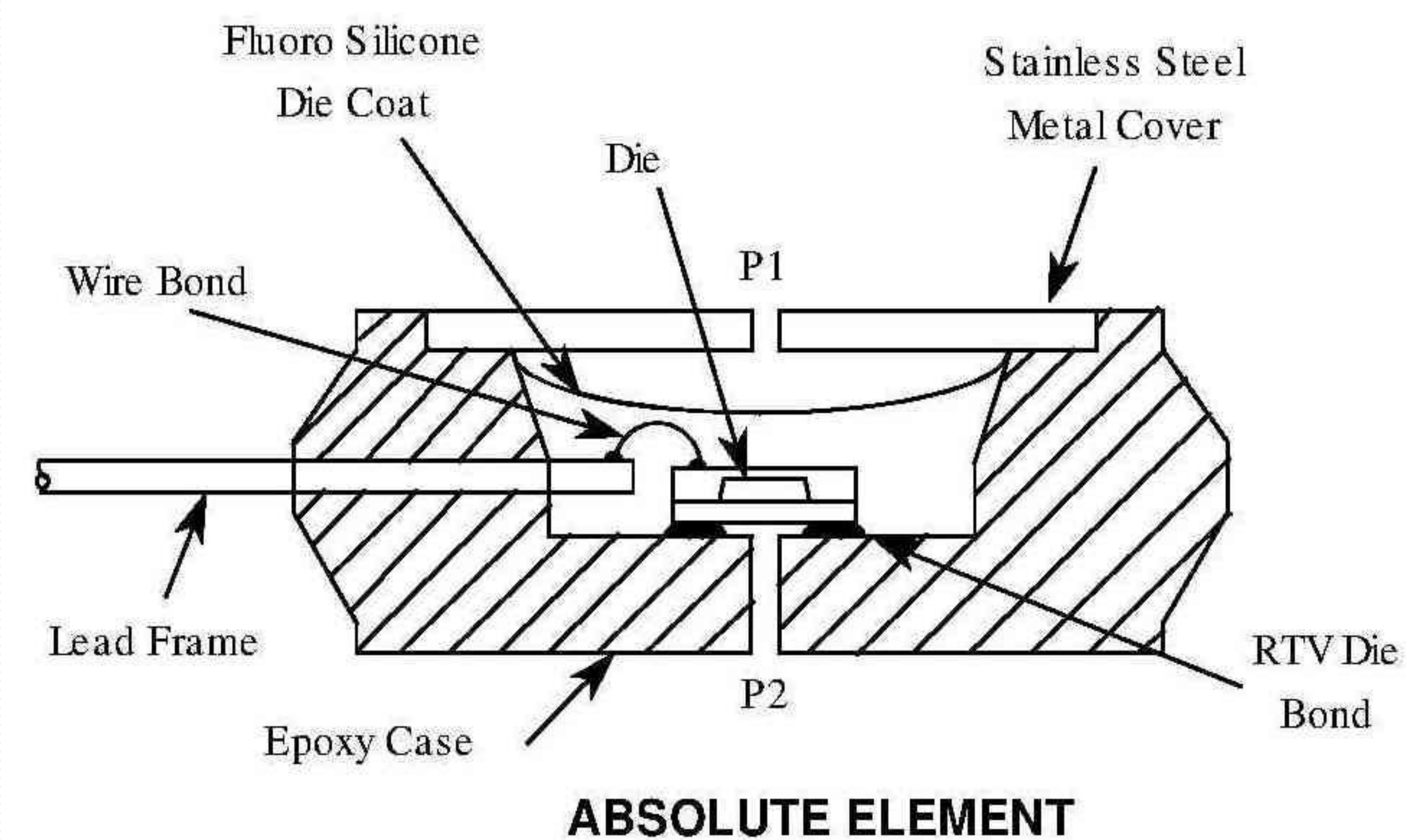


Construction: Cross-Sectional Diagram of Differential/Gauge Pressure Sensing Element



(Source: Data sheet of MPX5700)

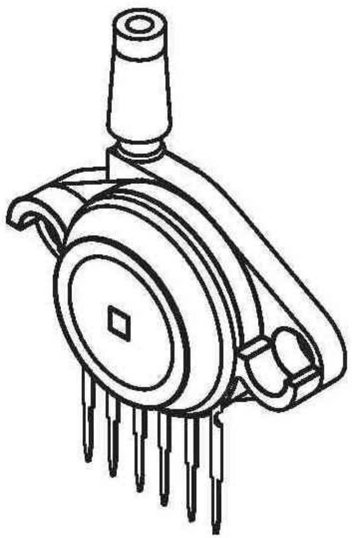
Construction: Cross-Sectional Diagram of Absolute Pressure Sensing Element



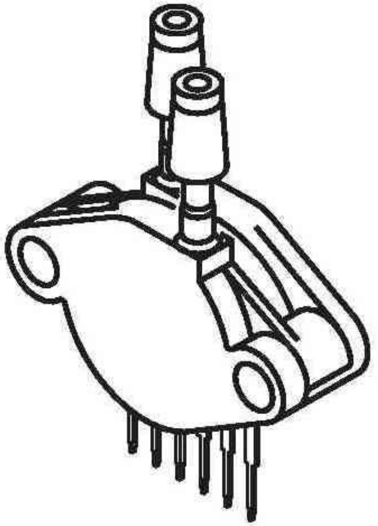
(Source: Data sheet of MPX5700)

MPX5700 ....

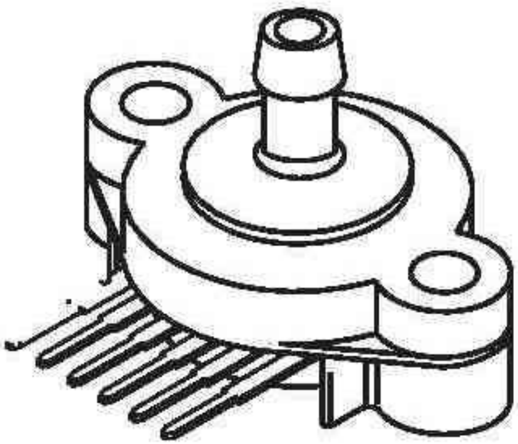
Packages and Pins



MPX5700AP/GP/GP1
CASE 867B-04



MPX5700DP
CASE 867C-05



MPX5700ASX
CASE 867F-03

PIN 1: V_{OUT} PIN 2: GROUND PIN 3: V_{CC}

PIN 4: V_1 PIN 5: V_2 PIN 6: V_{EX}

(Source: Data sheet of MPX5700)

Thank you!