SMART SENSORS

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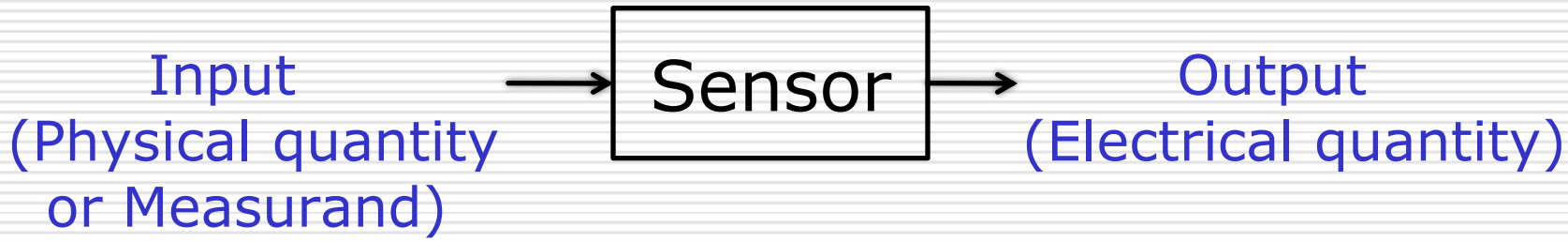
Smart-Sensor Basics

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"**



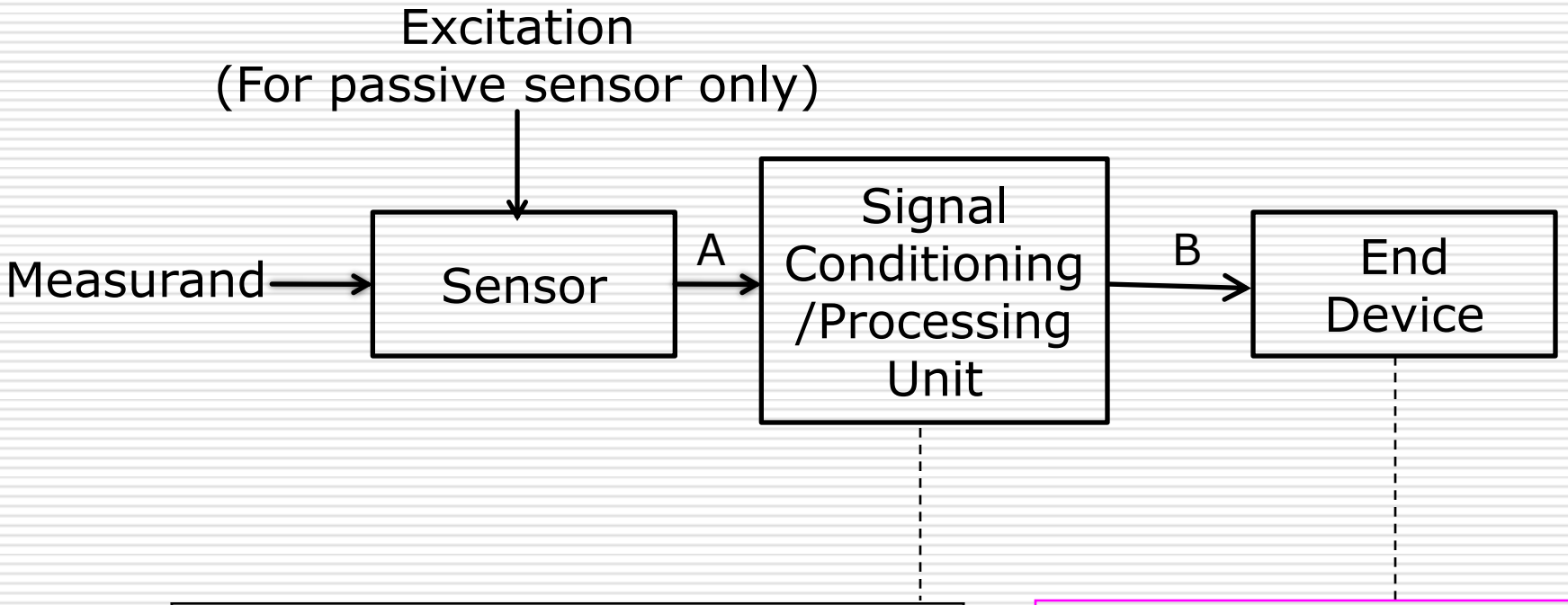
Sensor Input

- Input to the sensor is the *sensed or measured quantity, called as* ***measurand***
- Examples of measurand are:
  - Temperature
  - Pressure and force
  - Torque
  - Displacement, velocity and acceleration
  - Flow, level and head
  - Humidity
  - Gas concentration
  - Voltage and current
  - Power and power factor

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.

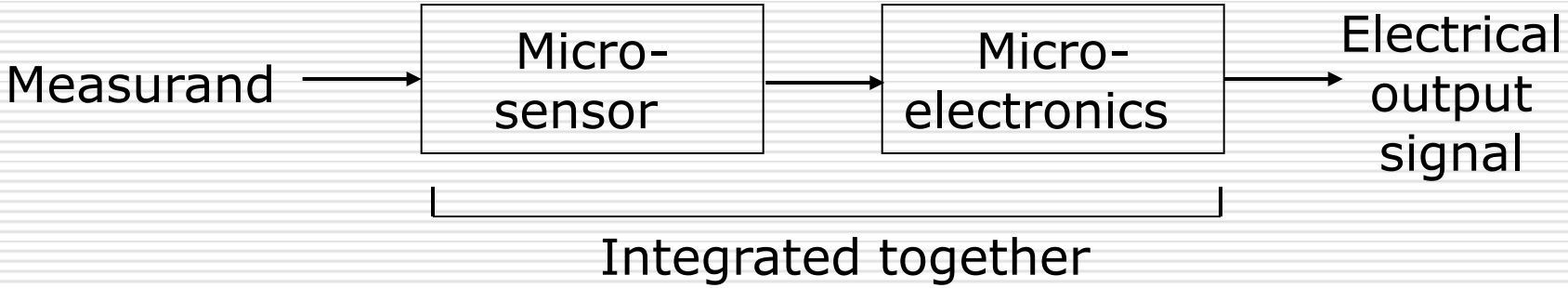
- Indicating device
- Display device
- Storage device
- Comm. device
- Data processor

Analog Electronic Circuits used for Signal Conditioning

- Amplifiers
  - D.C. coupled
  - A.C. coupled
  - Differential
  - Instrumentation
- Operational circuits
  - Adder
  - Subtractor
  - Multiplier
  - Divider
  - Integrator
  - Differentiator
- Active filters
  - Low pass
  - High pass
  - Band pass
  - Band reject (notch)
- Modulators/Demodulators
  - Pulse width modulator (PWM)
  - Amplitude detector
  - Phase sensitive amplitude detector

What is a Smart Sensor?

- Most of the sensors now ***labeled as Smart Sensors*** by their manufacturers and ***accepted as Smart Sensors*** by 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".*

