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Case Studies of Smart Sensors and Smart MEMS Devices

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Case Study # 1

Smart Temperature Sensor with Voltage Output

or

Three-Terminal IC Temperature Sensor

or

Voltage-Output IC Temperature Sensor

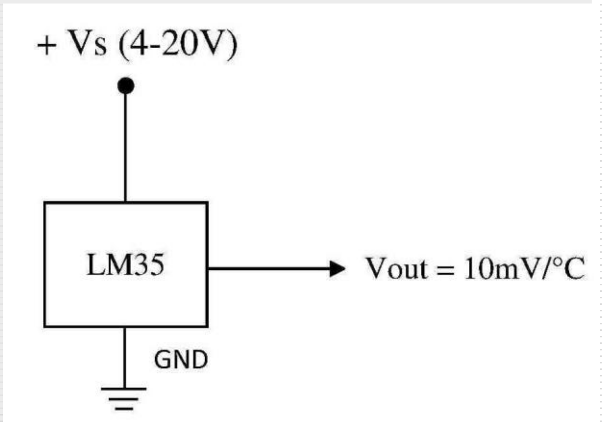
LM35/LM34

Manufacturer: National Semiconductor Corporation

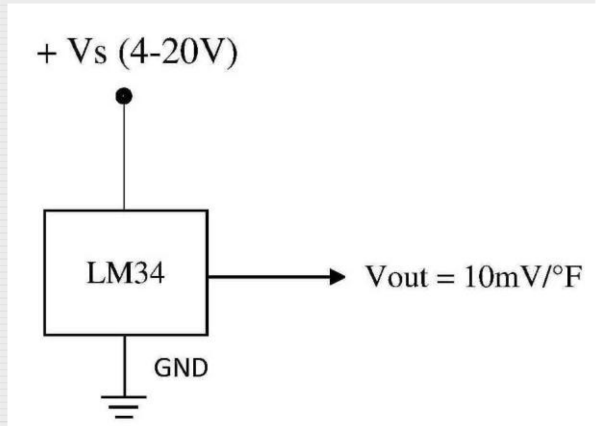
Website: www.national.com

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)
  - Supply Voltage: 4 to 20 V



- LM34: Fahrenheit Temperature Sensor
  - Range: -50 to + 300 °F
  - Output (Sensitivity): 10 mV/°F
  - Accuracy: ±0.4 °F (typical)
  - Linearity: ±0.3 °F (typical)
  - Supply Voltage: 4 to 20 V



Principle of LM35/LM34 (1)

- 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.
- It refers to the energy gap (in electron volts, eV) between the top of the valance band and the bottom of the conduction band.
- In other words, it is the smallest amount of energy in eV required to free on outer-shell electron (or valance electron) from its orbit about the nucleus to become a mobile charge carrier (i.e. free electron).

Principle of LM35/LM34 (2)

- In conductors, the valance band and conduction band overlap, hence they may not have a band gap.
- In insulators, the band gap is too large to be bridged.
- In semiconductors, the band gap is small. Electrons can gain energy to jump from valance band to conduction band by adsorbing either phonons (heat energy) or photons (light energy).
- So, band gap in a semiconductor will decrease as its temperature is raised.

Principle of LM35/LM34 (3)

- This property (temperature sensitivity) of semiconductors forms the basis of all silicon temperature sensors.
- Values of band gap at 300K (i.e., 27°C) for some semiconductors of interest are:

  Si : 1.11 eV
  Ge : 0.67 eV
  Se : 1.74 eV
  GaAs : 1.43 eV
  GaP : 2.26 eV
  GaS : 2.50 eV

Principle of LM35/LM34 (4)

- Voltage across forward-biased base-emitter junction of a transistor changes with temperature and is given by

$$V_{BE} = V_{Go} \left(1 - \frac{T}{To}\right) + V_{BEo}\left(\frac{To}{T}\right) + \frac{nKT}{q} \ln\left(\frac{To}{T}\right) + \left(\frac{kT}{q}\right) \ln\left(\frac{IE}{Is}\right)$$

………………Eq. (1)

where T = Actual temperature in kelvins

To = Reference temperature in kelvins

I_E = Emitter current

I_s = Reverse saturation current

V_{GO} = Band-gap voltage at absolute zero temperature

V_{BEO} = Base-emitter voltage at temperature To and current I_s

K = Boltzmann's constant = $1.38*10^{-23}$ J/K

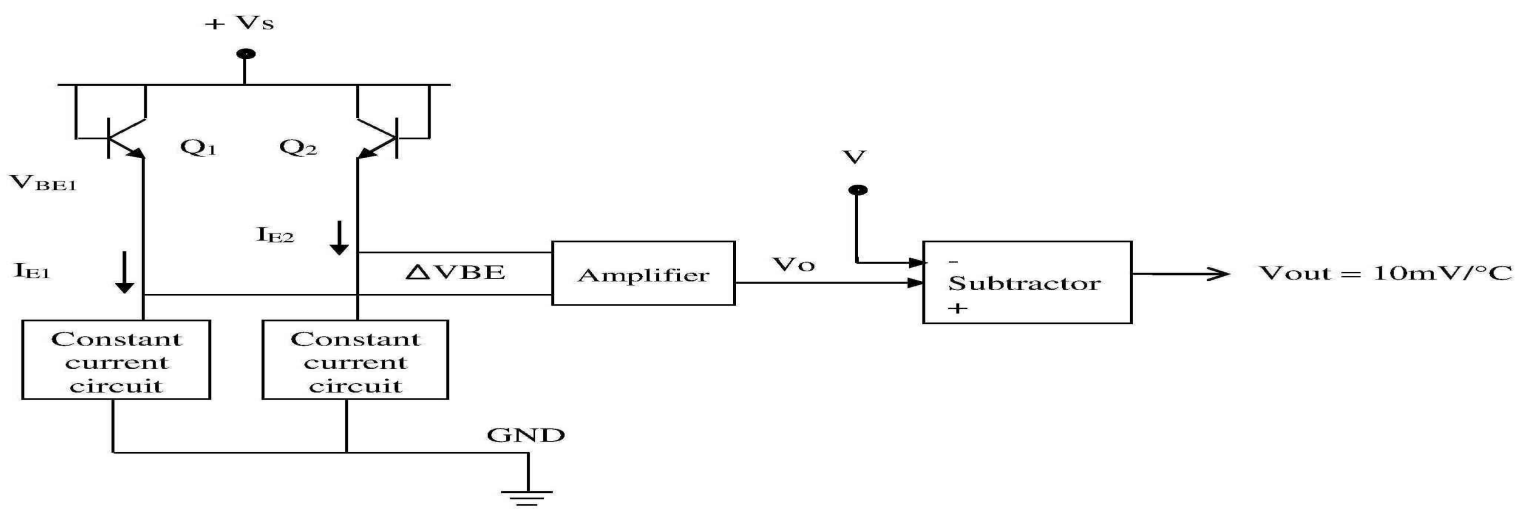
q = Charge on an electron = $1.6*10^{-19}$ C

n = A device -dependent constant

Principle of LM35/LM34 (5)

- Let us have two identical transistors, Q1 and Q2, operating at the same temperature T and same reverse saturation current Is, but working with different emitter currents I_{E1} and I_{E2}, respectively, and connect their base-emitter voltages in differential mode, as shown below.
- Then the differential output voltage is given by

$$\Delta V_{BE} = V_{BE1} - V_{BE2} \qquad \text{.. Eq (2)}$$



Note: This is not the actual circuit of the device; created to explain the underlying concepts.

Principle of LM35/LM34 (6)

If we substitute the values of V_{BE1} and V_{BE2} from equation (1) into equation (2), we get

$$\Delta V_{BE} = V_{BE1} - V_{BE2}$$

$$= \left(\frac{kT}{q}\right) \ln \left(\frac{IE1}{IE2}\right), \quad \text{where} \quad I_{E1} > I_{E2}$$

Thus, ΔV_{BE} is directly proportional to absolute temperature T in kelvins.

Design Values for LM35

(With reference to the Conceptual Circuit Schematic of LM35 shown in next slide)

$I_{E1} = 2 * I_{E2}$ (by design)

