The Fascinating World of SMART SENSORS

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SMART SENSORS

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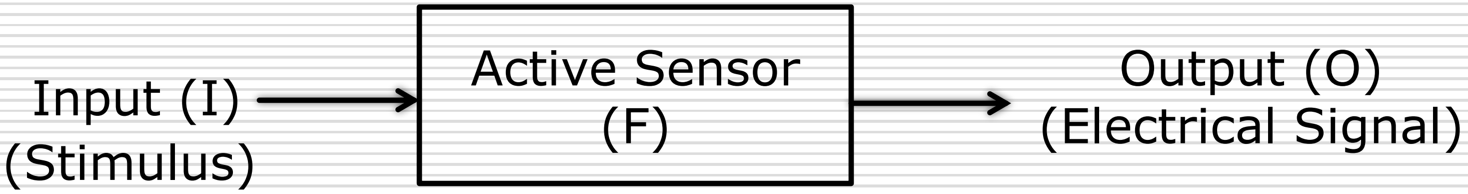
Basics of Smart Sensors
CONTENTS

1. Sensor Basics
2. Signal conditioning or processing
3. Sensor versus Transducer
4. What is a Smart Sensor?
5. Four levels of integration
6. Advantages of Smart Sensors

Active or Generating Sensor

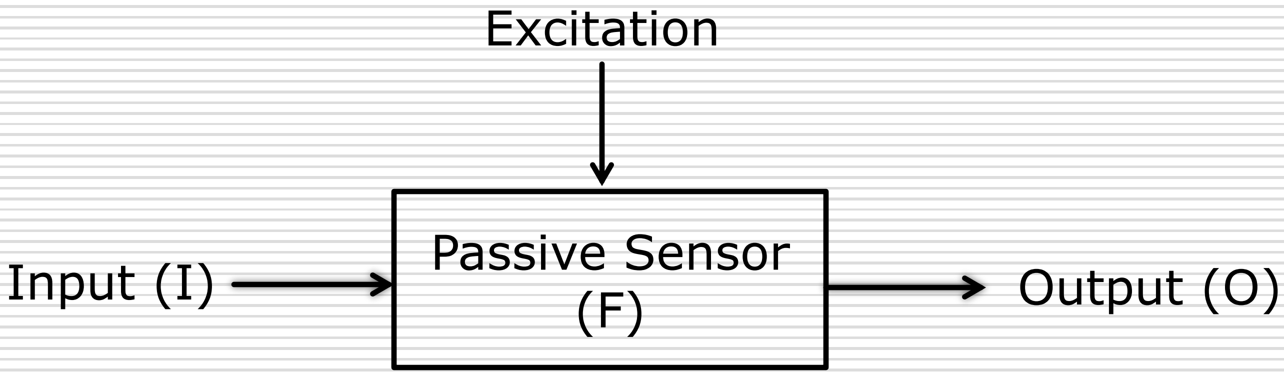


O = F.I.

O α I is preferred

- Stimulus source supplies energy

Passive or Parametric Sensor



$$O = F.I.$$

$O \; \alpha \; I$ is preferred

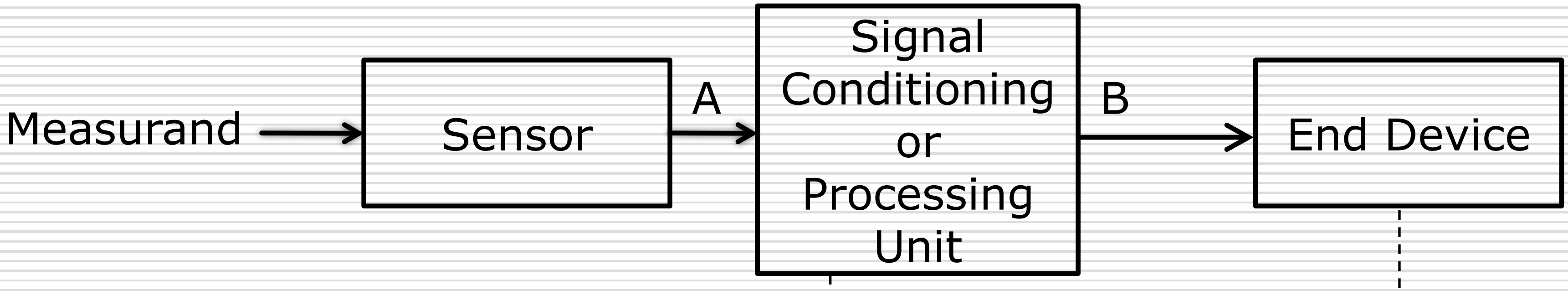
- Excitation is usually a constant voltage
- Sometimes constant current excitation is used
- Excitation source supplies energy

1.1 Signal Conditioning or Processing

- Instrumentation System
- Feedback Control System
- Signal Conditioning or Processing Circuits
  - Electrical Circuits
  - Analog Electronic Circuits
  - Converters