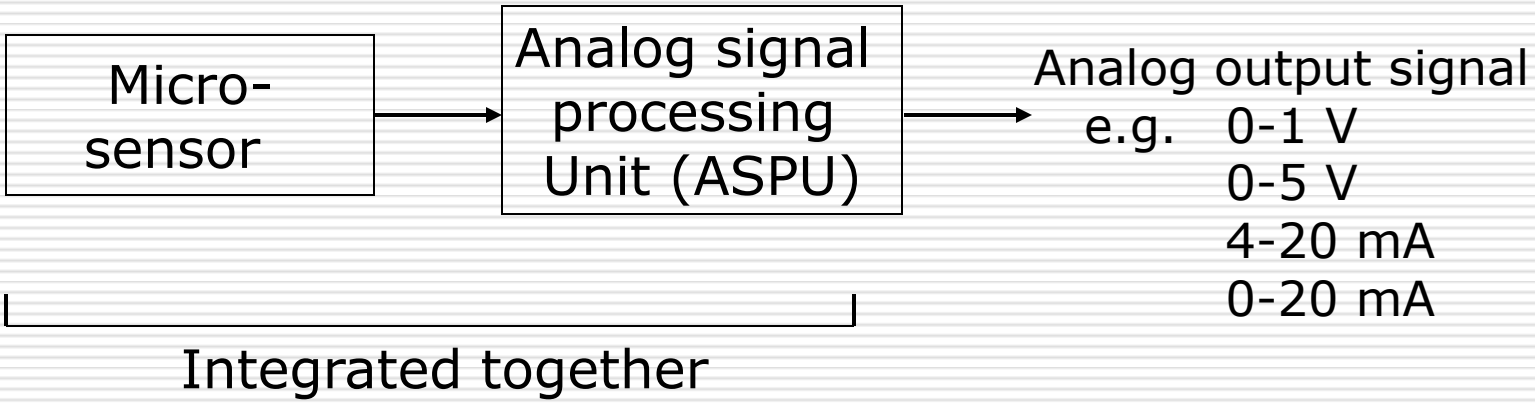


Levels of Integration

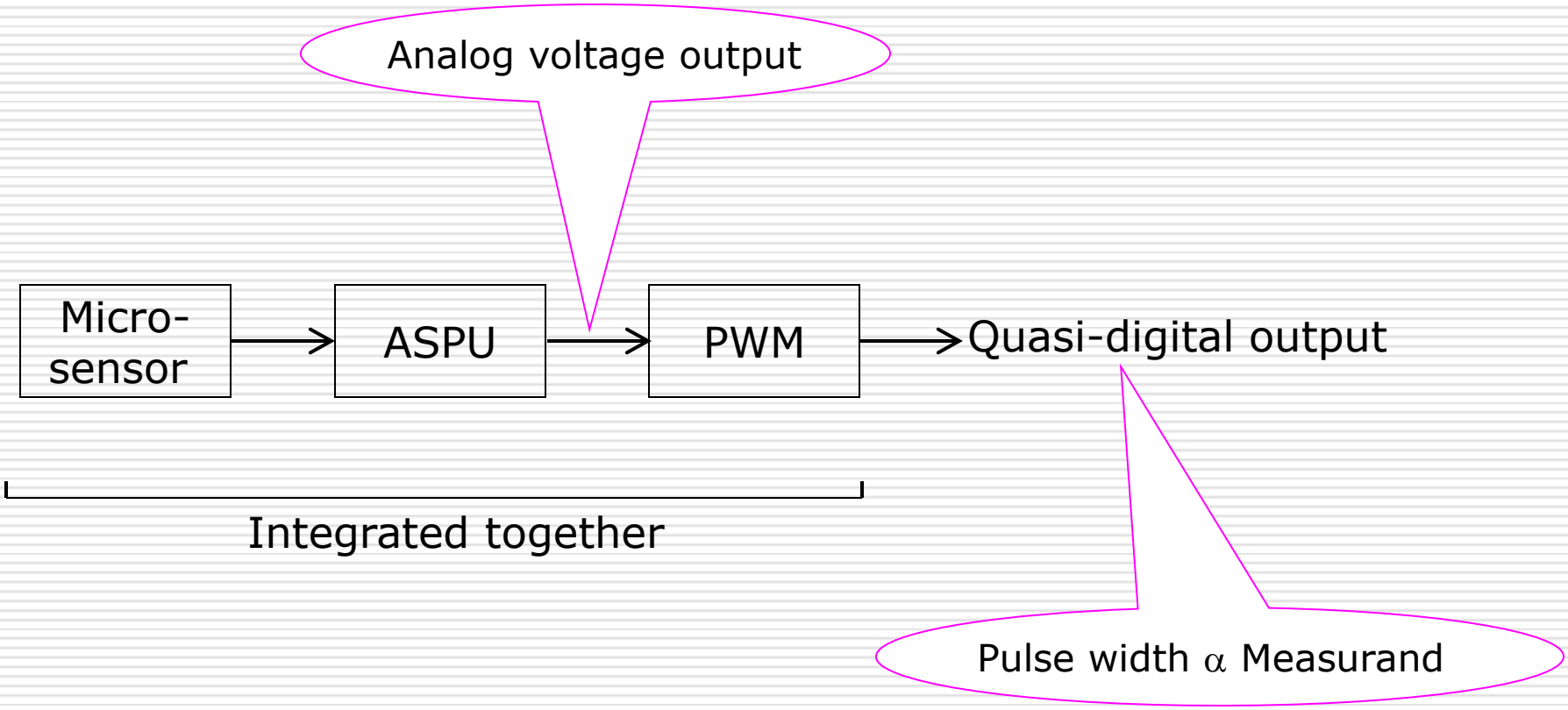
- The output signal of smart sensor can have one of three forms:
  - Analog
  - Digital
  - Quasi-digital (PWM or pulse frequency)