So $\Delta V_{BE} = (kT/q) \ln 2 = BT$ *(say)*

where B is another constant given by

$B = (k/q) \ln 2 = 59.8\ \mu V/K$

- ΔV_{BE} is amplified by a factor of 167 to get Vo, so

  $V_o = 59.8\ \mu V/K * 167 = 10\ mV/K$

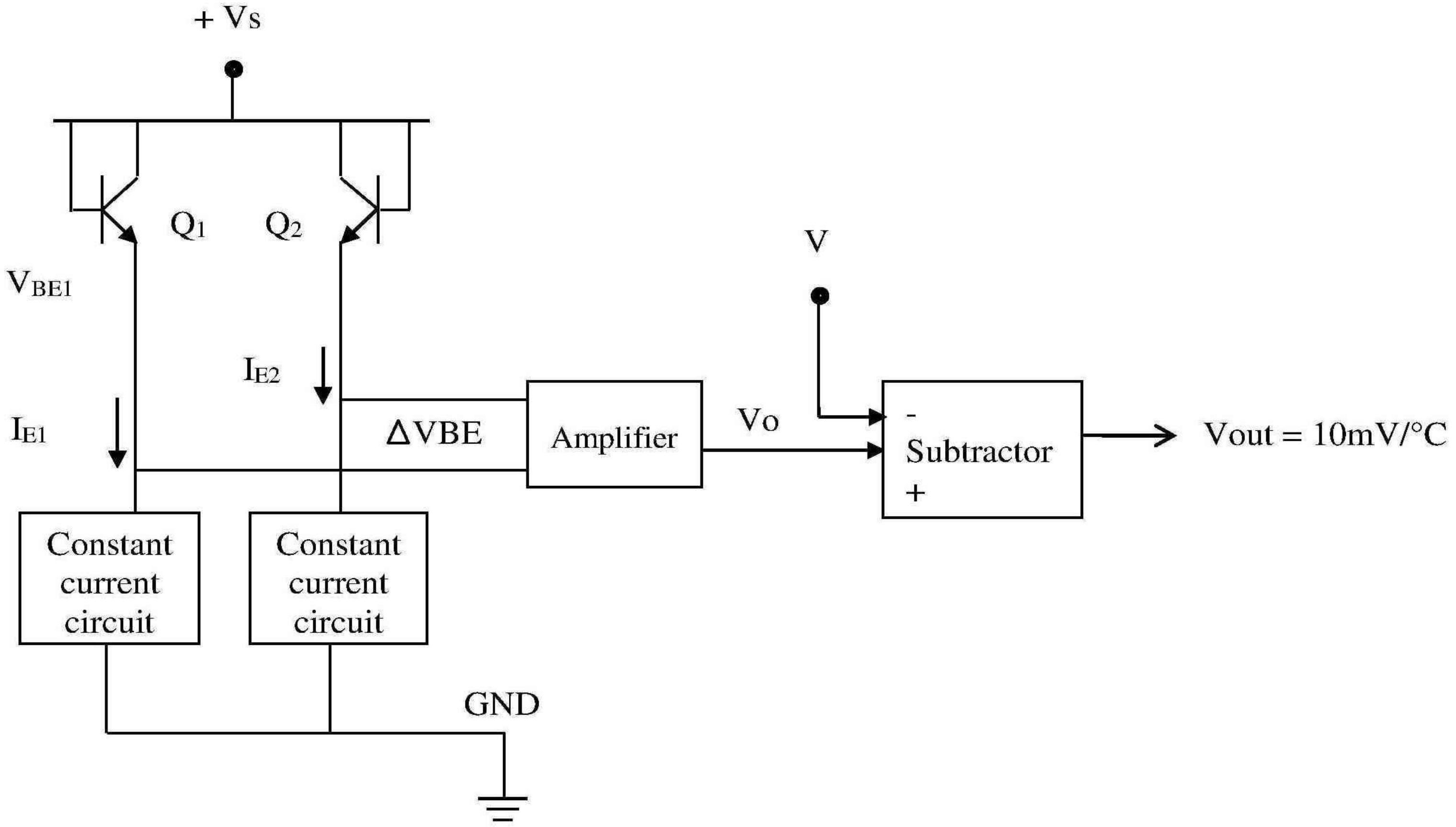
- Corresponding to 0°C or 273K, Vo = 2730 mV
- A fixed voltage V=2.730 V is subtracted from Vo
- *Therefore, final output V_{out} is given by*

  $V_{out} = 10 mV/°C$

So the final output is

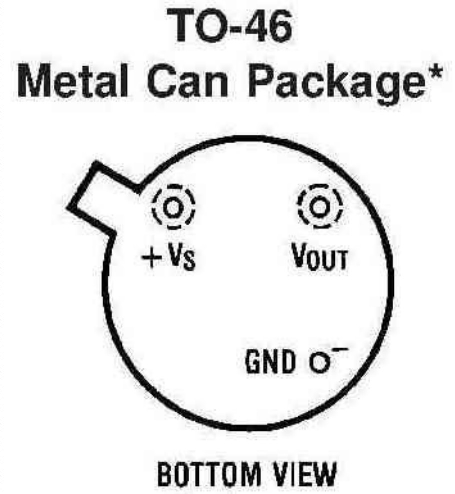
0mV at 0°C, +1500mV at +150°C, -550mV at -55°C)

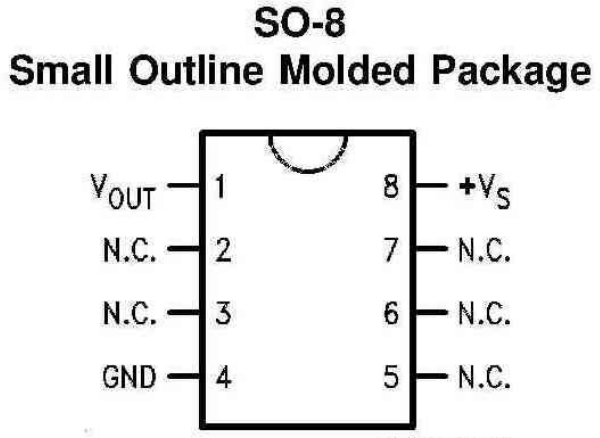
Conceptual Circuit Schematic of LM35

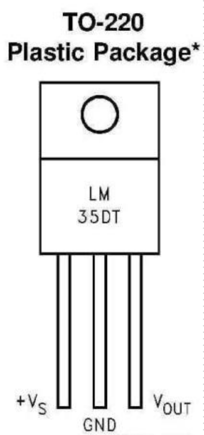


Note: This is not the actual circuit of the device; created to explain the underlying concepts.

Packages and Pins of LM35



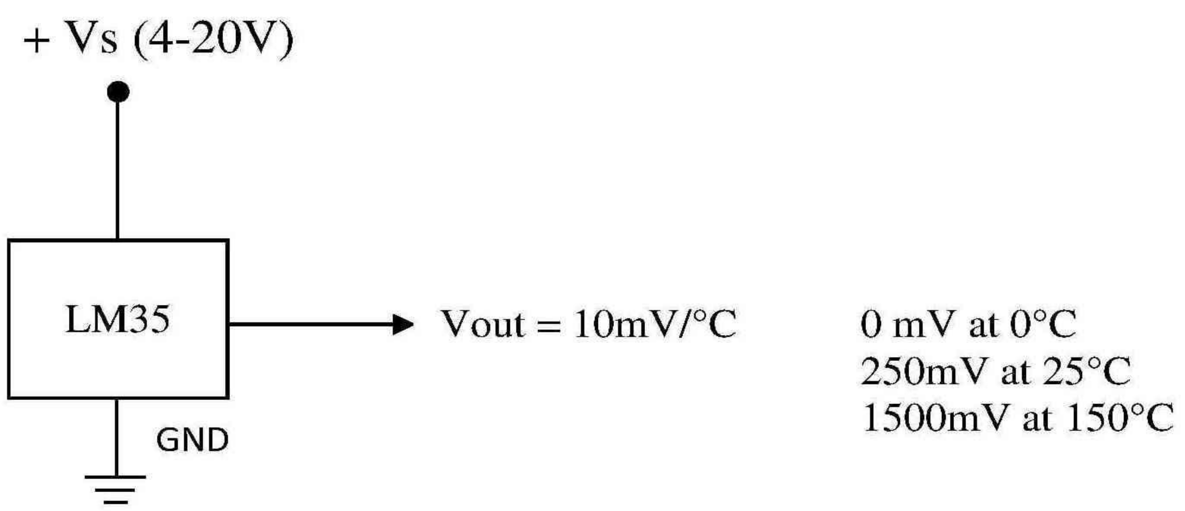




LM35 Application Circuits (1)

1. Circuit for sensing positive temperatures only

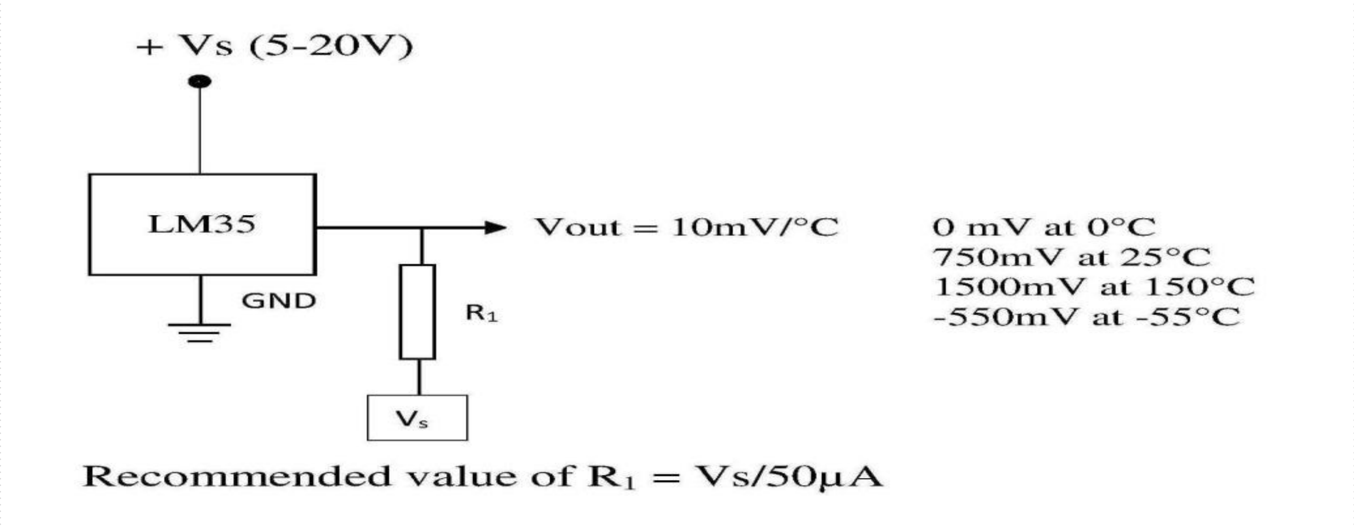
- Uses single power supply (Vs only)
- Output is always positive for positive temperatures
- For input temperature of 0°C, Vout = 0 mV
- For input temperature of 25°C, Vout = 250 mV
- For input temperature of 150°C, Vout = 1500 mV



LM35 Application Circuits

2. Circuit for sensing temperature over full range

- Uses dual power supply (+Vs and -Vs)
- Output is +ve for +ve temperatures and –ve for –ve temperatures
- For input temperature of 0°C, Vout = 0 mV
- For input temperature of 150°C, Vout = 1500 mV
- For input temperature of -55°C, Vout = -550 mV