Signal Conditioning or Processing …

Instrumentation System



1. Incompatible magnitude of A

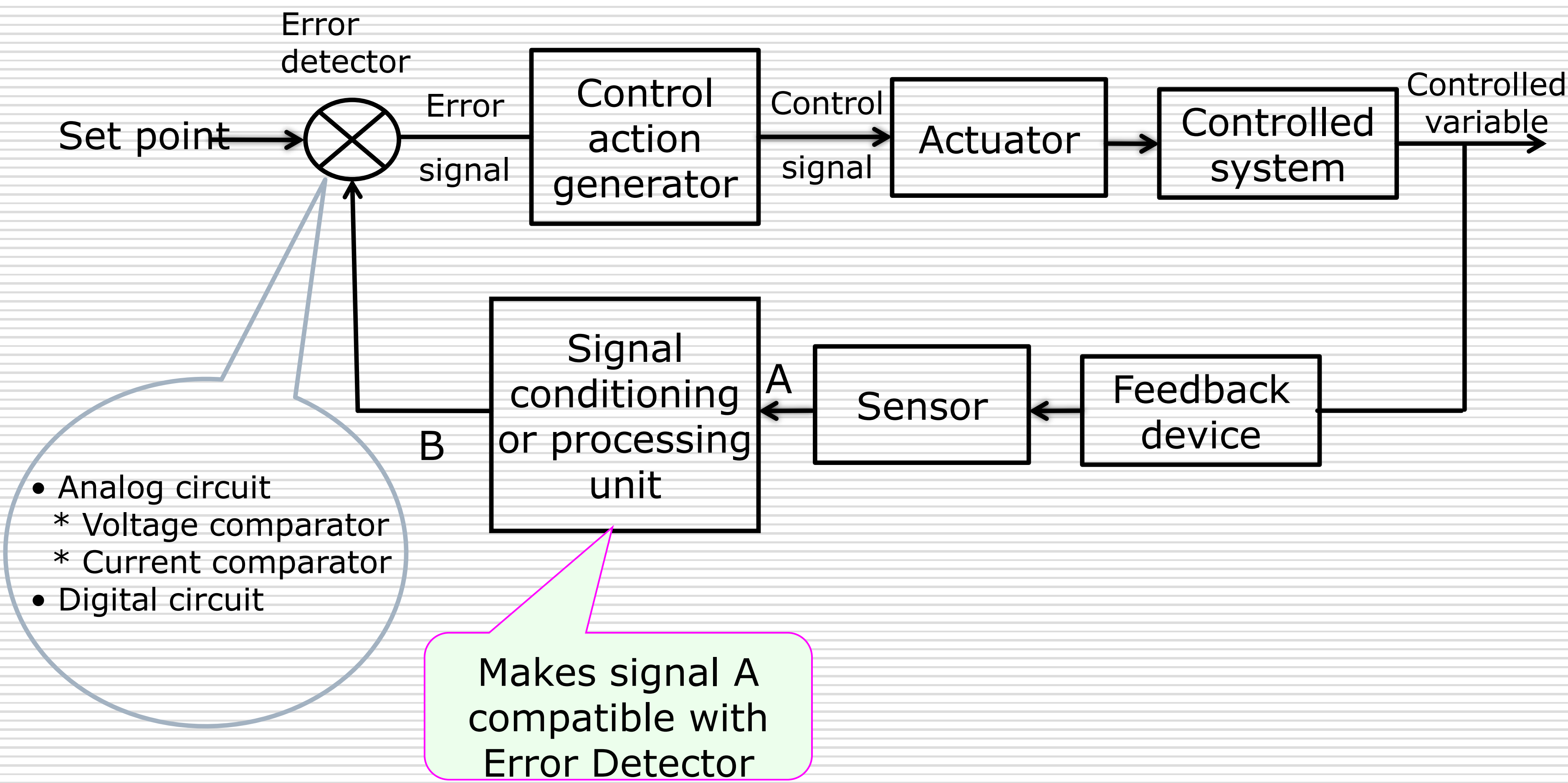
2. Incompatible form of A

3. Conditions or processes signal A to make it compatible with End Device

- Indicating device
- Display device
- Storage device
- Recording device
- Data processor
- Communication port

Signal Conditioning or Processing …

Feedback Control System



Electrical Circuits

- Wheatstone bridge
  - Quarter sensor bridge
  - Half sensor bridge
  - Full sensor bridge
- Potential divider

Signal Conditioning or Processing ... Analog Electronic Circuits

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

Converter Circuits

(a) Analog to Digital Converter (ADC)

(b) Voltage to Frequency Converter (VFC)

1.2

Sensor Versus Transducer

- Sensor: Senses input quantity and gives an electrical output
- Transducer: Converts one form of energy into another form for instrumentation or control
- Input transducer $\Leftrightarrow$ Sensor
- Output transducer $\Leftrightarrow$ Actuator

1.3

What is a Smart Sensor?

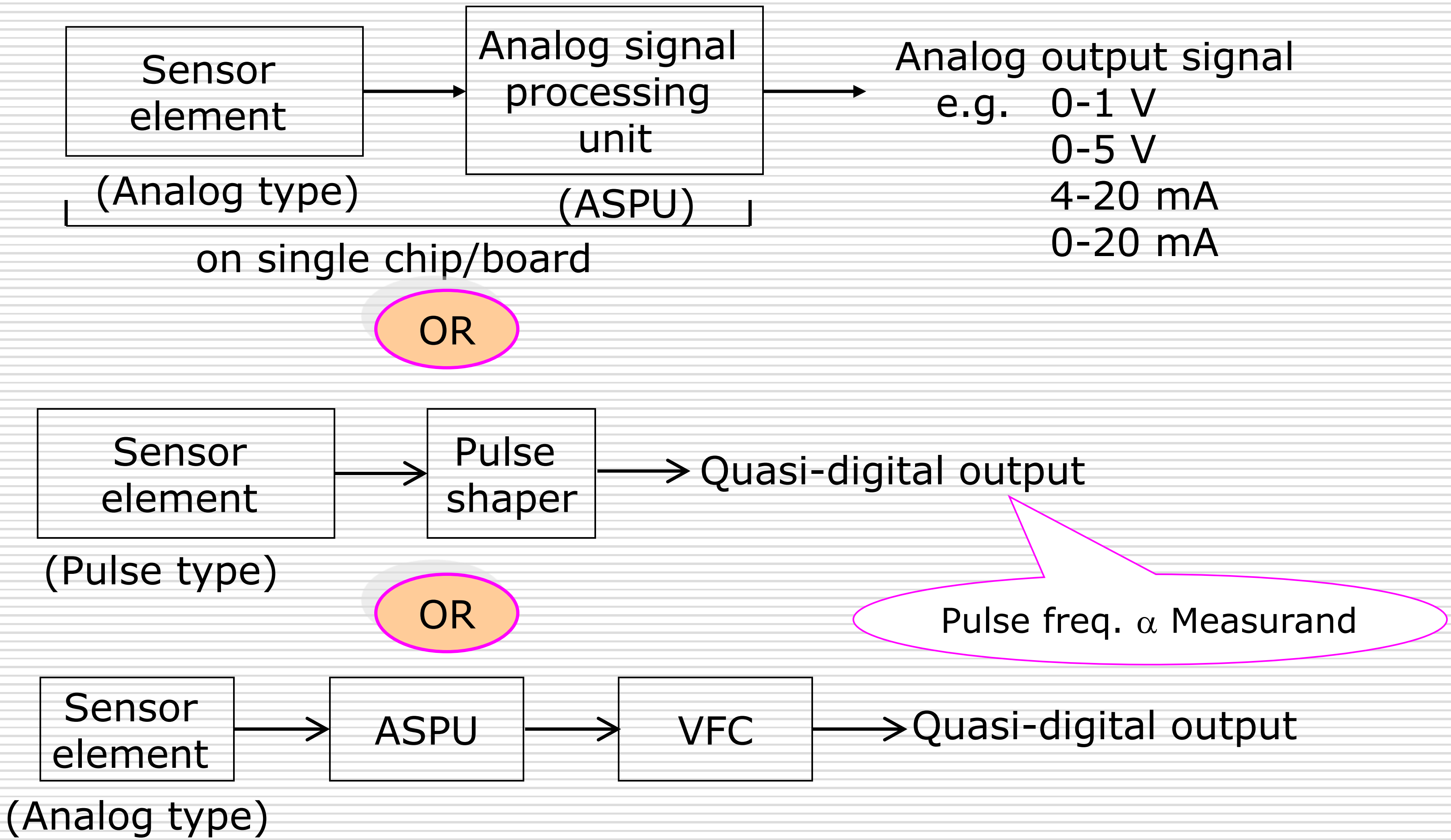
- No standard definition so far.
- A good definition may be as follows:

If the sensor element(s) is(are) integrated with necessary electronics on a single semiconductor chip or board, so that the output signal is fully, or at least more, compatible with the intended end device, then the integrated device is called as Smart Sensor.