- 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

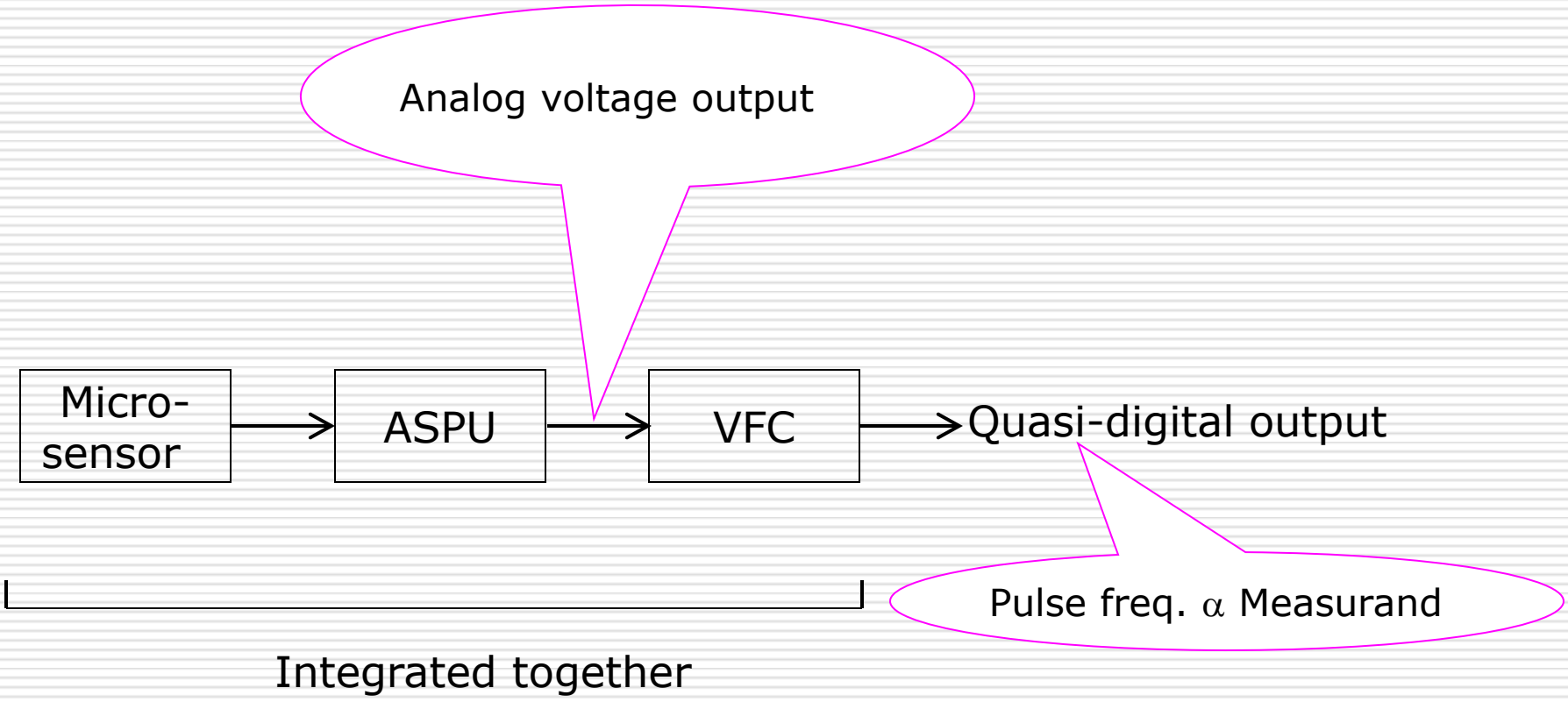
Smart Sensor with Analog Output



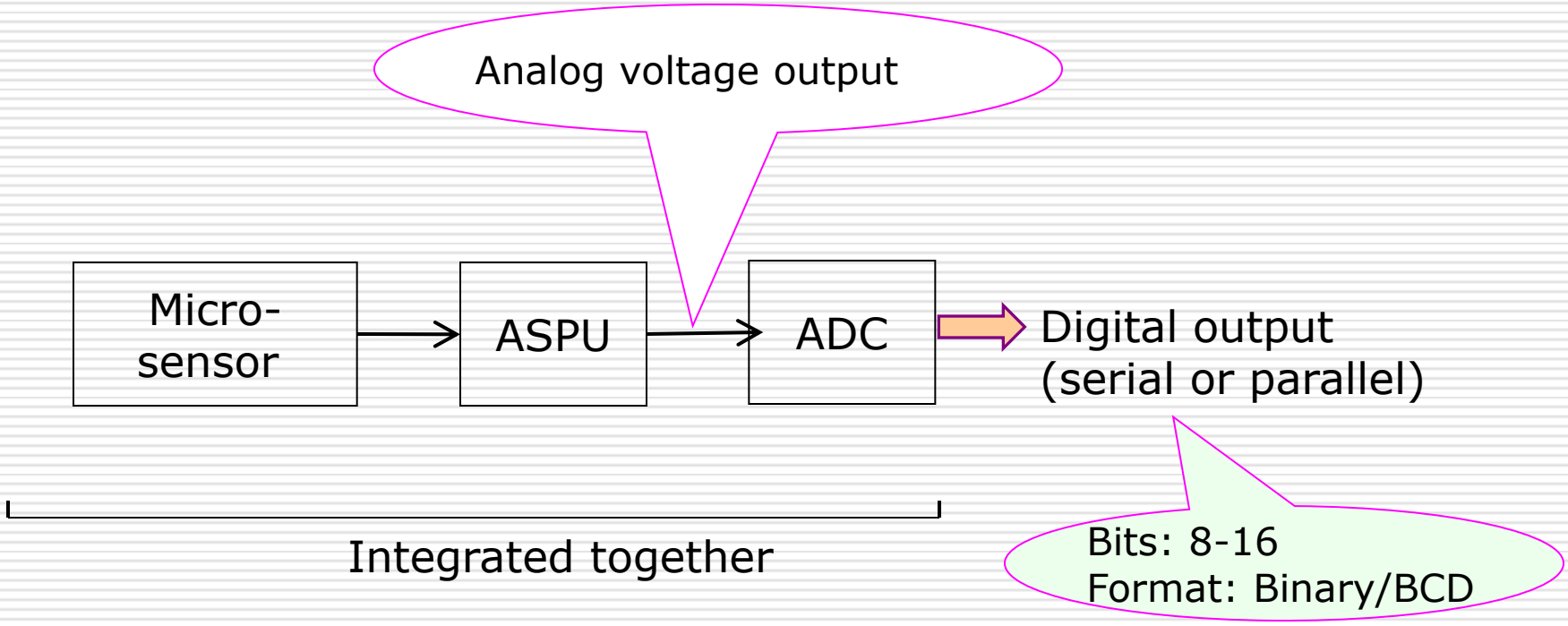
Smart Sensor with PWM Output



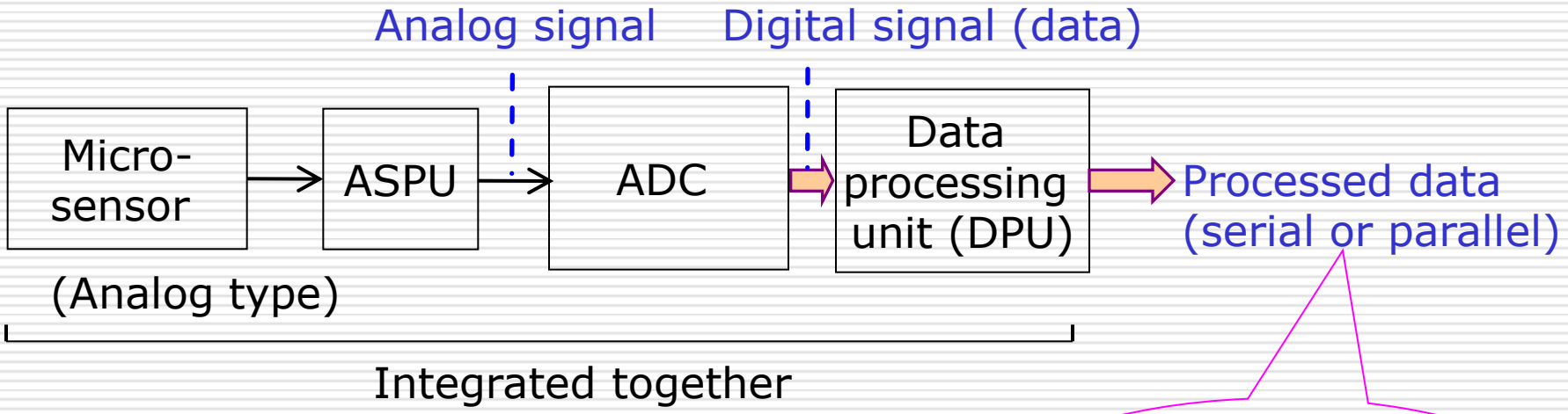
Smart Sensor with Pulse-Frequency Output



Smart Sensor with Digital Output



Intelligent Sensor



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

DPU = Microcontroller

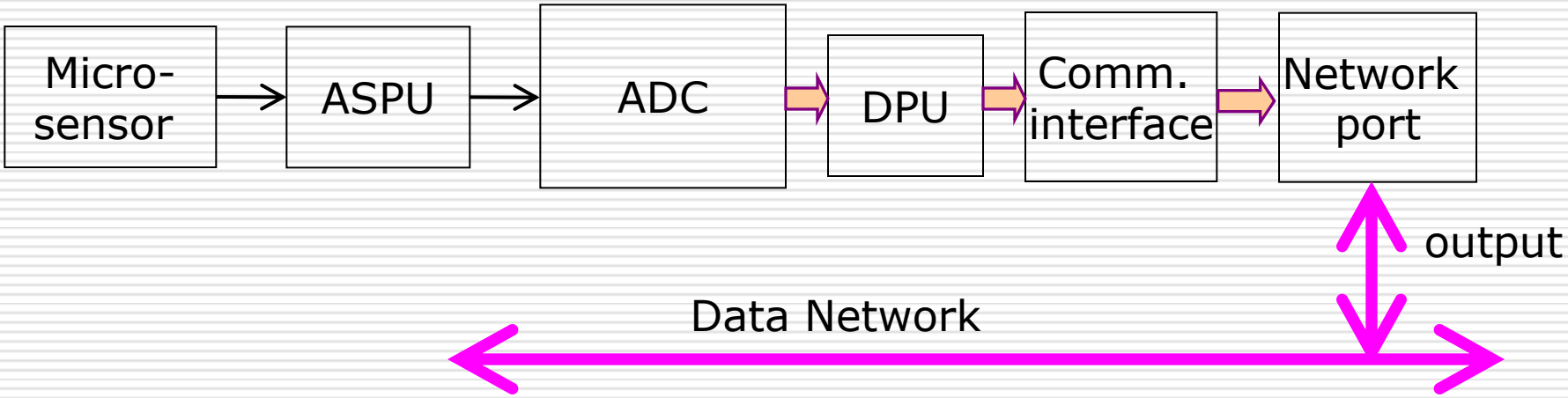
OR

μP + memory + I/O interface

OR

DSP +memory + I/O interface

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 Integrating DPU

- 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
  - On-chip EEPROM or flash-RAM
  - Storage of field-measurement data
- Higher flexibility

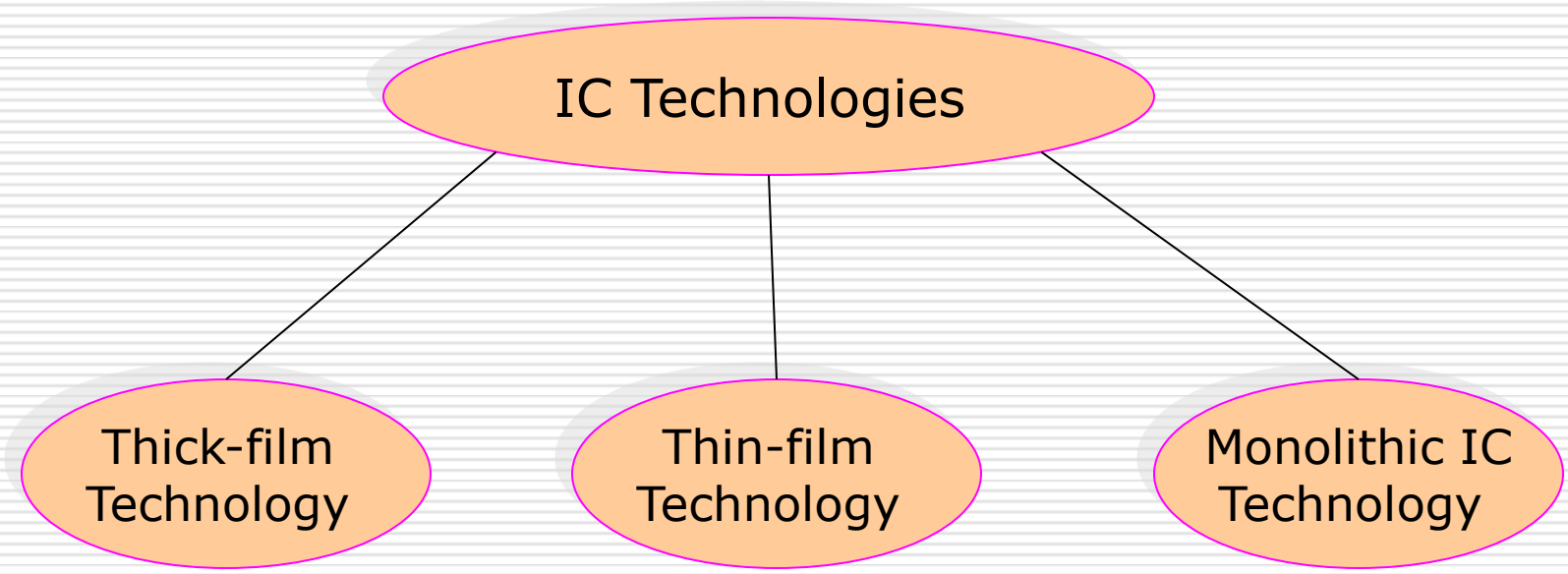
Smart-Sensor Technologies

Smart Sensor Technologies

Two types of technologies used:

- IC Technologies
- Micromachining Technologies

IC Technologies & Capabilities



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

- R & C
- Conductors
- Sensor elements

- 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.