Case Study # 2

Smart Temperature Sensor with Current Output

or

Two-Terminal IC Temperature Sensor

or

Current-Output IC Temperature Sensor

AD590/AD592

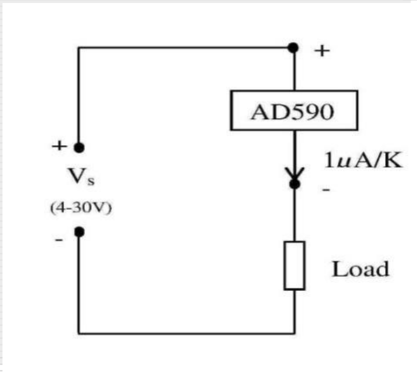
Manufacturer: Analog Devices

Website: www.analog.com

Major Specifications

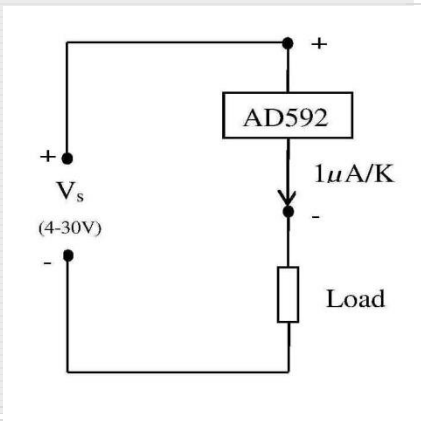
❑ AD590: Two-Terminal IC Temperature Sensor

- Range: -55°C to +150°C
- Output (Sensitivity): 1μA/K
- Accuracy: ±0.5 °C (typical)
- Linearity: ±0.3 °C (over full range)
- Power Supply Range: 4V to 30V



❑ AD592: Two-Terminal Precision IC Temperature Sensor

- Range: -25°C to + 105°C
- Output (Sensitivity): 1μA/K
- Accuracy: ±0.5 °C (typical)
- Linearity: ±0.15 °C (over full range)
- Power Supply Range: 4V to 30V



Note that AD592 has better linearity but smaller temperature range than AD590

Principle of AD590/592

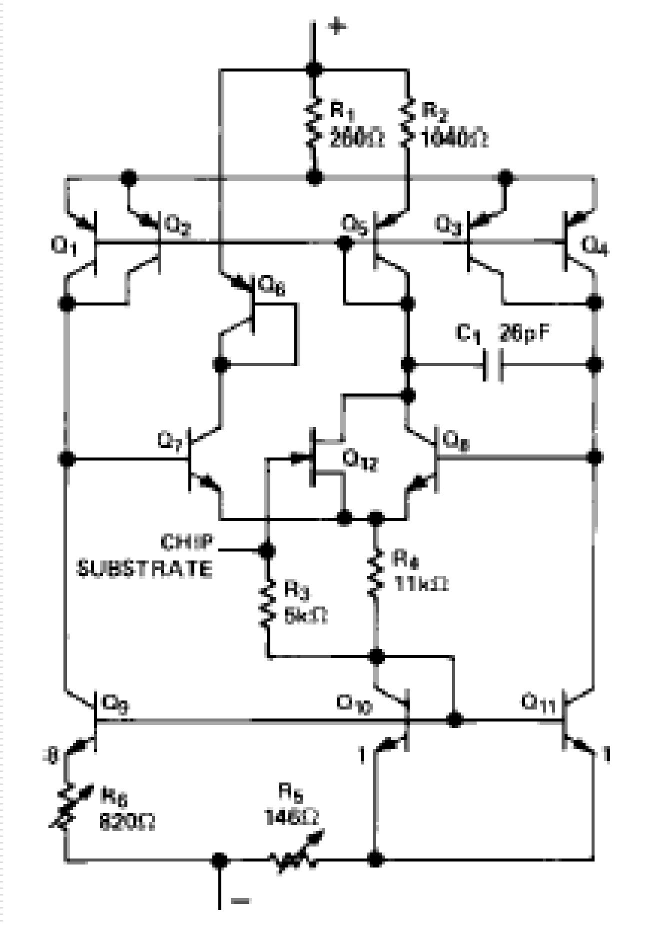
- These sensors, like LM35 and LM34, are also based on temperature sensitivity of band gap voltage of silicon junction. The detailed principle can be seen from the Case Study of LM35/34.
- So the following equation is applicable to AD590/AD592 too:

$$\Delta V_{BE} = V_{BE1} - V_{BE2}$$
$$= \left(\frac{kT}{q}\right) \ln \left(\frac{IE1}{IE2}\right), \quad \text{where} \quad I_{E1} > I_{E2}$$

- However, ΔV_{BE} is converted here to a proportional total device current, which is the output current signal proportional to absolute temperature T, namely

$I_{out} = 1\mu A/K$

Circuit Diagram of AD590



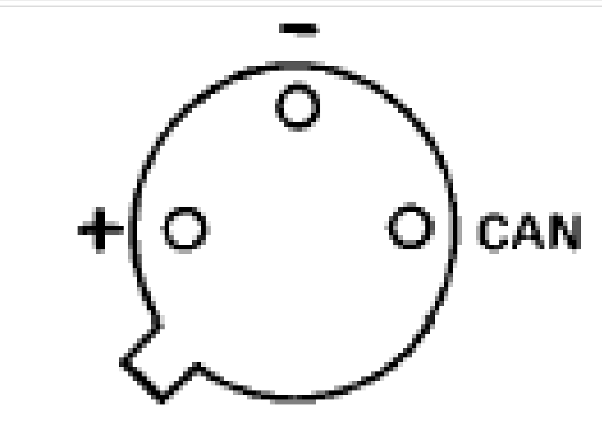
(Source: Data Sheet of AD590)

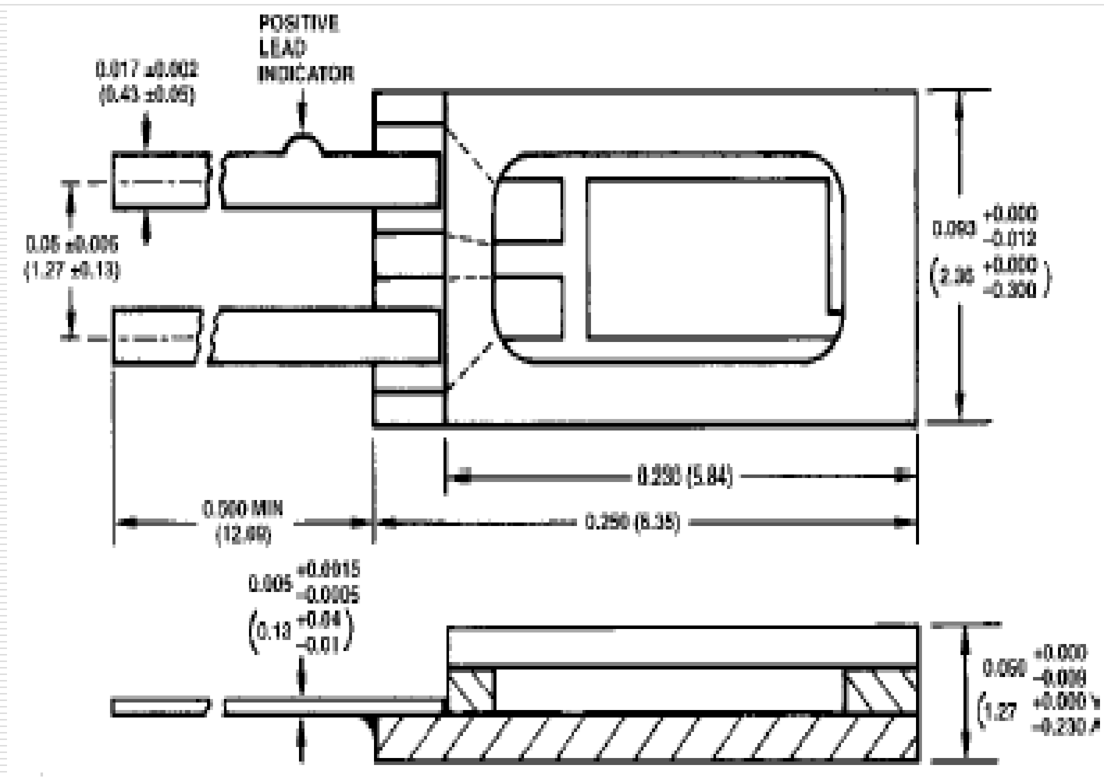
AD590........