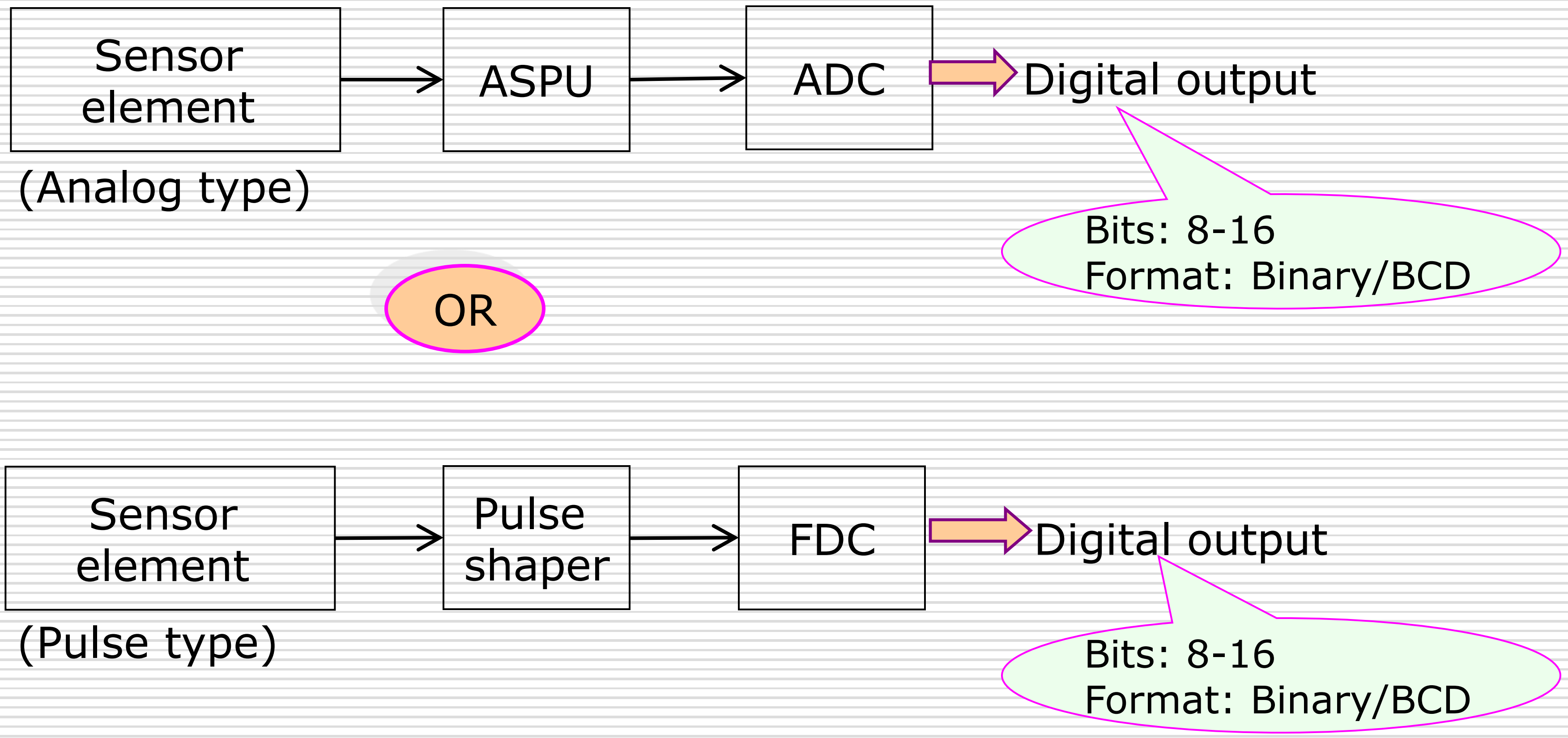
1.4 Four Levels of Integration

- I Level : Smart sensor with analog or quasi-digital output
- II Level : Smart sensor with digital output
- III Level : Intelligent sensor
- IV Level : Network sensor

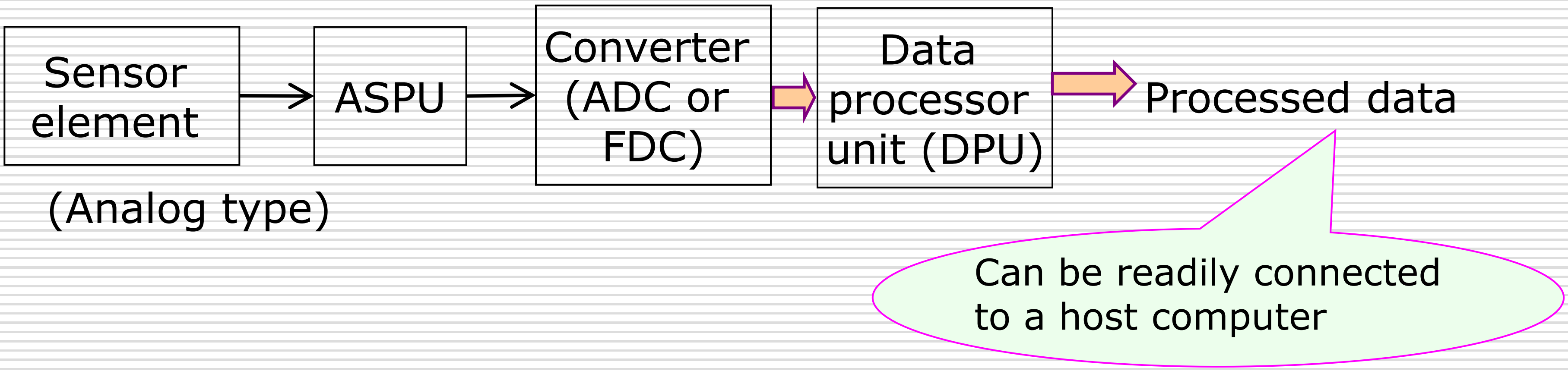
Smart Sensor with Analog or Quasi-Digital Output