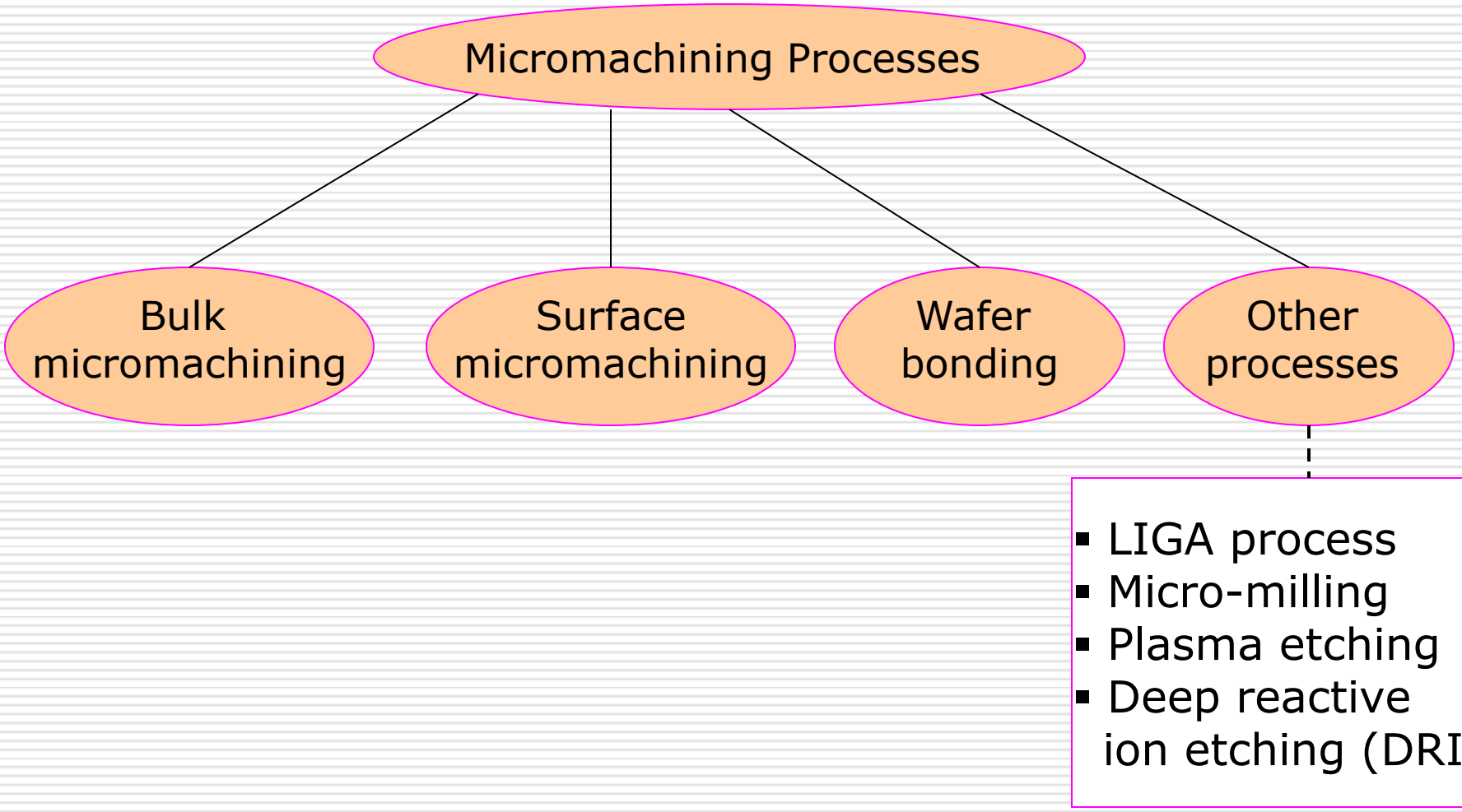
Monolithic IC Technology: Advantages

- 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)

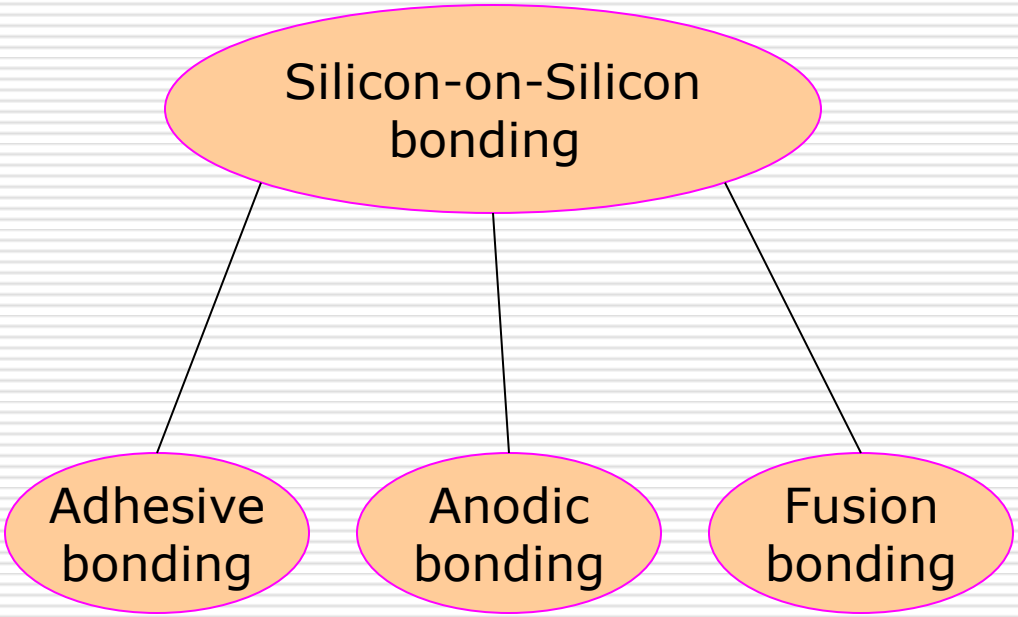
- Common Etchants (examples)
  - Ethylene-diamine pyrocatechol (EDP)
  - Potassium hydroxide (KOH)

- Structures Produced (example)
  - Diaphragm

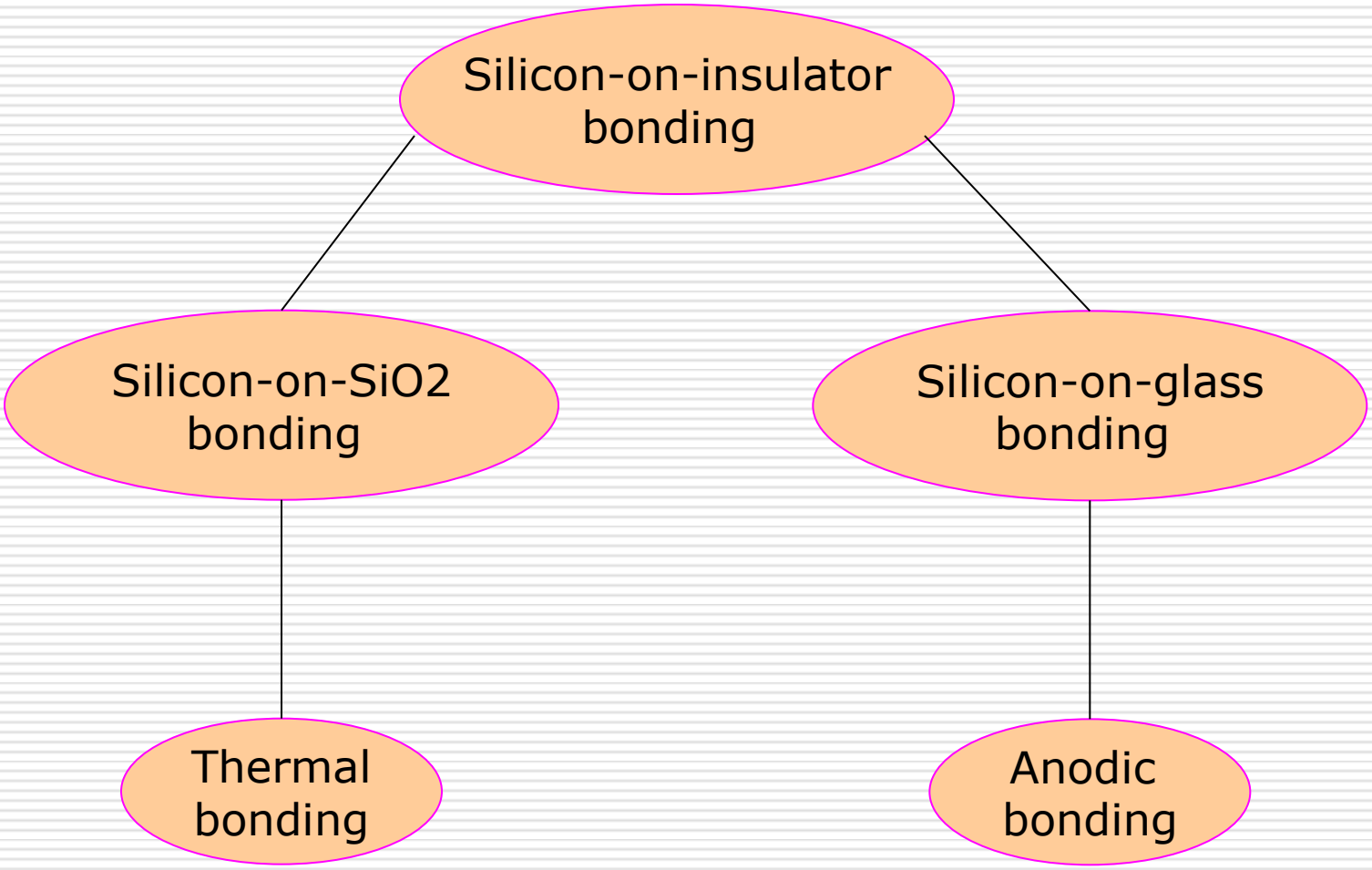
Surface Micromachining

- 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

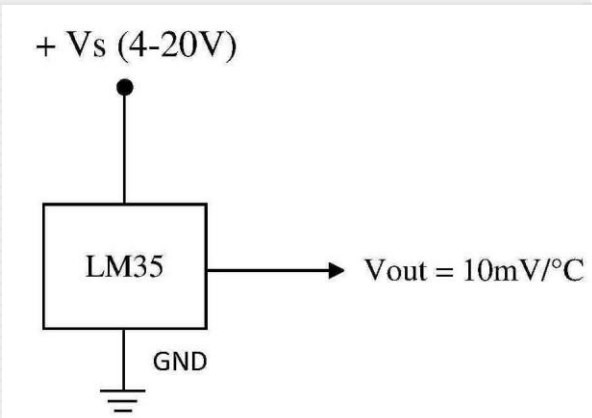
Manufacturer: National Semiconductor Corporation