Packages and Pins of AD590

Flat Package

TO52 Package

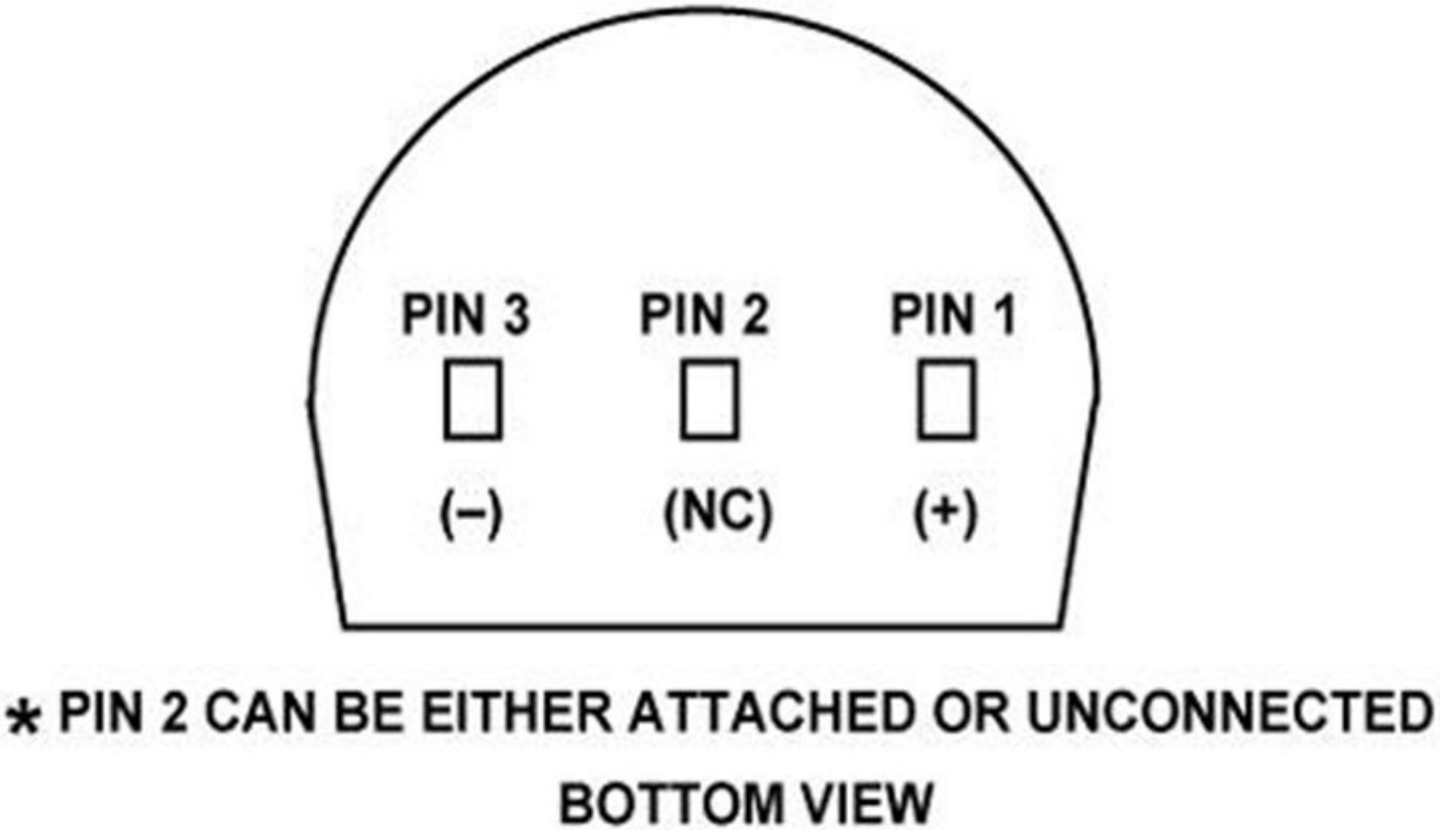




(Source: Data Sheet of AD590)

Package and Pins of AD592

TO-92 Package



(Source: Data Sheet of AD592)

Case Study # 3

Smart Humidity and Temperature Sensor

SHT7x / SHT1x

Manufacturer: Sensirion Corporation

Website: www.sensirion.com

Salient Features

- Senses relative humidity and temperature
- Also measures dew point
- 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
- Digital serial output
- Self calibration
- Evaluation kits from the manufacturer

Performance Features

- Fast response
- Ultra low power consumption
- Automatic power down feature
- Excellent long term stability
- Excellent performance-to-price ratio
- Insensitivity to external disturbance (EMC)
- Fully calibrated digital output
- Data with CRC bits

Devices in SHTxx Series

Pin-Type Package

SHT 71

SHT 75

SMD Package

SHT 10

SHT 11

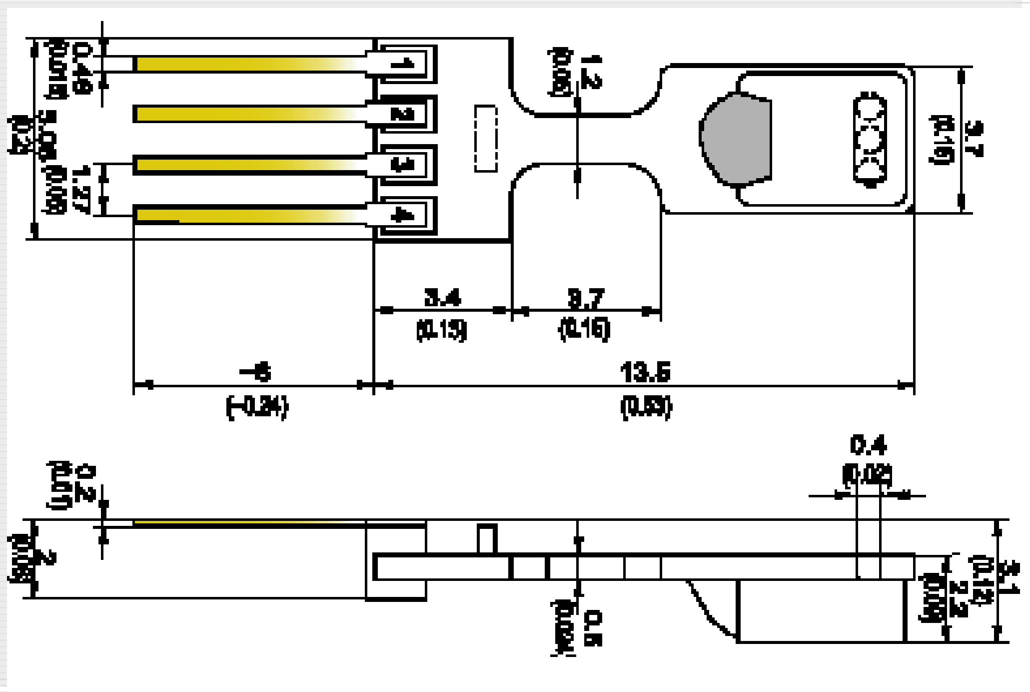
SHT 15

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% for all**				
RH Stability	**<0.5% per year for all**				
Temp. Accuracy @ 25^0C	± 0.4^0C	± 0.3^0C	± 0.5^0C	± 0.4^0C	± 0.3^0C
Temp. Range	**-40 to +120^0C for all**				
Power Consumption	30μW	20μW	30μW	30μW	30μW
Response Time	**4s for all**				
Package	4-Pin SIL		SMD (LCC)*		

**Surface mounting device (leadless chip carrier)*

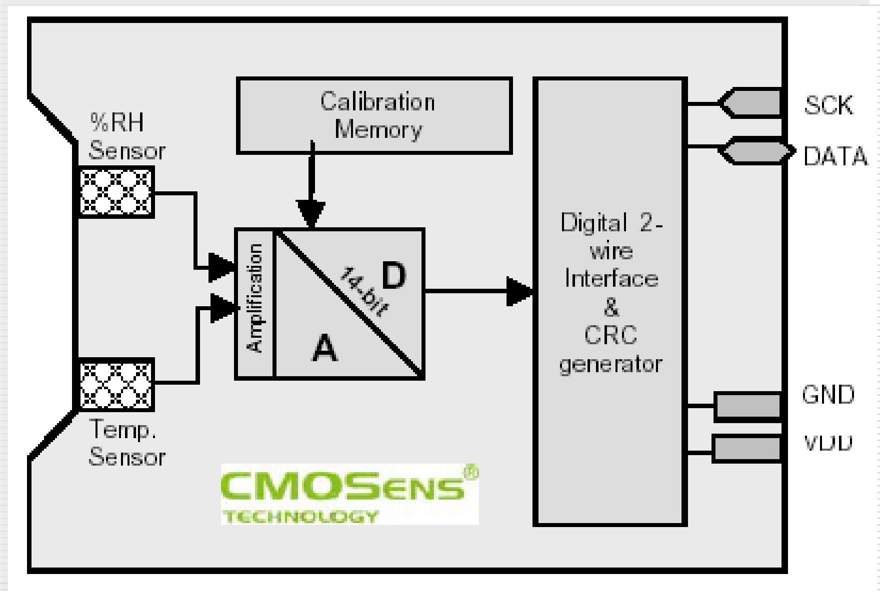
Dimensions of SHT7x



(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

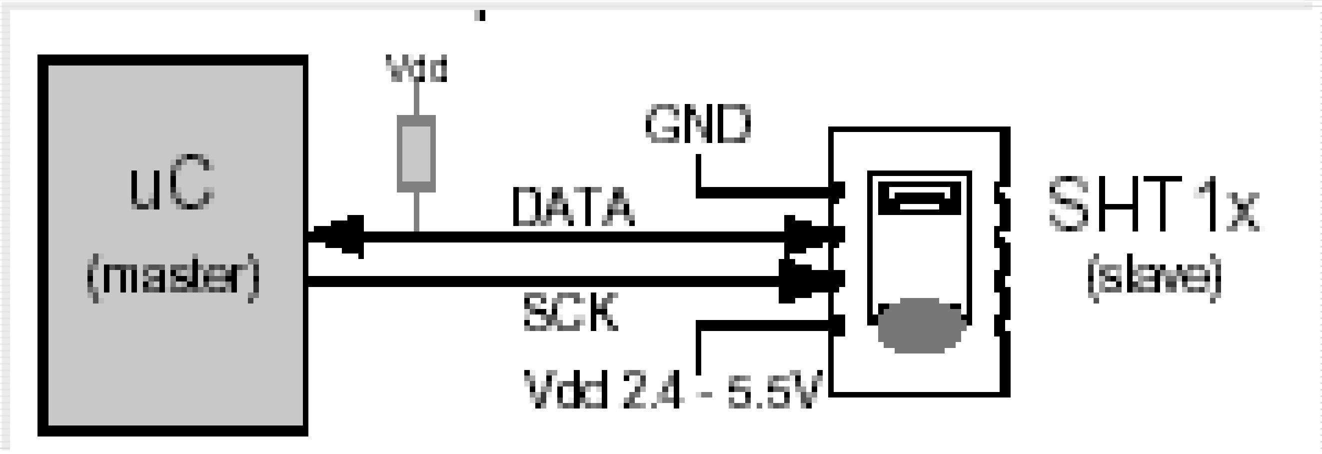


Serial interface of SHTxx is similar to but not compatible with I²C

On-Chip Circuitry

- Amplifiers for amplifying outputs of sensors
- 14-bit ADC for analog to digital conversion
- Serial interface circuit for 2-wire serial transmission
- 8-bit CRC generator for error control
- Calibration circuit for self calibration
- Calibration memory for storing calibration coefficients

Interfacing SHTxx with µC



(Source: Data sheet of SHTxx)