Smart Sensor with Digital Output



Intelligent Sensor

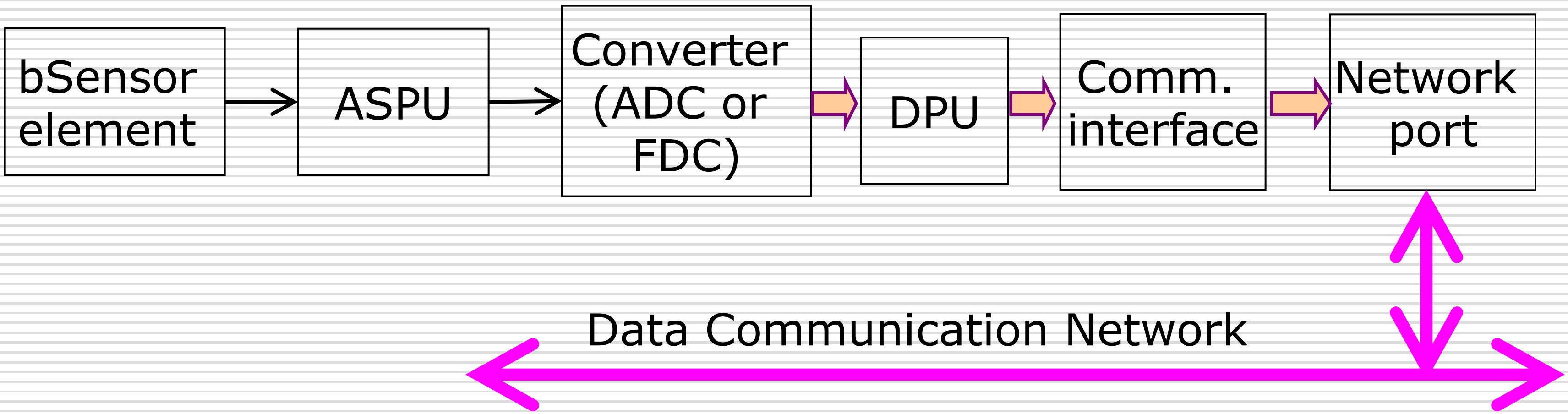


DPU = μP + memory + I/O interface

OR

DSP +memory + I/O interface

Network Sensor



"Output is the processed data on a network port, which allows networking of such smart sensors without any further interface circuits or data manipulation."

1.5 Advantages of Smart Sensors

I Advantages of integrating ASPU with basic sensor

II Additional advantages of integrating ADC

III Additional advantages of integrating DPU

IV Additional advantages of integrating Network Port

Advantages of Integrating ASPU

1. User's Convenience

- No design of SC
- No selection of SC
- No wiring
- Compact size

2. Superior Performance

- Sensor-specific SC circuits perform better
- No external noise, resulting in high SNR
- Negative feedback to reduce nonlinearity
- Compensating circuits to reduce effect of temp./ excitation

3. High Reliability

- Reduced component count
- Reduced wiring

4. Cost Reduction

- Electronics and sensor made concurrently
- Mass production

Additional Advantages of Integrating ADC

- Digital Output
  - Error free transmission
  - Compatibility with digital systems
- Cost Production
  - On-chip ADC is cheaper than external ADC

Additional Advantages of Integrating DPU

- Performance Improvement
  - Linearize response using software
  - Reduce cross sensitivity using software
  - Automatic self-calibration
  - Self diagnostics
- Simpler Interfacing
  - Data formatting as per need
  - DPU can talk easily with external computer
- Internal Data Logging
  - On-chip EEPROM or flash-RAM
  - Storage of field-measurement data
- External data processing reduced
- Flexibility as more functions are performed in software

Additional Advantages of Integrating Network Port

- Ease of networking
- Reduced cost of networking
- Reduced time for networking

2

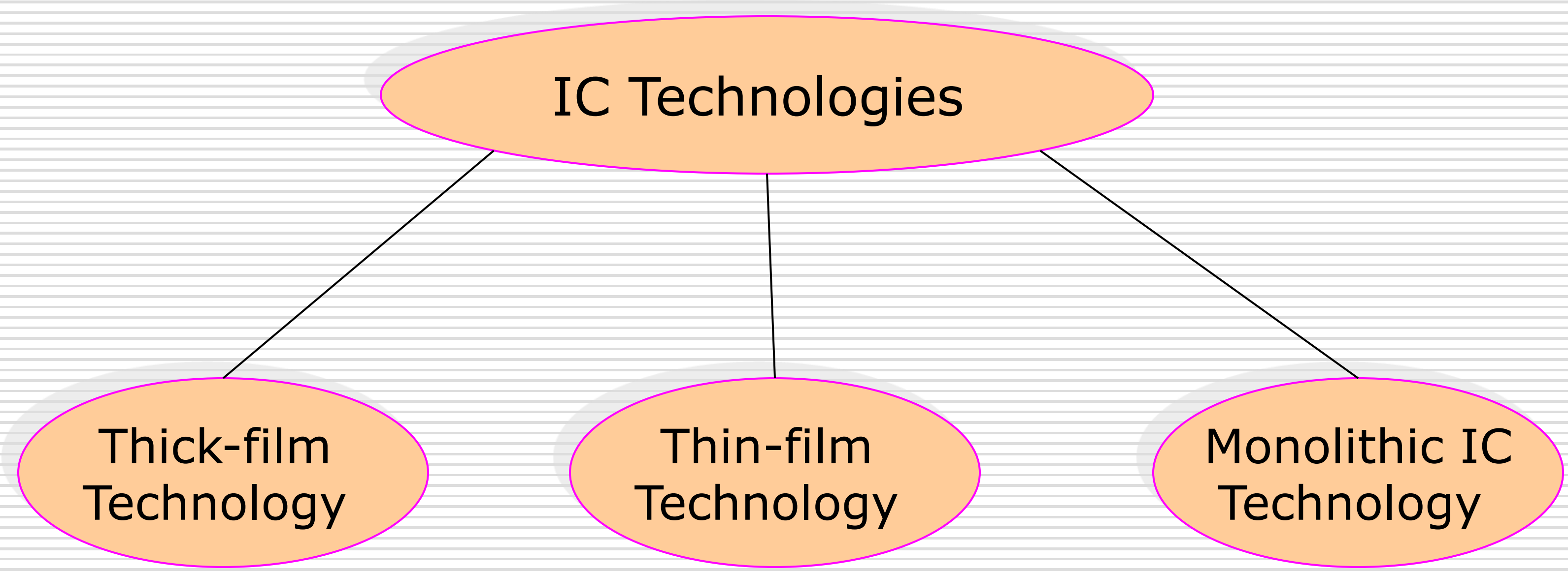
Smart Sensor Technologies

Two types of technologies used:

- IC Technologies
- Micromachining Technologies

2.1

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

2.2

Thick-Film Technology

Process : Print → Dry → Fire → Trim

Material: Paste or Ink + Substrate

Paste : Suspended particles of selected material

Dispersed in an organic solvent

Alongwith glass get

Particle Material:

Conductive → For interconnections & small inductances

Resistive → For resistances and sensors

Dielectric → For capacitors and sensors

Other materials → For sensors and sensor supports

Thick-Film Sensor Elements Successfully Developed / Manufactured

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

Advantages of Thick Film Technologies

- Low-value resistances and high-value capacitances possible
- Small inductances possible
- Components can withstand high temperatures
- Large voltage / current excitation can be used
- Heaters can be integrated
- Compact and sturdy components
- Economical for low-volume production