Website: www.national.com

Major Specifications

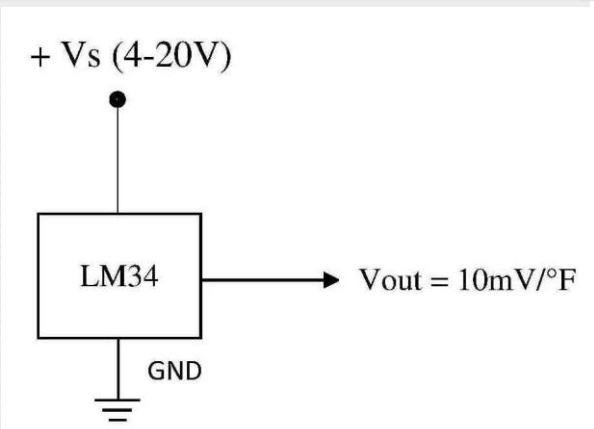
LM35: Centigrade (or Celcius) Temperature Sensor

- 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)

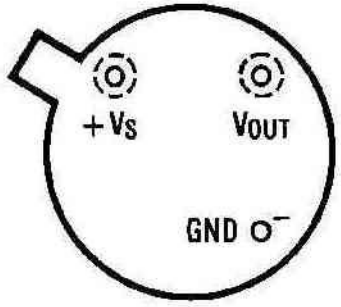


Principle of LM35/LM34

- 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*

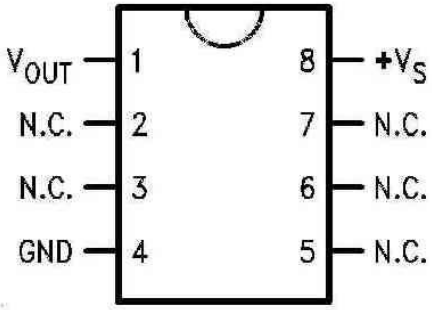


BOTTOM VIEW

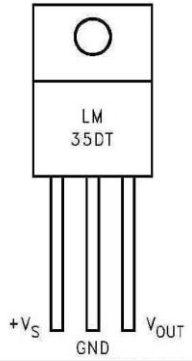
TO-92
Plastic Package

BOTTOM VIEW

SO-8
Small Outline Molded Package



TO-220
Plastic Package*



Case Study # 2

Smart Humidity and Temperature Sensor

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

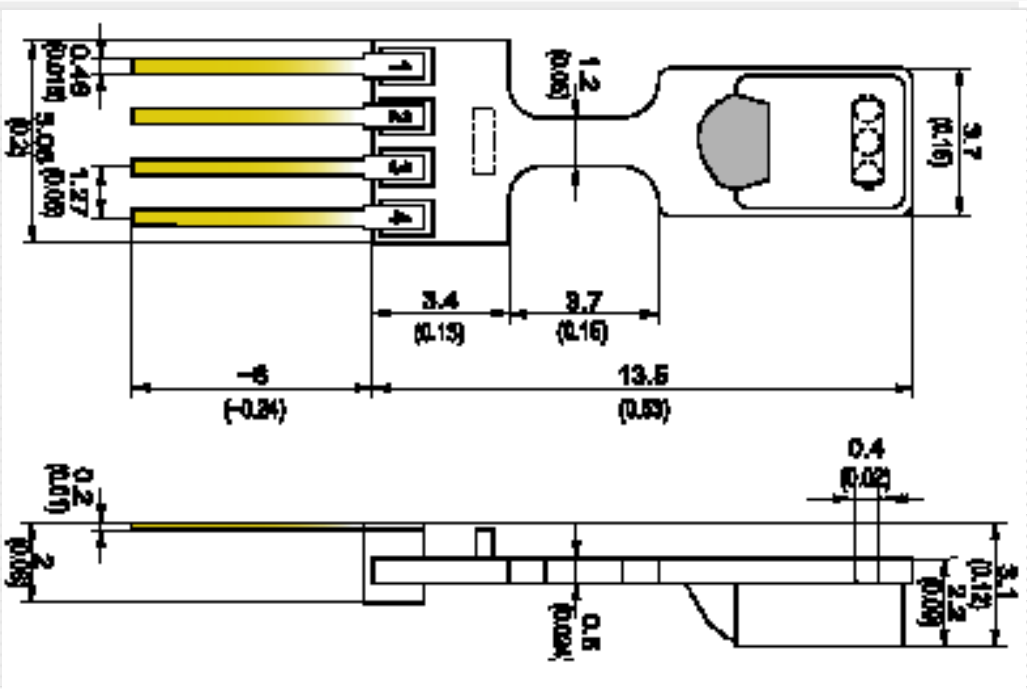
SHT 15

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)*

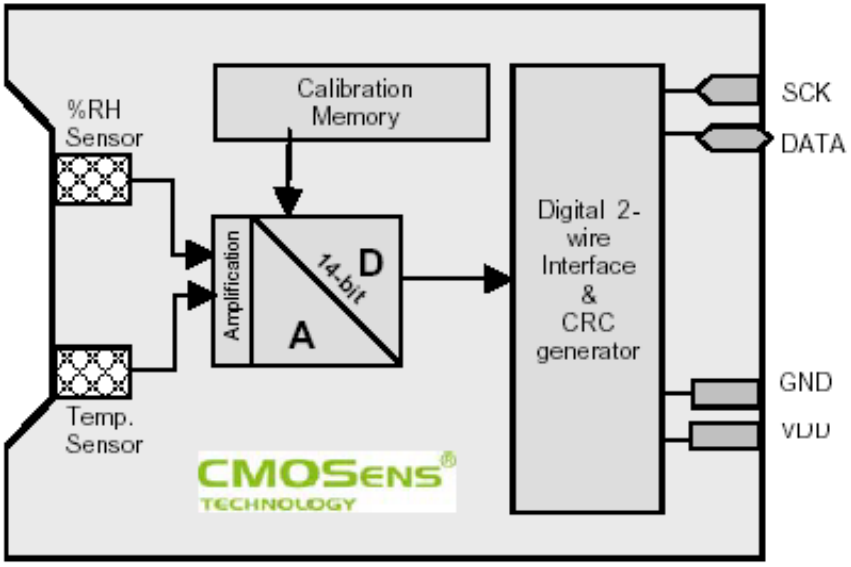
Dimensions of SHT7x



(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 I^2C interfaces.