SCK: Serial clock, used to synchronize the communication between microcontroller and SHTxx

DATA: Tristate pin, used to transfer data in and out of SHTxx
Changes after the falling edge of SCK
Valid on the rising edge of SCK

Vdd: Power supply may be decoupled with a 100nF capacitor across pins Vdd and GND

Case Study # 4

Smart Acceleration Sensor

or

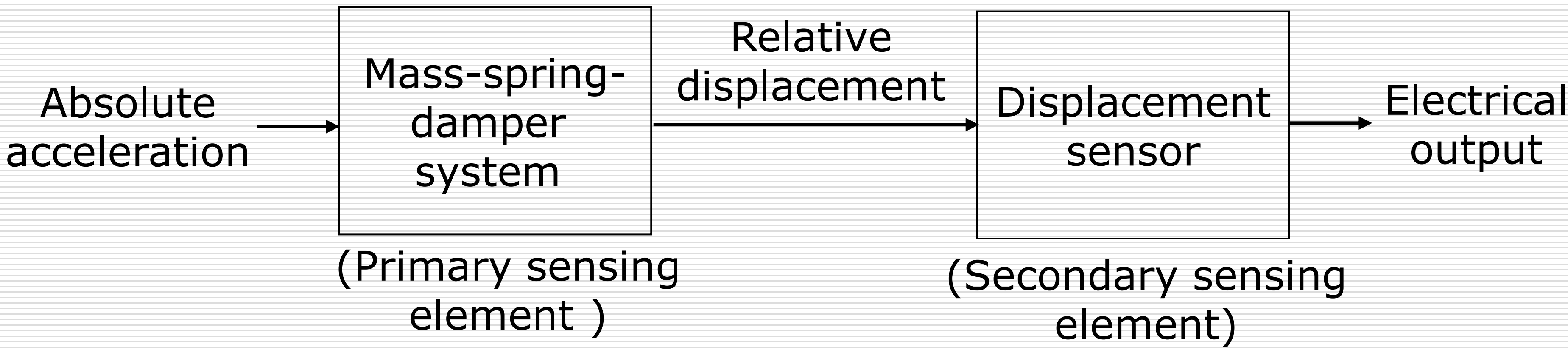
iMEMS Accelerometer

ADXL
150/250/210/311

Manufacturer: Analog Devices

Website: www.analog.com

Basic Principle of Acceleration Sensors



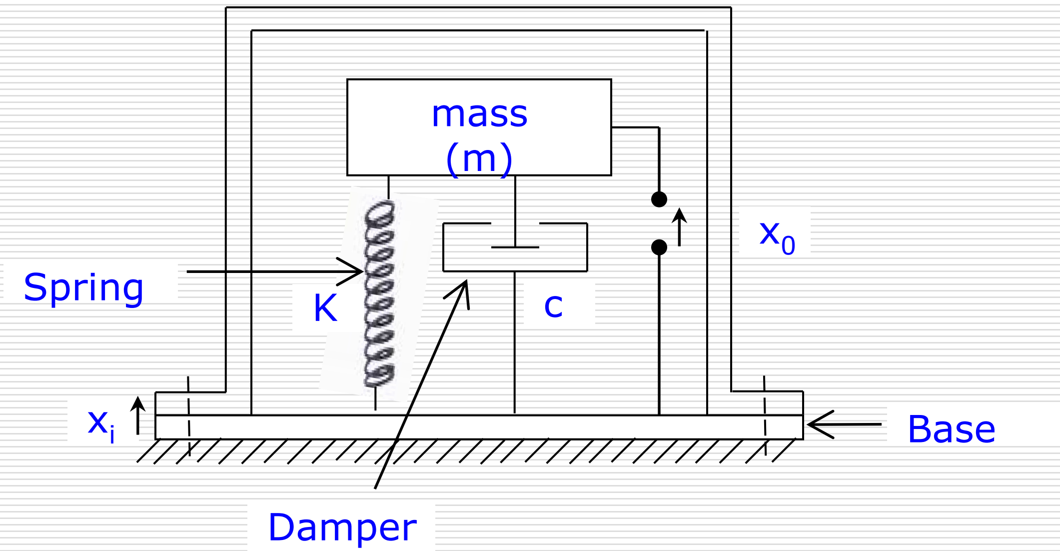
Displacement Sensor Options

(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

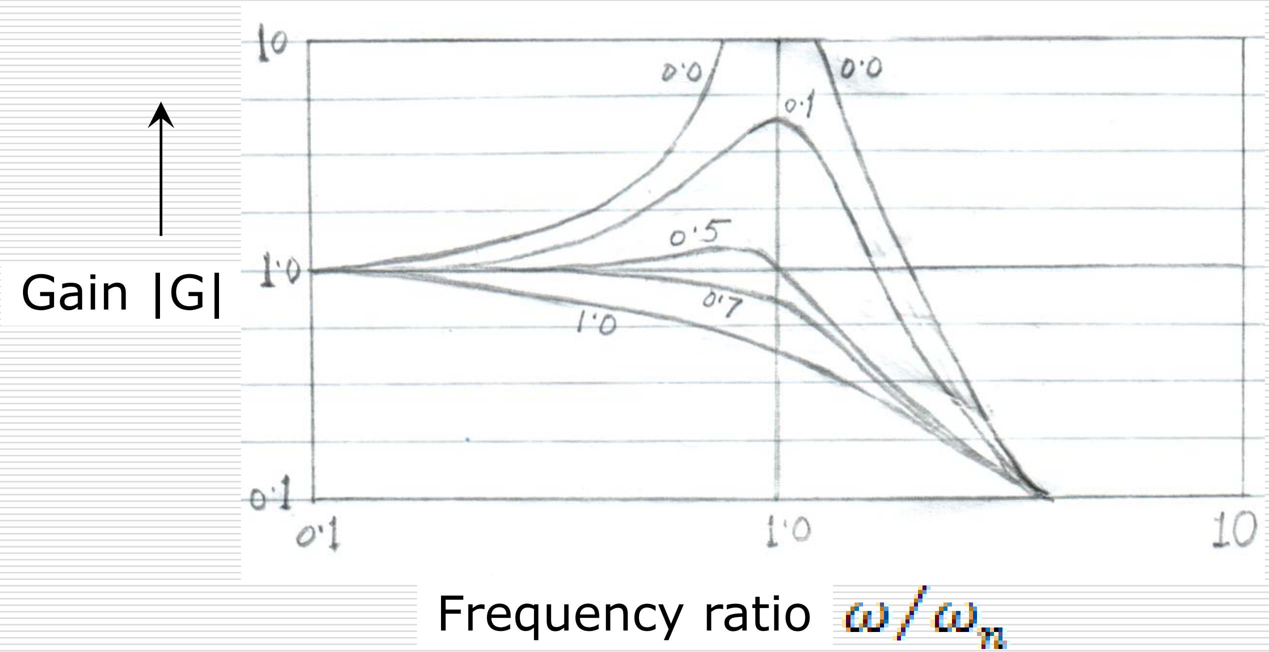
$$G(j\omega) = \frac{1/\omega_n^2}{1 + \left(j\omega/\omega_n\right)^2 + 2j\,\xi\left(\omega/\omega_n\right)}$$

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-Pin leadless chip carrier (LLC) package
  PWM output
- ADXL 345: Three-axis
  14-Pin land grid array (LGA) package
  Digital serial output (SPI and I^2C)

)

Common Features of ADXL Series

- MEMS sensing element and ASPU on a single IC chip
- 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)
- Single-supply operation
- Large frequency bandwidth
- Bandwidth adjustment with a single capacitor
- Output is ratiometric to supply voltage
- Self test feature
- 1000 g shock survival
- MEMS is fabricated using surface micromachining process and electronic circuitry with monolithic IC technology.

Principle of ADXL-150

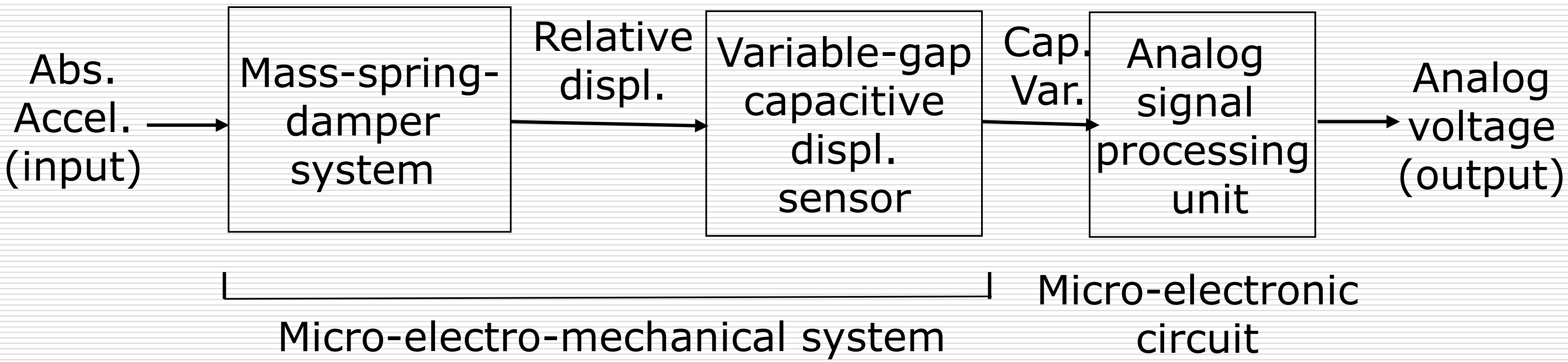
- A mass-spring-damper (MSD) system converts absolute acceleration of the mass to relative displacement of the mass with respect to the base (silicon substrate).

- A variable-gap capacitive sensor converts this relative displacement to capacitance variation.