2.3 Thin-Film Technology

- Film thickness: 1 – 50 μm
- Process: Deposit thin-film by vacuum evaporation or other similar technique
- Patterns: By masking
- No printing, drying and firing unlike thick-film technology

Thin-Film Substrate

- High-purity alumina
- Low-alkalinity glass
- Silicon
- Silicon oxide

Thin-Film Deposition Techniques

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

Thin-Film Materials

- For conductors: Aluminium or gold
- For resistors: Nichrome
- For dielectrics: Silicon dioxide
- For sensors (some materials)
  - Strain gauge: Nichrome, polycrystalline silicon
  - RTD: Platinum
  - Conductivity sensor: Platinum
  - Gas sensor: Zinc oxide
  - Piezo-resistive pressure sensor: Nichrome, polycrystalline silicon
  - Magneto-resistive sensor: Nickel, Cobalt, iron alloys
  - Thermo-anemometric flow sensor: Gold

Thin-Film Components

- Thin-film resistors
- MOS capacitors
- Conductors
- Thin-film sensors

Advantages of Thin-Film Technology

- Almost any metal can be deposited as thin film.
- Miniaturization (smaller dimensions than thick-film devices).
- Add resistances, capacitances and sensors to monolithic IC.
- Economical for high-volume production.

2.4

Monolithic IC Technology

- Processes: Expitaxy, planar diffusion, etching, metallization
- Patterns: Created with photolithography
- Substrate: Usually silicon
- Dimensions: Sub-micrometre
- Capability: R, C, diodes, transistors, conductors

Monolithic IC Process

Step I: Epitaxial growth

Step II: Isolation diffusion

Step III: Base diffusion

Step IV: Emitter diffusion

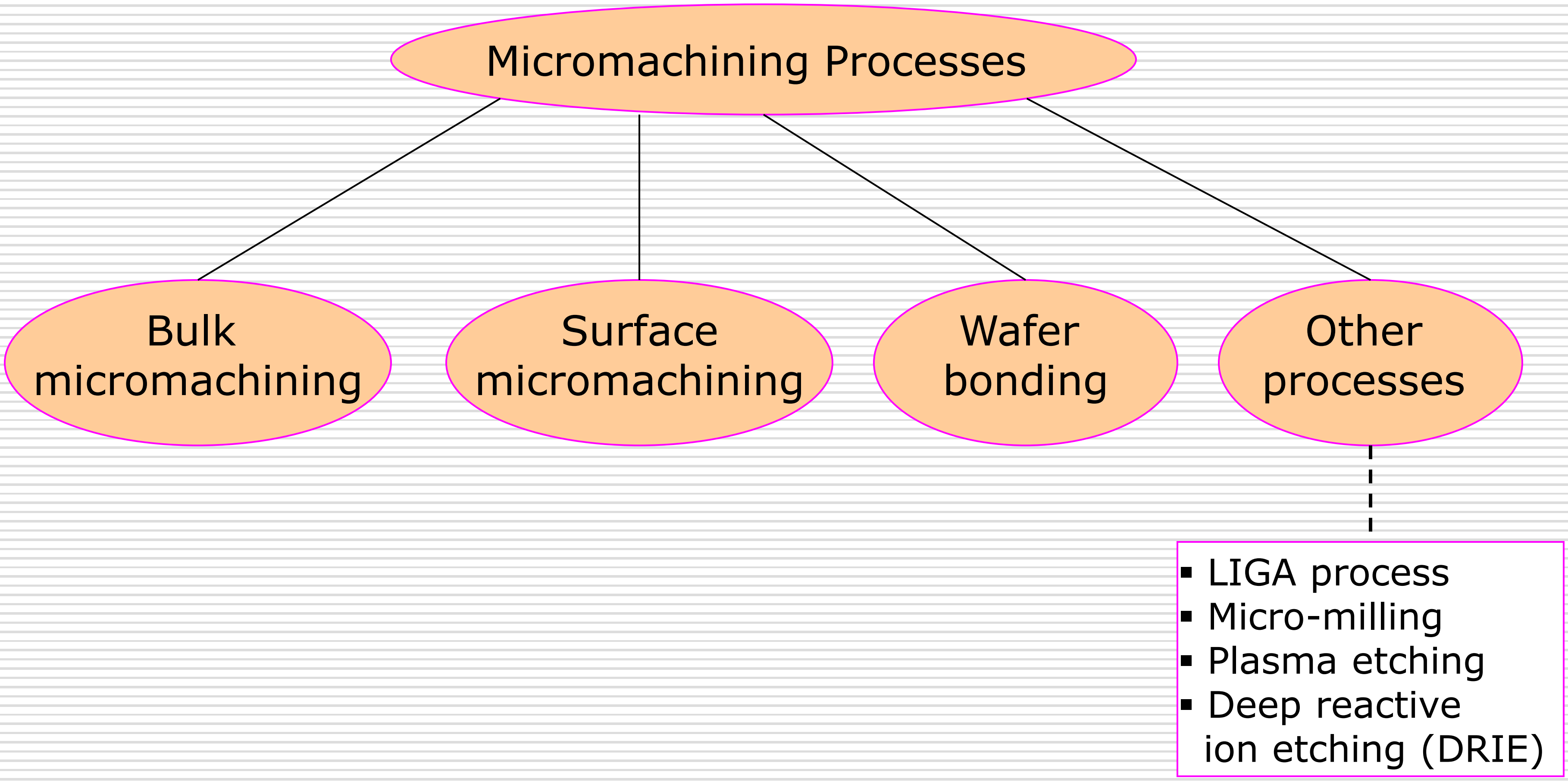
Step V: Metallization

Step VI: Packaging

Comments on Monolithic IC Technology

- Advantages
  - Active and passive devices can be made
  - Very high density of devices
- Limitations
  - A few types of sensors only
  - Resistances in medium-range only
  - Capacitances of small values only
  - No inductances