Case Study # 3

Smart Acceleration Sensor

or

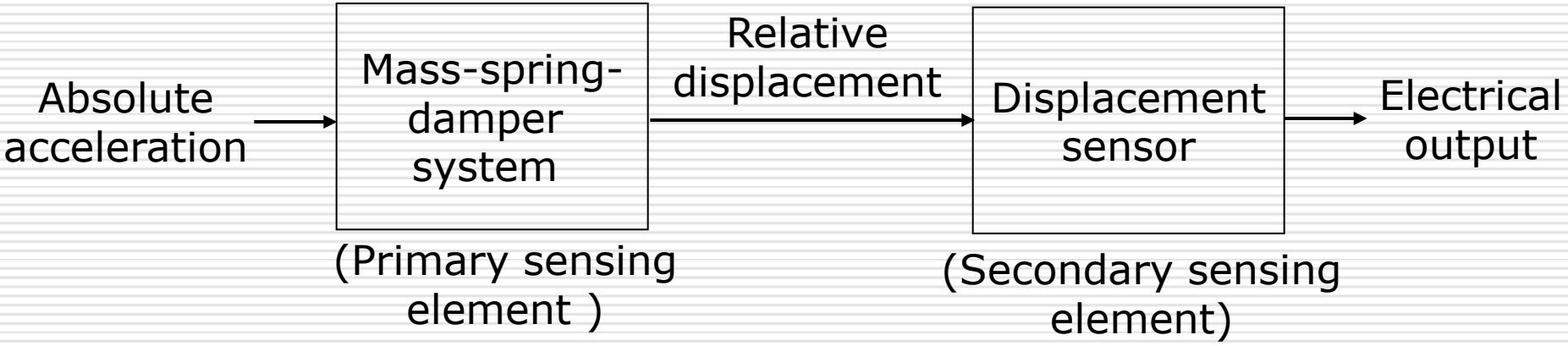
iMEMS Accelerometer

ADXL
150/250/210/311

Manufacturer: Analog Devices

Website: www.analog.com

Basic Principle of Acceleration Sensors



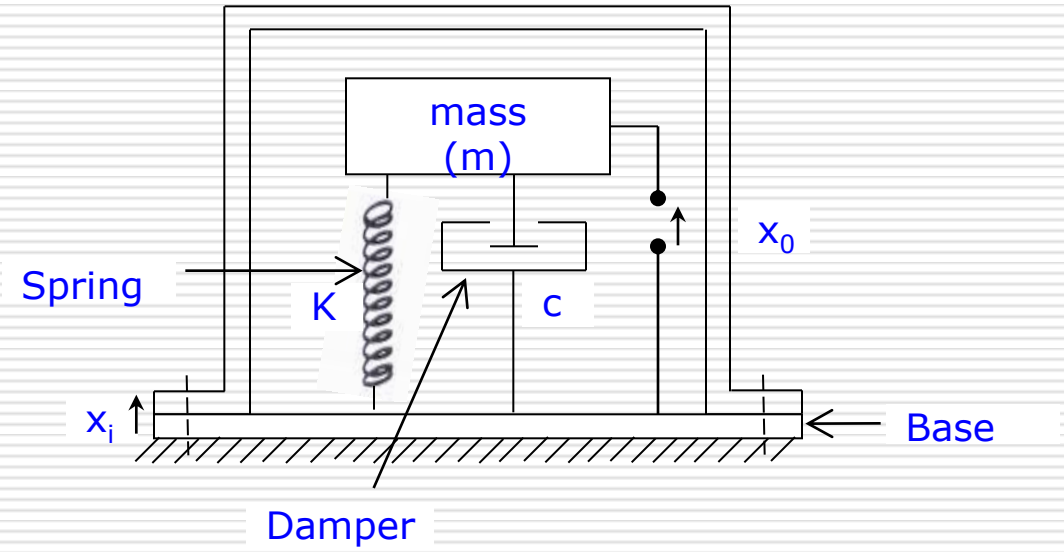
Displacement Sensor Options

(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

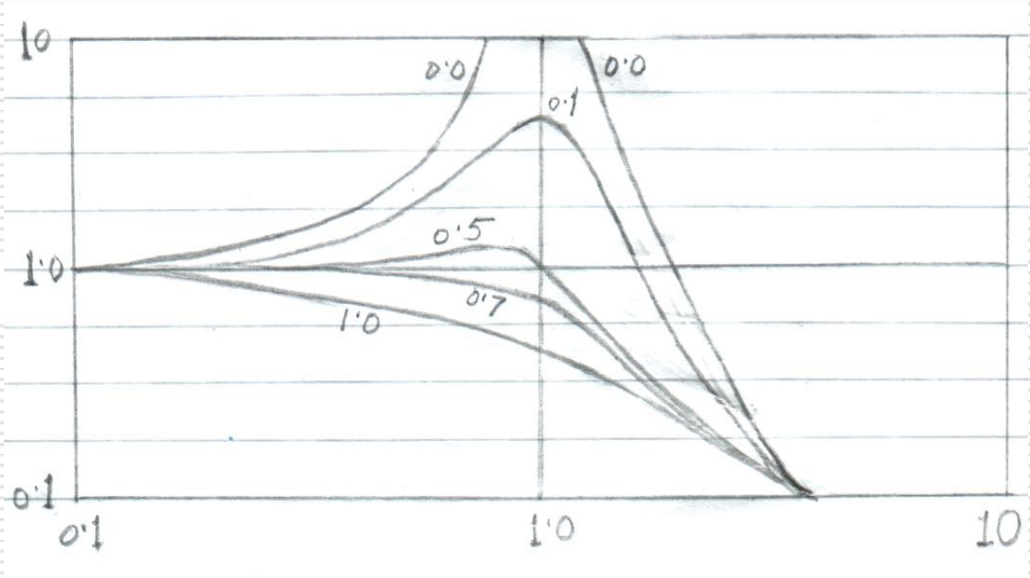
$$G(j\omega) = \frac{1/\omega_n^2}{1 + \left(j\omega/\omega_n\right)^2 + 2j\,\xi\,(\omega/\omega_n)}$$

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



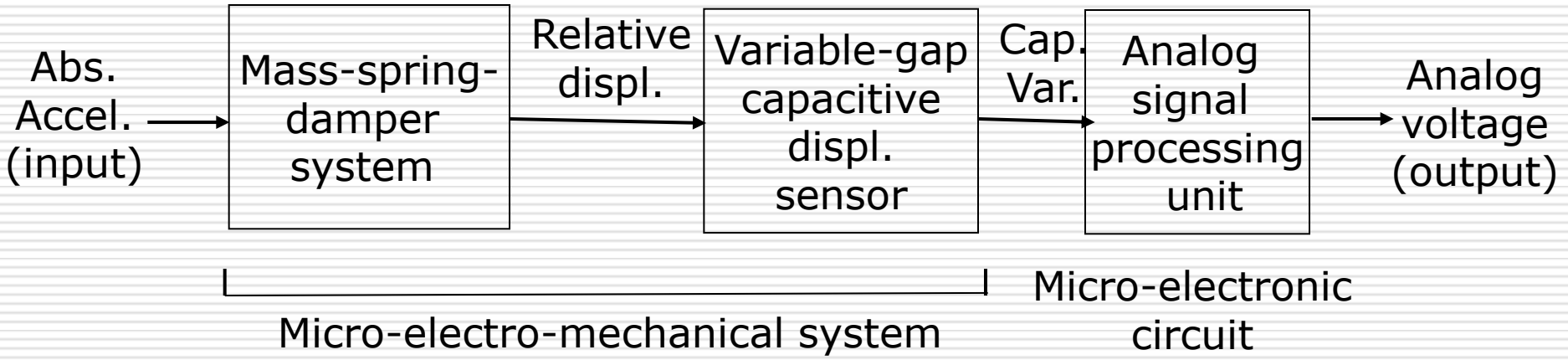
Smart Acceleration Sensors: ADXL Series

- 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**

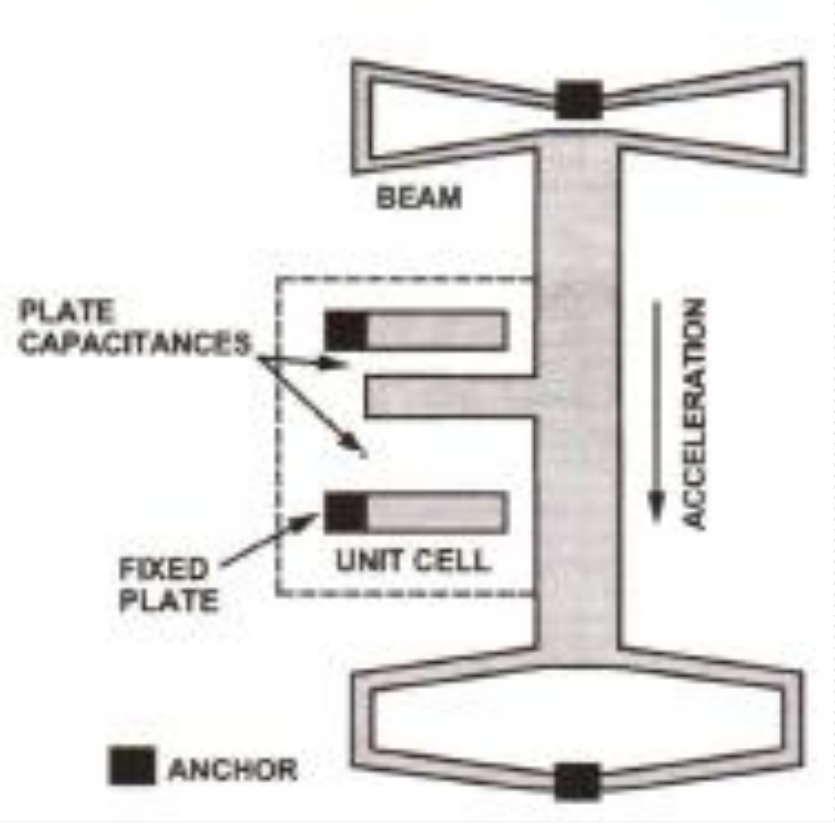
Common Features of ADXL Series

- 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

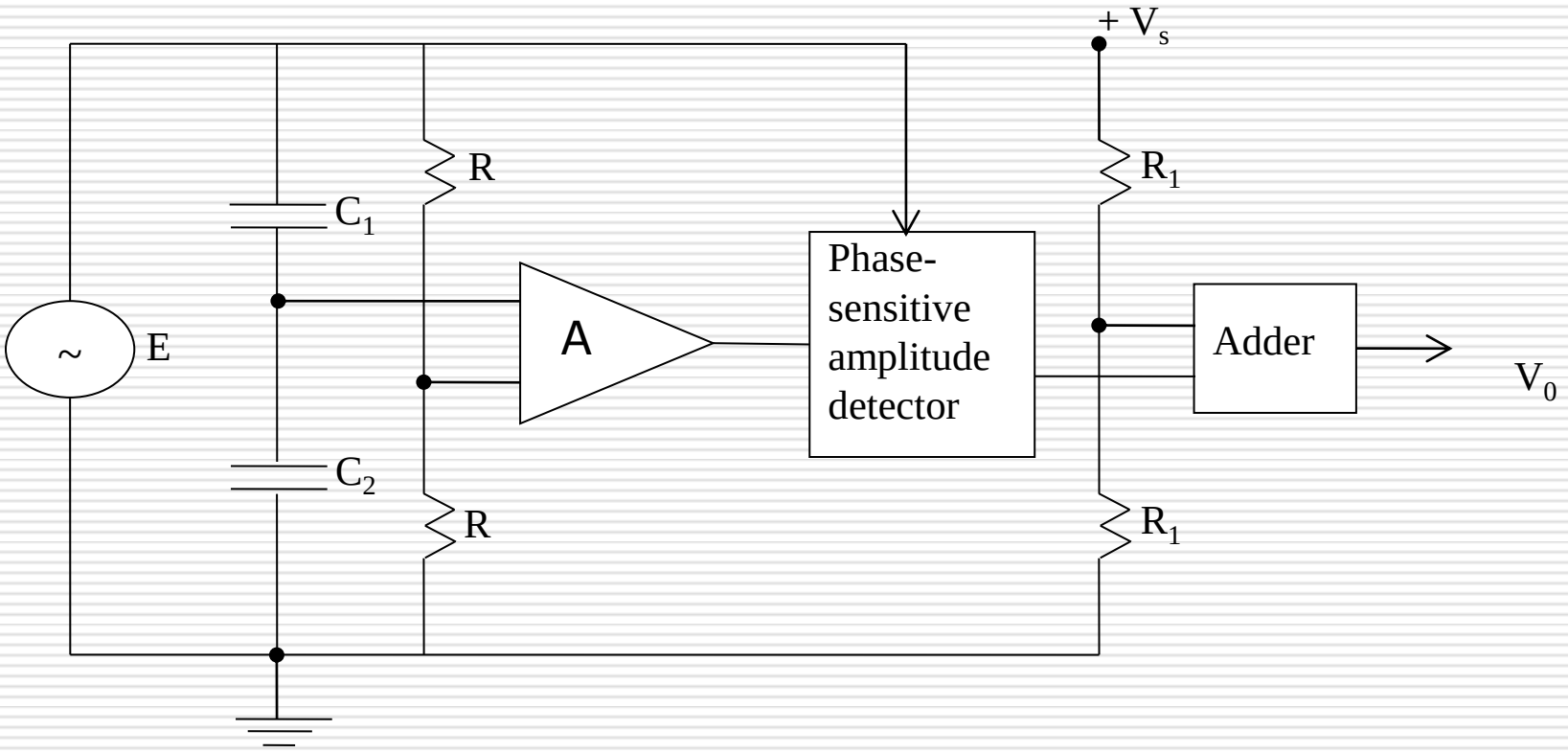


Sensor (MEMS) of ADXL



(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.