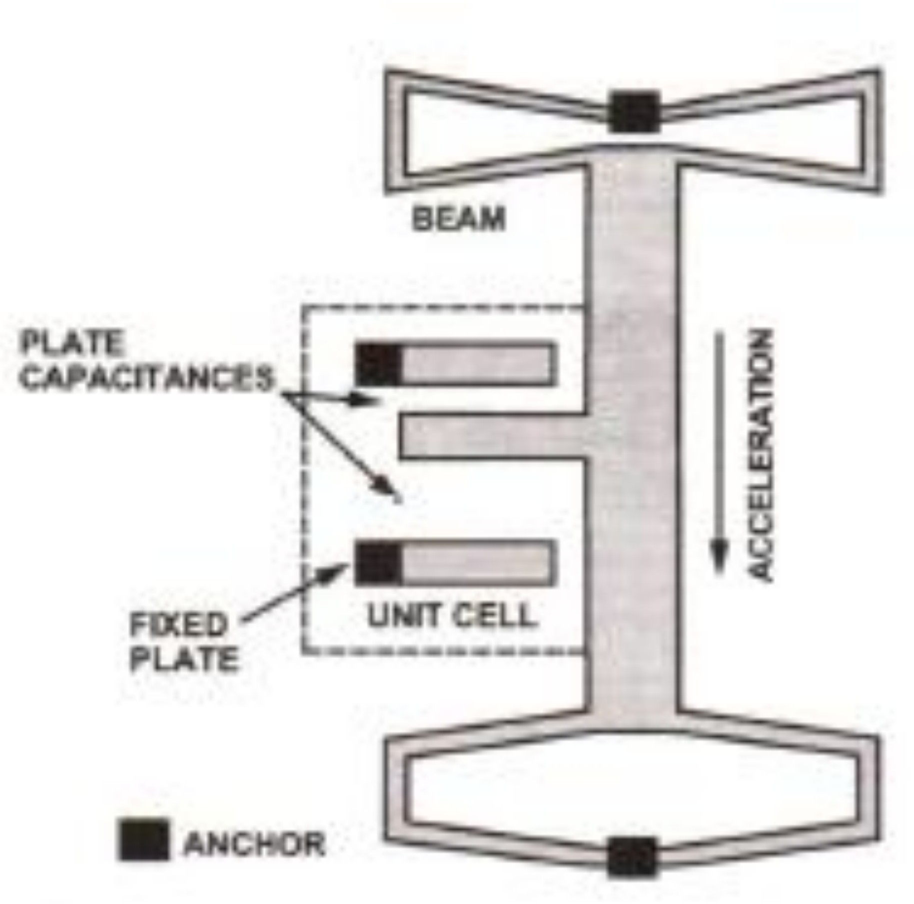
- MSD system and capacitive sensor are made on a silicon chip as a micro-electro-mechanical system (MEMS) using surface micromachining technique.

- An analog signal processing unit , integrated on the same silicon chip using monolithic IC technology, converts the capacitance variation to an analog voltage output.

Functional Block Diagram of ADXL-150



MEMS of ADXL

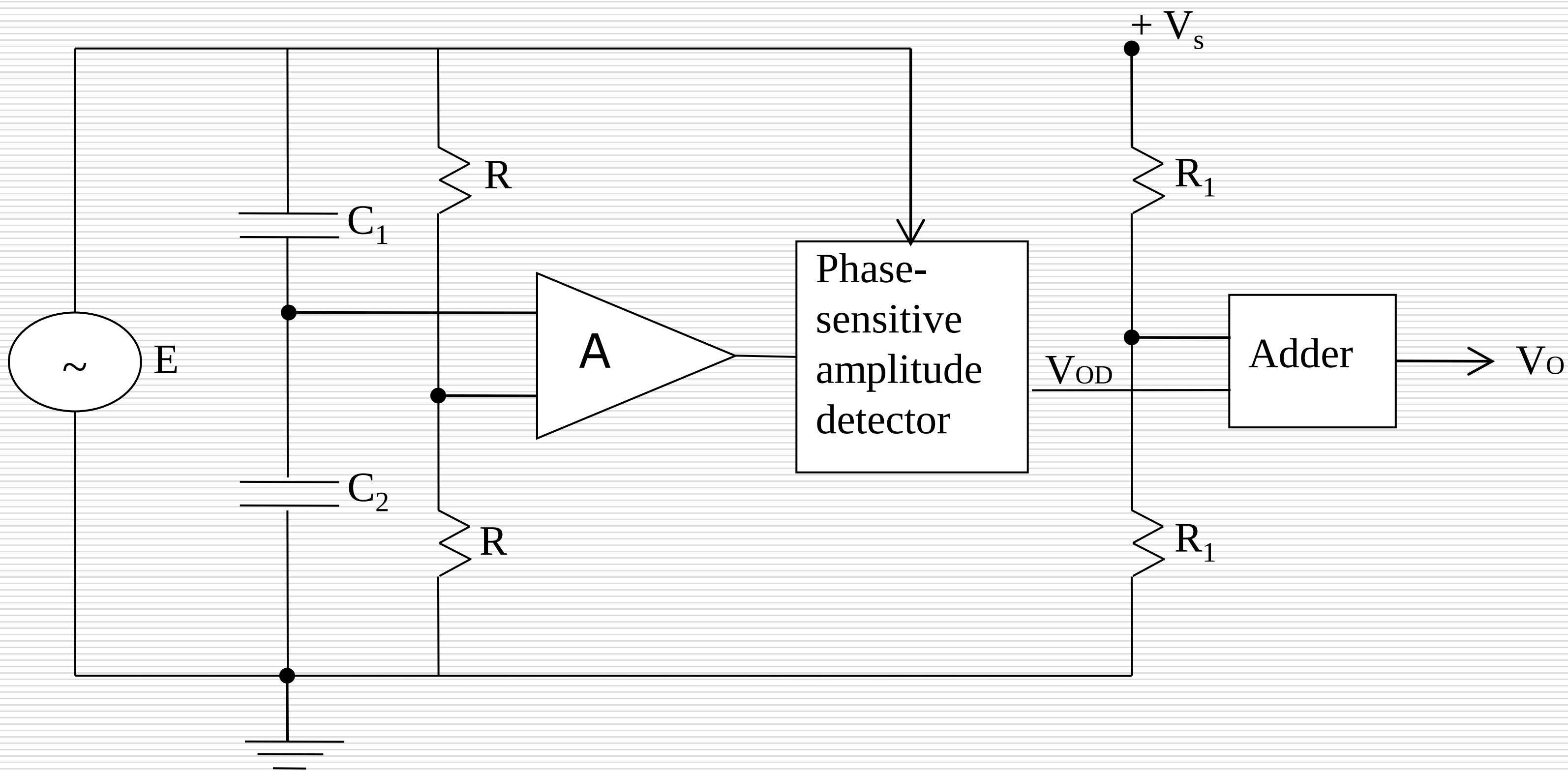


(Source: Data sheets of ADXL-150)

Details of MEMS of ADXL

- Primary and secondary sensing elements are fabricated as a micro-electro-mechanical system (MEMS) using a proprietary surface micromachining process.
- Made by depositing poly-silicon on a sacrificial oxide layer that is then etched away leaving behind the suspended primary sensing element.
- Secondary sensing element has several capacitance cells for relative displacement of the mass (beam) w.r.t. the base (silicon substrate).
- MEMS also has several capacitance cells for electro-statically forcing the beam during self test.
- During self-test a force equivalent to 20% of full-scale acceleration acts on the beam and a proportional voltage-change appears on the output pin.

ASPU of ADXL-150



For acceleration = 0 : $C_1 = C_2 = C$, $V_{OD} = 0$

For acceleration = a : $C_1 = C + \triangle C$ & $C_2 = C - \triangle C$, $V_{OD} = +ve$

For acceleration = -a : $C_1 = C - \triangle C$ & $C_2 = C + \triangle C$, $V_{OD} = -ve$

Output of ADXL-150

- Output of ASPU is ratio-metric and given by

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

where

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 final 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 Nominal value 5.0 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

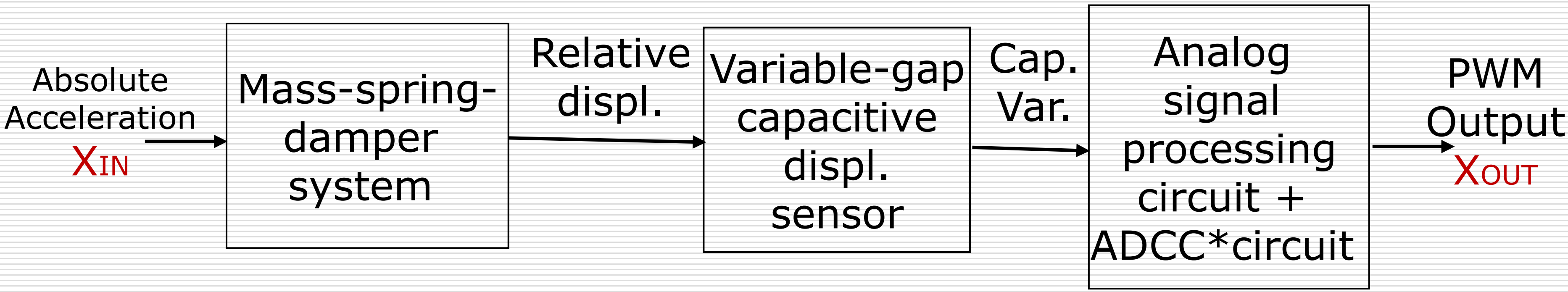
Important Features of ADXL-210E

- Dual-axis sensor on a single IC chip
- Ultra-small chip (5x5x2 mm)
- Duty-ratio or 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)
- Input range : ± 10 g