2.5 Micromachining Technologies & Capabilities



2.6 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
  - Anistropic etching

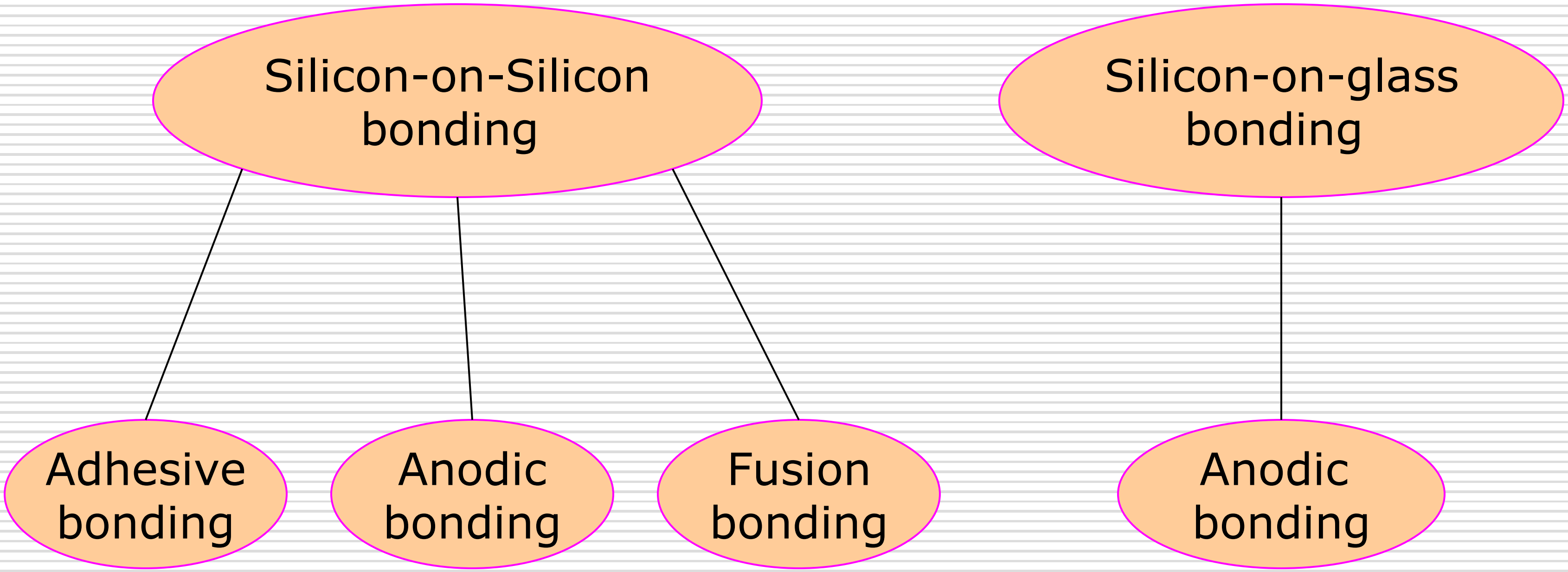
2.7

Surface Micromachining

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

2.8

Wafer Bonding



3 Smart (MEMS) Accelerometer

- Acceleration sensor on a single silicon chip
- MEMS device
- Made by Analog Devices
- Readily available in market
- Three versions

(a) ADXL 150: Single-axis acceleration sensor
DC output

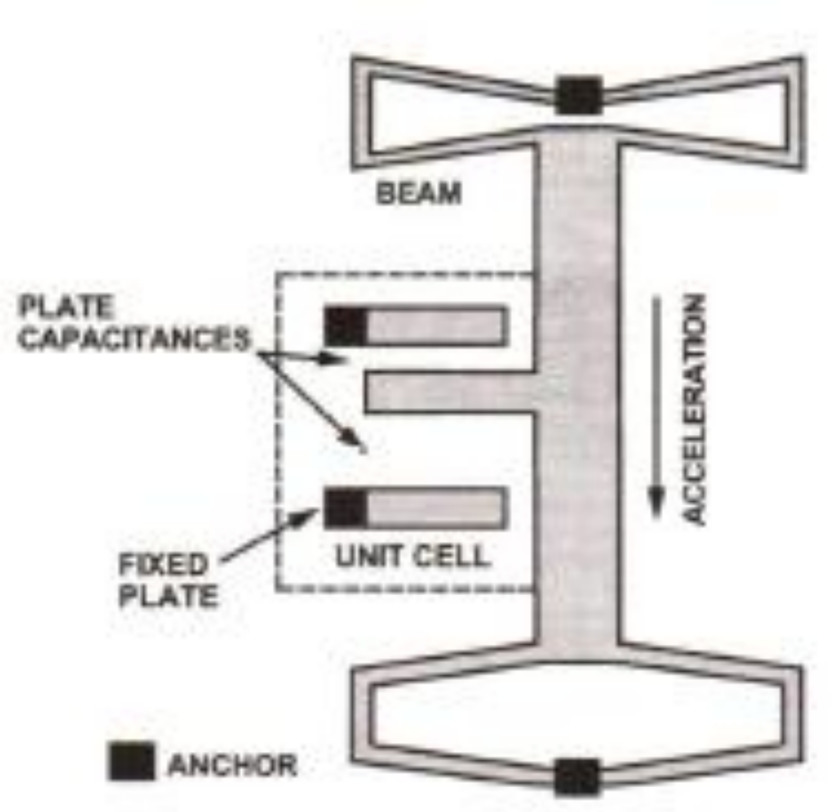
(b) ADXL 250: Dual-axis acceleration sensor
DC output

(c) ADXL 210: Dual-axis acceleration sensor
PWM output

Principle

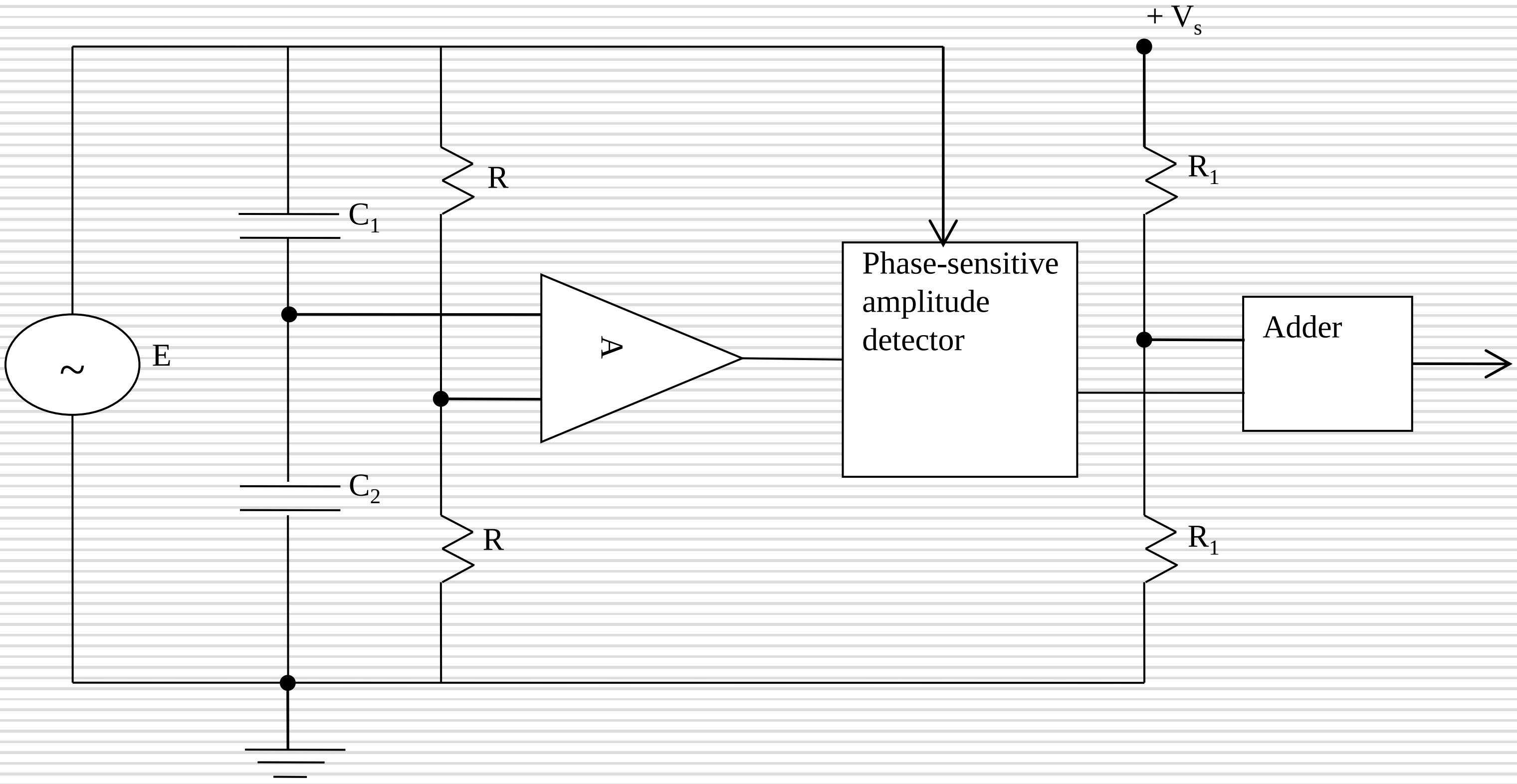
- Well known principle of vibration pickups.
- Mass-spring-damper (mechanical) system converts absolute acceleration of sensor assembly into relative displacement of mass.
- Uses variable-gap capacitive sensor to sense relative displacement of mass w.r.t. base.