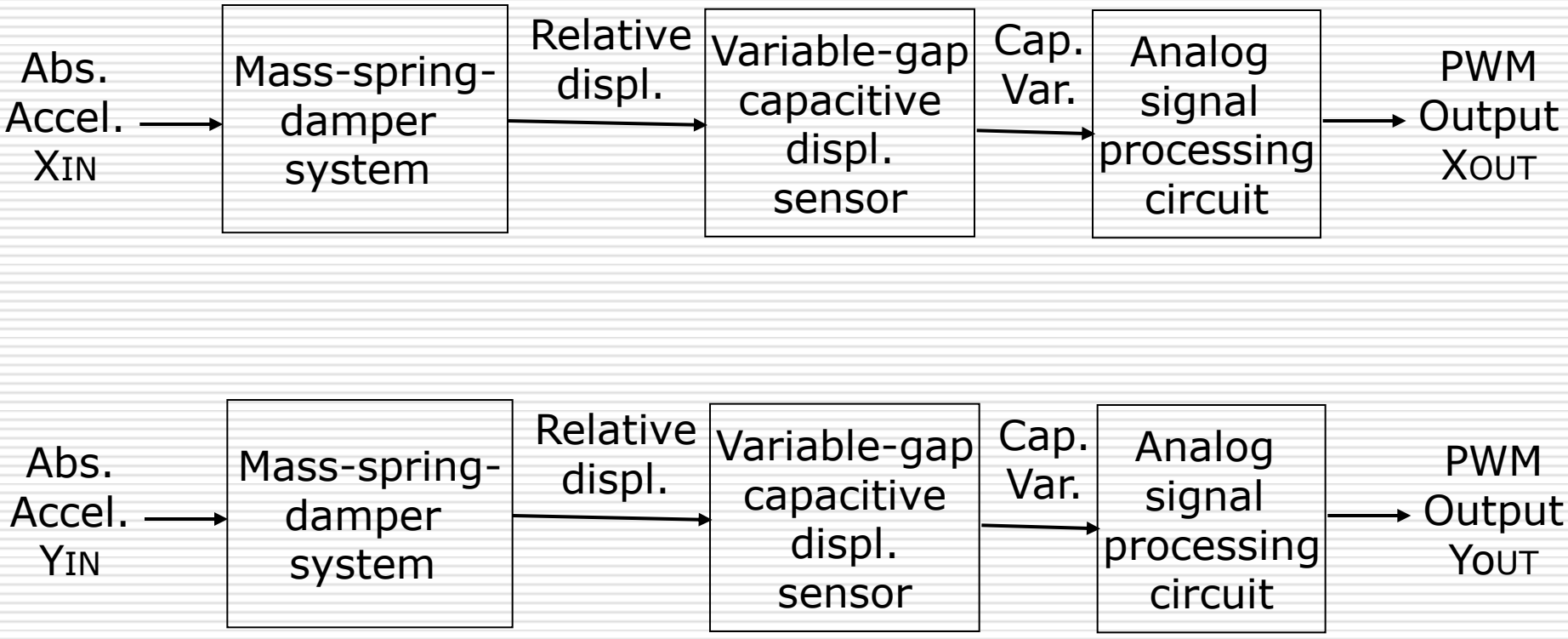
Specifications of ADXL-150

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

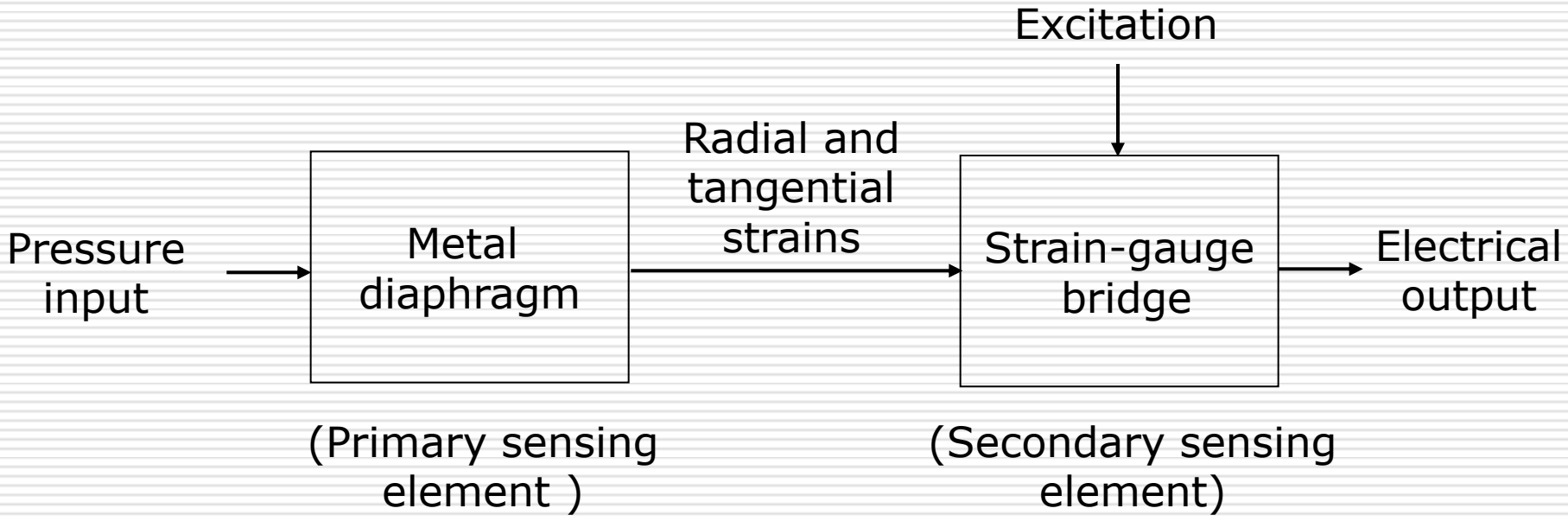
Integrated Silicon Pressure Sensor

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

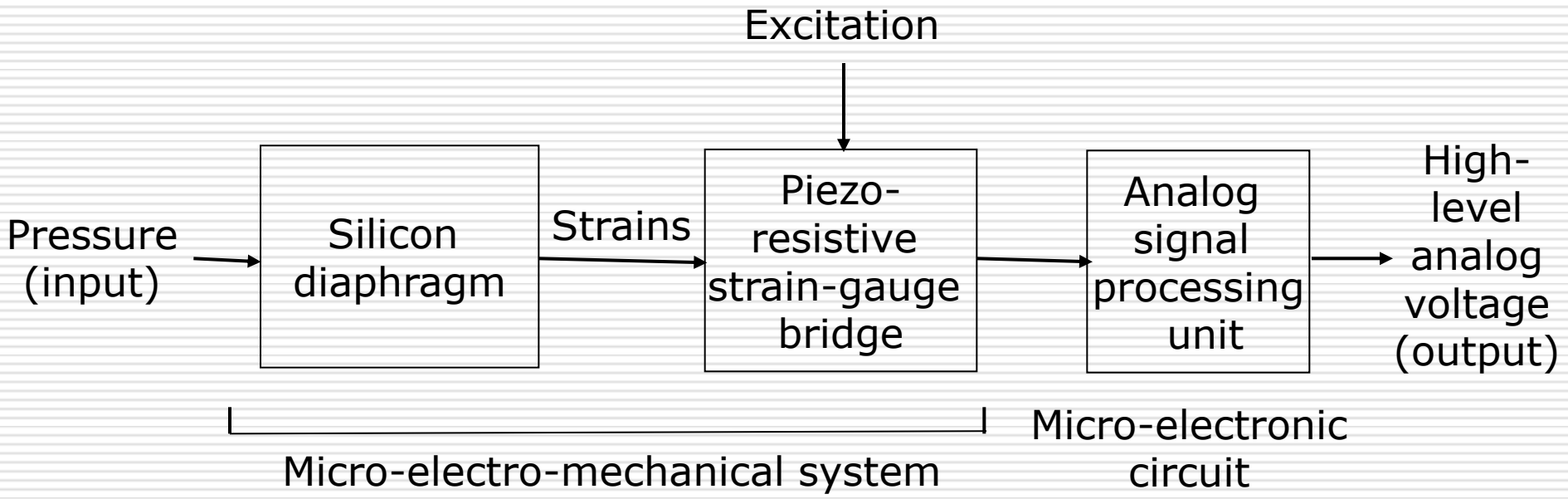
- MPX5700A
  - Smart ***absolute*** pressure sensor
  - Has single pressure port
- MPX5700D
  - Smart ***differential*** pressure sensor
  - Has two pressure ports
- MPX5700G
  - Smart ***gauge*** pressure sensor
  - Has single pressure port

MPX5700……..