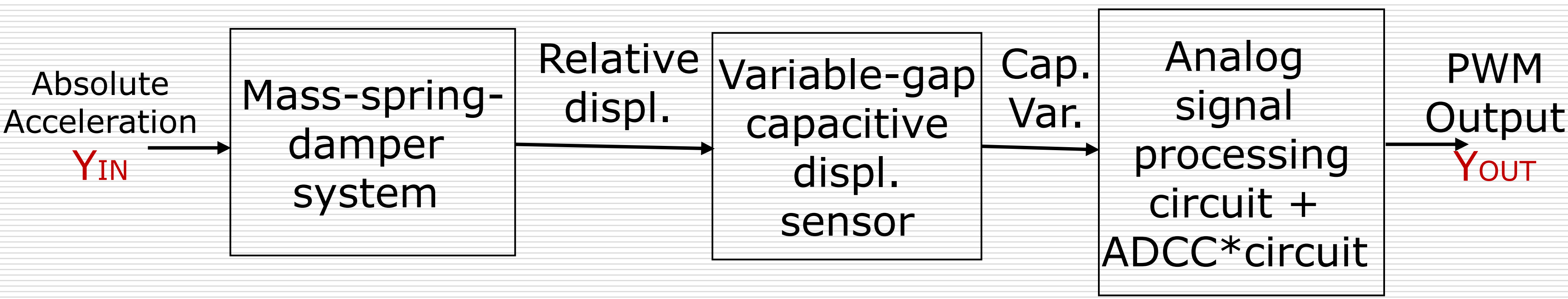
Principle of ADXL-210E

- Two sensors made on a single IC chip are oriented along mutually perpendicular directions.
- Each sensor (MEMS) is similar to that of ADXL-150.
- Output of each sensor (capacitance variation) is given to an analog signal processing circuit which converts it to an analog voltage.
- The analog voltage is converted into PWM output by an analog to duty-ratio converter (ADCC).
- The two analog signal processing circuits share a common oscillator to excite the two sensors.
- ADXL-210E gives two PWM outputs, XOUT and YOUT, on two different pins.

Functional Block Diagram of ADXL-210E



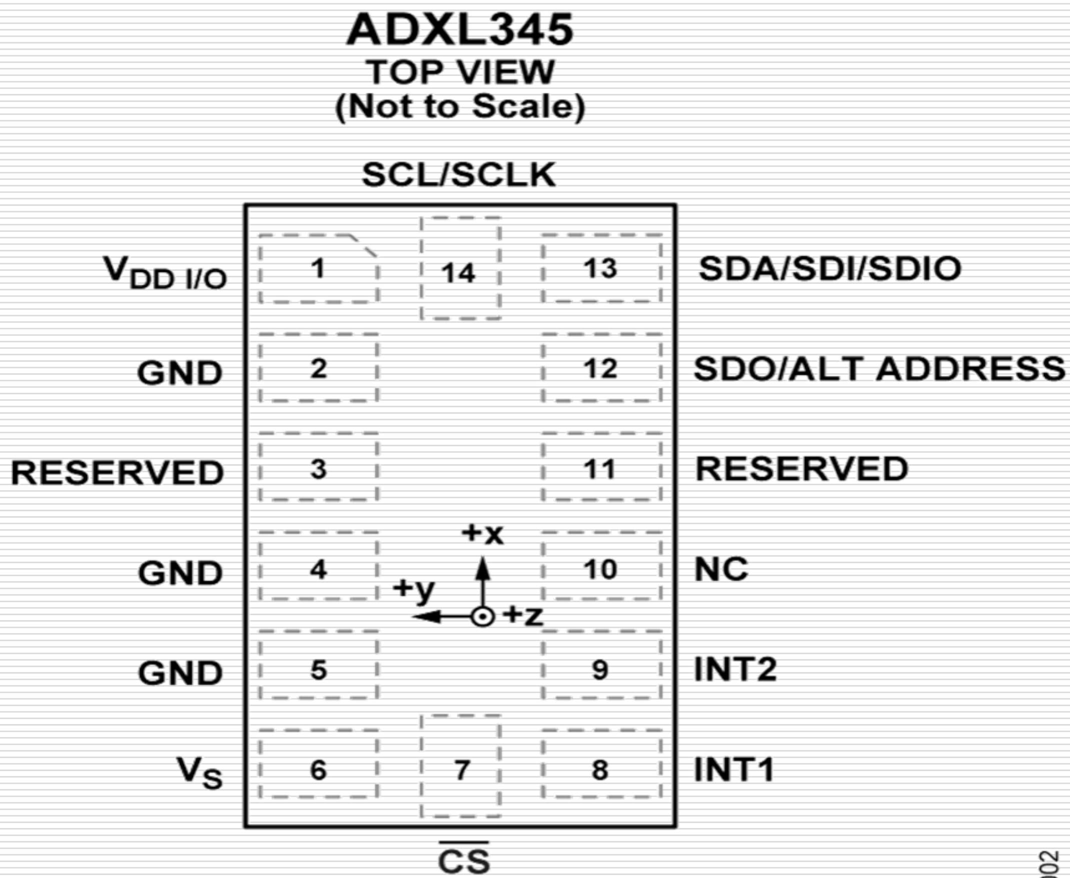
*ADCC: Analog to Duty-Cycle Converter



Important Features of ADXL-345

- Three-axis sensor on a single IC chip
- Ultra-small and thin package (3x5x1 mm)
- Digital serial output: SPI (3 & 4 wire) and I^2C
- 13-bit resolution
- Wide operating voltage range (2.0V – 3.6V)
- Input range: ± 16 g

Pin Diagram of ADXL-345

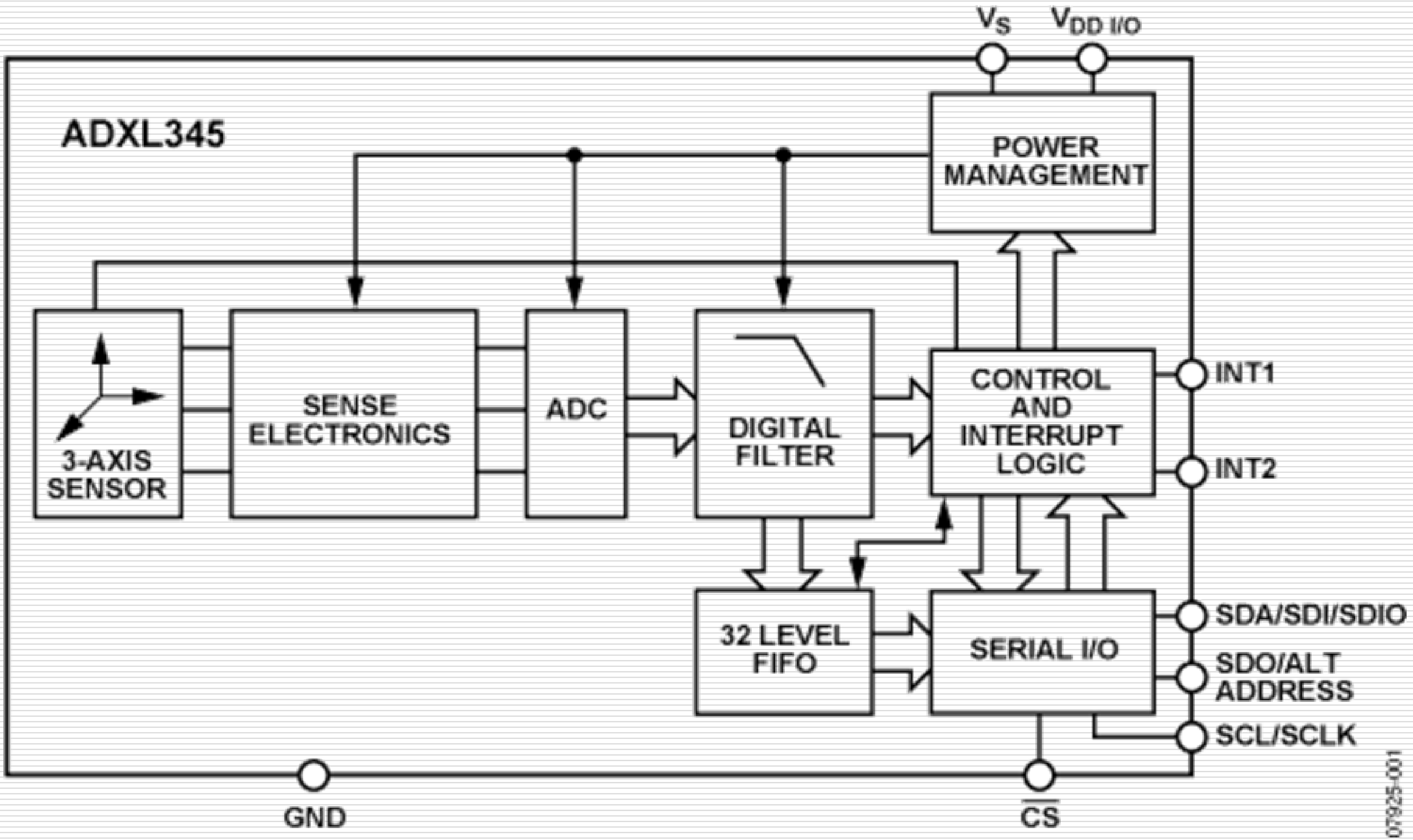


NOTES
1. NC = NO INTERNAL CONNECTION.

14-TERMINAL LAND GRID ARRAY [LGA]
(CC-14-1)

Source:
Data sheets
of ADXL-345

Functional Block Diagram of ADXL-345



(Source: Data sheets of ADXL-345)

Case Study # 5

Smart Pressure Sensor

or

Integrated Silicon Pressure Sensor

MPX5700 Series

Manufacturer: Freescale Semiconductor Inc.