Sensor Element



(Source: Data sheets of ADXL150)

ASPU of ADXL 150



For acceleration = 0, C1 = C2 = C

For acceleration = a, C1 = C + △C & C2 = C — △C

Sensor Output of ADXL 150

The d.c. voltage output of the signal processing circuit is given by

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

where

V0 = output voltage

Vs = supply voltage

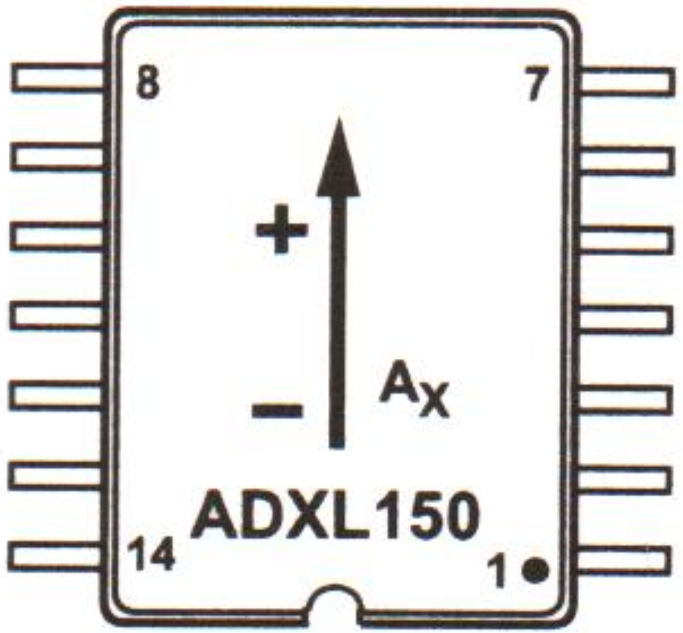
S = sensitivity of the smart sensor in V/g

a = acceleration in g

The maximum value of S.a is less than ± $V_s/2$.
Therefore, the sensor output V_0 is always positive.

Physical Dimensions of ADXL 150

- 14-pin DIL package
- Sensitive axis is Ax



(Source: Data sheets of ADXL150)

4

Sensor Networking

1. Network hierarchy in Industry

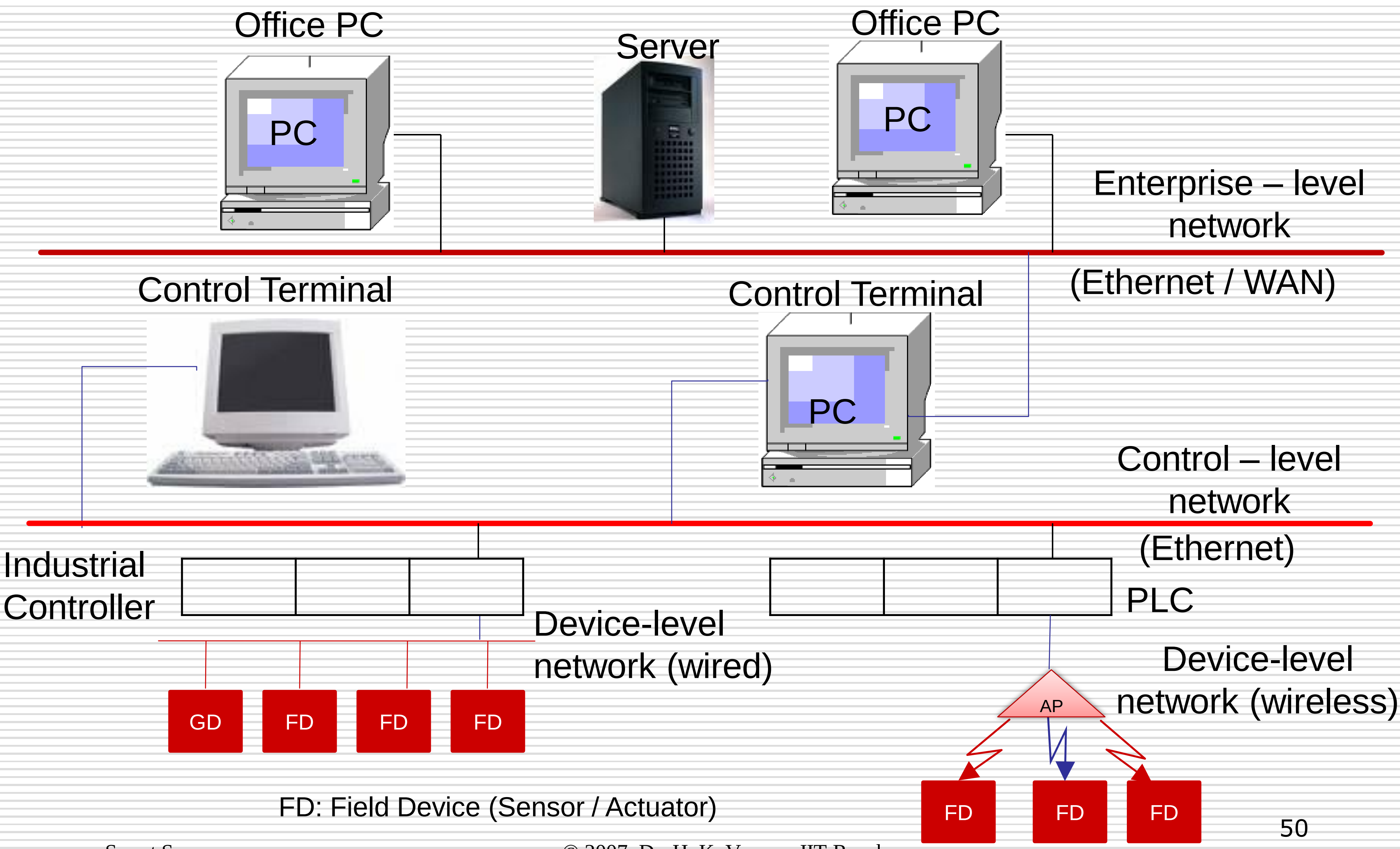
2. Wired Network Technologies / Protocols