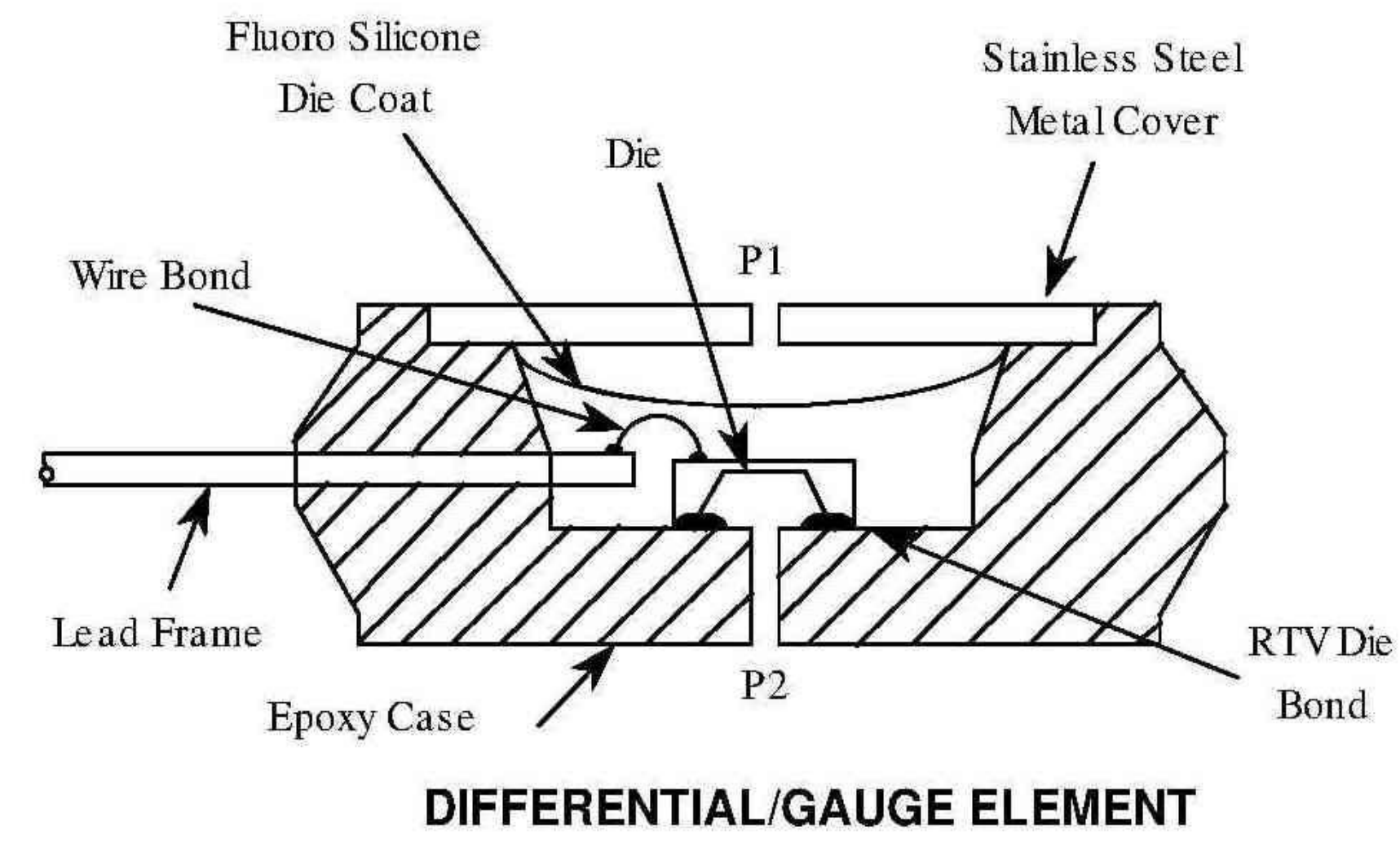
Operating Characteristics of MPX5700

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

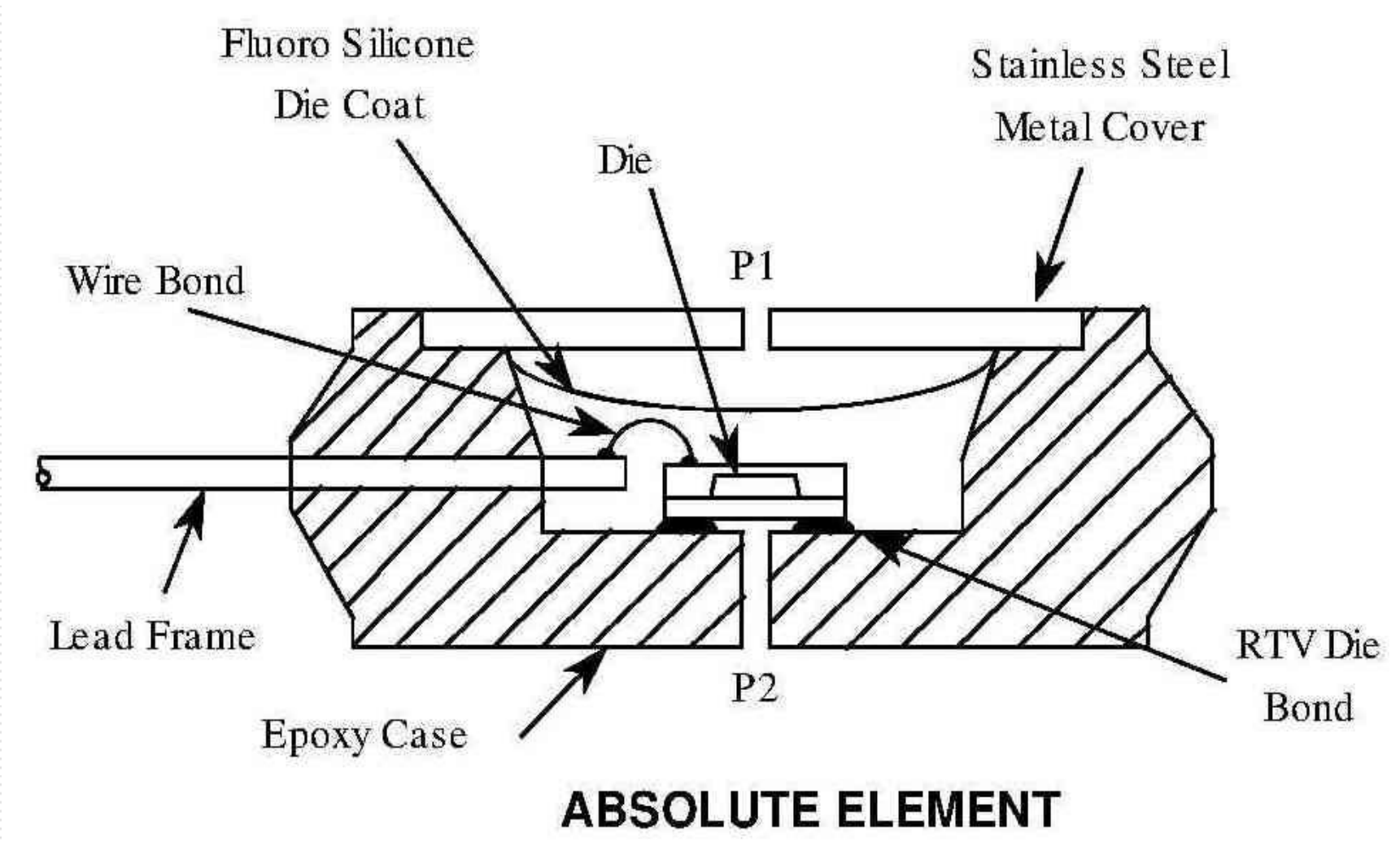


Construction: Cross-Sectional Diagram of Differential/Gauge Pressure Sensing Element



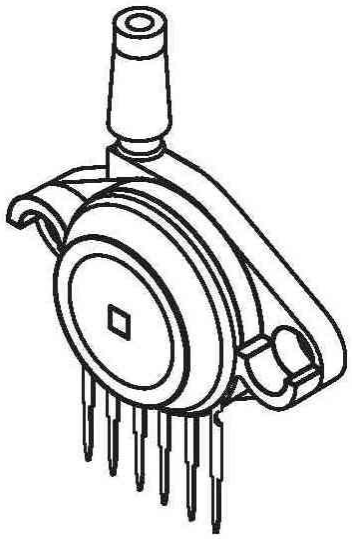
(Source: Data sheet of MPX5700)

Construction: Cross-Sectional Diagram of Absolute Pressure Sensing Element

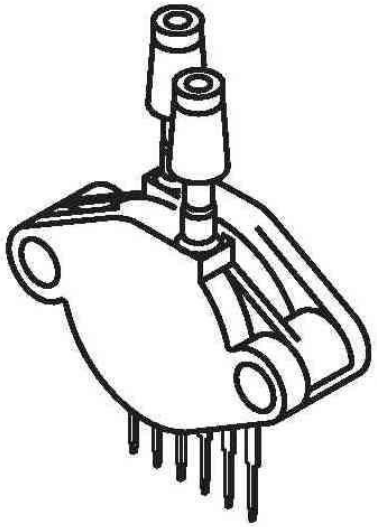


(Source: Data sheet of MPX5700)

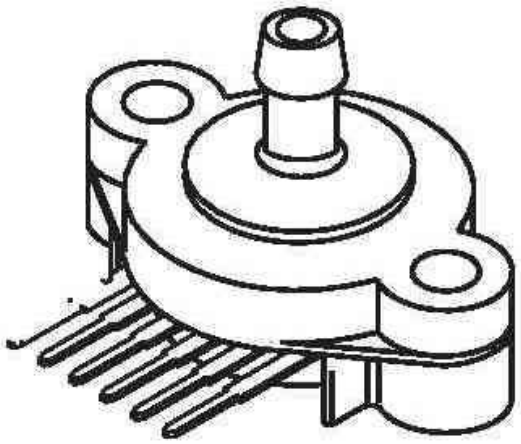
Packages and Pins



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!