3. Wireless Network Technologies / Protocols

4.1 Network Hierarchy in Industry

- **Enterprise Network**
  - Server + office PCs + Workstations in offices
  - Control Terminals in Control room
  - Ethernet if all located within premises
- **Control-Level Network**
  - Control terminals and controllers in Control Room
  - Generally Ethernet
- **Device-Level Network**
  - Field devices: sensors and actuators in plant
  - Wired or wireless network

Networks in Industry: Typical Layout



FD: Field Device (Sensor / Actuator)

Device-Level Networks: Special Requirements

1. Low latency or end-to-end delay
2. Low power consumption or long battery life
3. Low bandwidth
4. High data security
5. High network security

4.2 Wired Network Technologies/Protocols

- Device-Level Networks
  - EIA-RS422
  - EIA-RS485
  - HART Protocol / Standard
  - Fieldbuses
- General Networks
  - Ethernet Technology: IEEE 802.3 Standard

4.3 Wireless Network Technologies/Protocols

- Device-Level Wireless Networks
  - WiFi Technology: IEEE 802.11 Standard
  - Bluetooth Technology
  - Zigbee Technology: 802.15.4 Standard
  - Wireless Fieldbus
- General Wireless Networks
  - WiFi Technology: IEEE 802.11 Standard
  - Bluetooth Technology
  - WiMax Technology: IEEE 802.16 Standard
  - MBWA: IEEE 802.20

ISM Bands

- For Industrial, Scientific & Medical Purposes
- License - free

- Three ISM Bands
  - *ISM-900 : 902 to 928 MHz*
  - *ISM-2.4 : 2.4 to 2.4835 GHz*
  - *ISM-5.8 : 5.725 to 5.850 GHz*

WiFi Technology: IEEE 802.11 Standard

- WiFi stands for Wireless Fidelity
- WiFi Alliance promotes IEEE 802.11 standard
- IEEE 802.11 is a Wireless LAN standard
- WiFi provides wireless internet access in neighbourhood
- WiFi is seen as a wireless alternative of UTP cable for LAN

IEEE 802.11 Specs

IEEE 802.11 – 1997

- Specifies 3 physical media:
  - Infrared: 850 – 950 nm, 1 Mbps & 2 Mbps
  - DSSS: 2.4 GHz band, 1 Mbps & 2 Mbps
  - FHSS: 2.4 GHz band, 1 Mbps & 2 Mbps

IEEE 802.11a – 1999

- Uses 5.8 GHz ISM band with OFDM
- Data rates: 6, 9, 12, 18, 24, 36, 48 and 54 Mbps

IEEE 802.11b – 1999

- Uses 2.4 GHz ISM band with DSSS
- Data rates: 5.5 and 11 Mbps

IEEE 802.11g – 2002

- Uses 2.4 GHz ISM band with DSSS
- Data rates: 6, 9, 12, 18, 24, 36, 48 and 54 Mbps

Zigbee Technology

- Zigbee Alliance promotes the wireless network standard IEEE 802.15.4
- IEEE 802.15.4 is a wireless network standard specially suited for industrial environment (sensor networking)

- Highlights
  - Low bandwidth
  - Low latency
  - Long battery life

IEEE 802.15.4 Specs

- Specifies two frequency bands:
  - Lower band: 900 MHz band
  - Upper band: 2.4 GHz band
- Specifies DSSS for transmission
- Data rates : 20 – 250 kbps
- Range : 10 m

Bluetooth Technology

- Industry standard for short-range radio in office and house environment
- Supported by Bluetooth Special Interest Group
- Wireless alternative of cable connection for computers, mobile, telephone, hand-held devices (PDA) and industrial devices
- Supports voice as well as data
- Operates in 2.4 GHz license free band
- Uses FHSS
- GFSK modulation
- Features are:
  - ➢ Short range (10/100 m for 1mw/100 mw transmitter)
  - ➢ Medium data rate (upto 1 Mbps)
  - ➢ Secure

WiMAX Technology: IEEE 802.16 Standard

- WiMAX stands for Worldwide Interoperability for Microwave Access
- IEEE 802.16 is a Wireless MAN standard
- WiMAX forum promotes IEEE: 802.16 standard
- WiMAX provides last mile wireless broadband internet access
- WiMAX is seen as a wireless alternative of cable and DSL for MAN.

IEEE 802.16 Specs

IEEE 802.16 d – 2004 (Fixed WiMAX)

- Uses OFDM with 256 subcarriers
- Frequency: 2 – 11 GHz, 10 – 66 GHz
- Speed: 70 Mbps

IEEE 802.16 e – 2005 (Mobile WiMAX)

- Uses scalable OFDM
- Multiple Antenna Support through MIMO communication
- Frequency: 2 – 11 GHz, 10 – 66 GHz
- Speed: 70 Mbps

MBWA: IEEE 802.20 Standard

- Mobile Broadband Wireless Access
- Proposed to be **truly mobile** broadband wireless network
- IP based services
- Baseline specifications proposed

➢ Full mobility upto vehicle speed of 250 kmph

➢ Frequency band: licensed, below 3.5 GHz

➢ Packet-based architecture

➢ Low latency

5 Standards for Smart Sensors & Actuators

- **IEEE 1451: Family of standards for:**

  "Smart Transducer Interface for Sensors & Actuators"

  Initiated in 1993

- **Sponsored by**: Technical Committee on Sensor Technology of "IEEE Instrumentation & Measurement Society"

- **Cosponsored by**: National Institute of Standards & Technology (a division of US Department of Commerce)

- **Motivation:** To develop a **smart-transducer interface** as a single communication protocol usable by all sensors and actuators.

IEEE 1451 Family of Standards

Standards Approved by IEEE

- IEEE 1451.1:
- IEEE 1451.2:

Standards Drafted

- IEEE 1451.3:
- IEEE 1451.4:
- IEEE 1451.5:

Theme of IEEE 1451 Standards