Website: www.freescale.com

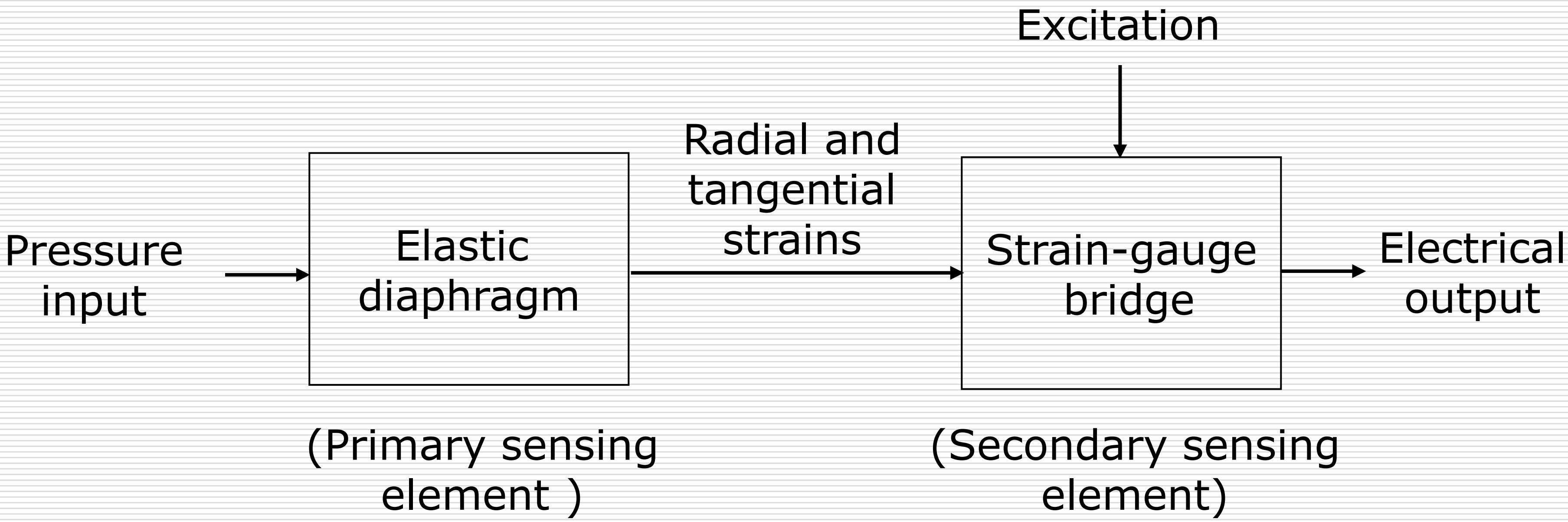
Types of Pressure and Pressure Sensor

- Types of Pressure
  - Differential pressure
  - Gauge pressure
  - Absolute pressure
- Types of Pressure Sensor
  - Diaphragm with strain-gauges
  - Vibrating diaphragm
  - Piezoelectric

Principle of Conventional Pressure Sensor of Diaphragm Type using Strain Gauges (1)

- An elastic diaphragm, acting as ***primary sensing element***, senses the pressure input and converts it into strains.
- Radial stress and strain are positive maximum at the periphery of the diaphragm
- So two strain gauges are placed along radial directions near the periphery of the diaphragm
- Tangential stress and strain are negative maximum at the centre of the diaphragm
- So two more strain gauges are placed along tangential directions near the centre of the diaphragm
- The four strain gauges are appropriately connected in a full bridge configuration
- This strain gauge bridge acts as ***secondary sensing element.***

Principle of Conventional Pressure Sensor of Diaphragm Type using Strain Gauges (2)



Salient Features of MPX5700

- Monolithic silicon pressure sensor
- Diaphragm based piezo-resistive sensor
- High-level analog output signal
- Combines micromachining, bipolar integrated-circuit 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
  - With an opening to expose other side of diaphragm to atmosphere.

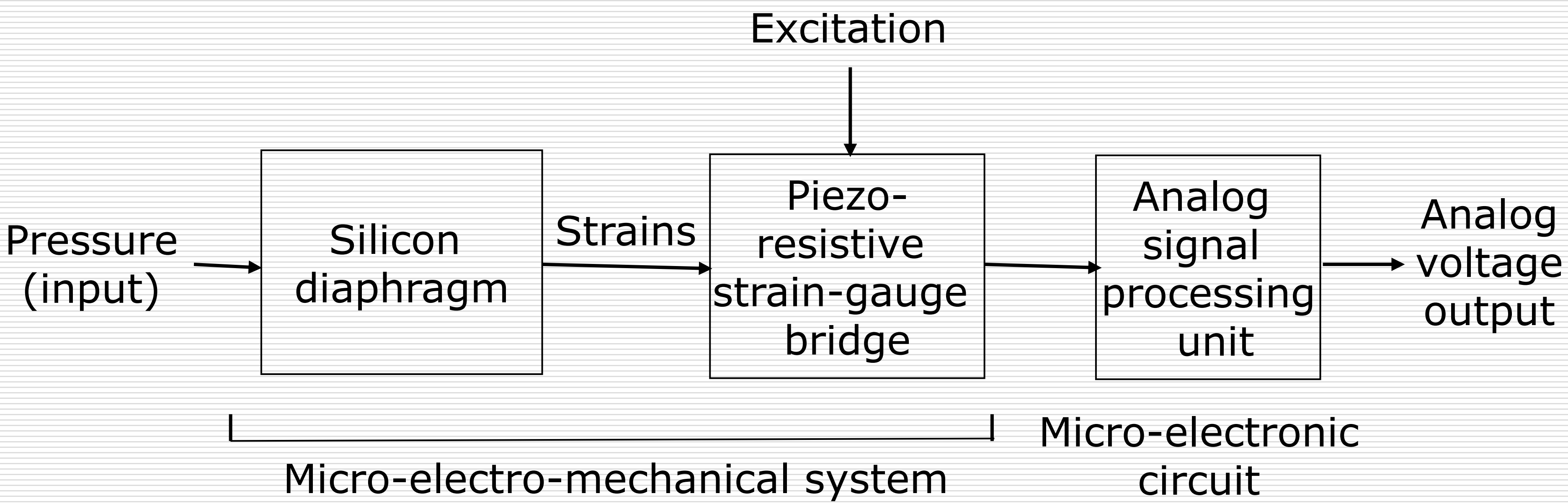
Principle of MPX5700

- A silicon diaphragm, serving as ***primary sensing element,*** converts pressure into tangential and radial strains.
- Strains are sensed by four piezo-resistive strain gauges connected as a full whetstone bridge, thus serving as ***secondary sensing element***.
- The bridge output is amplified by a 2-stage amplifier.
- The amplified output signal is 0-4.7V @5.0V supply.

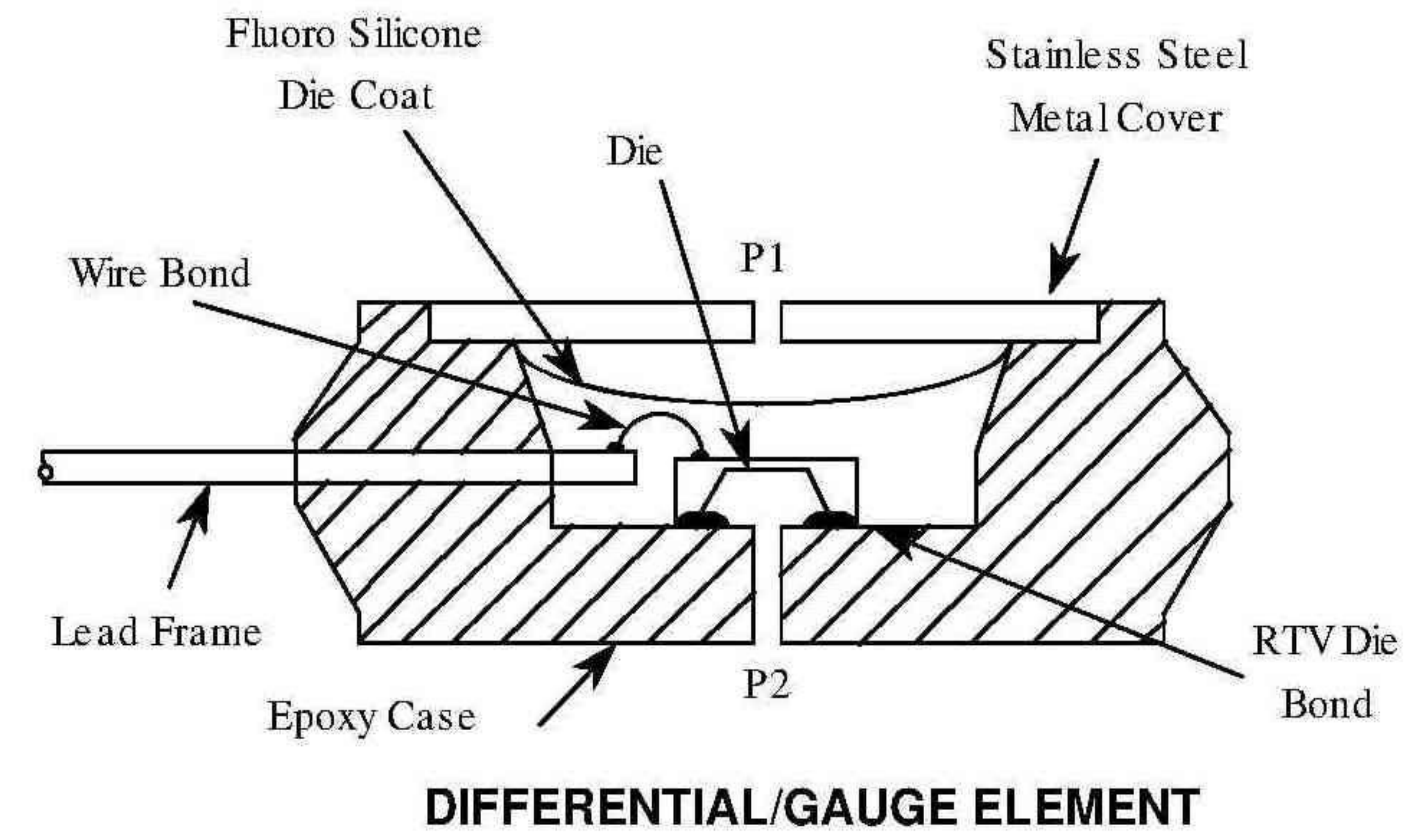
Operating Characteristics of MPX5700

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

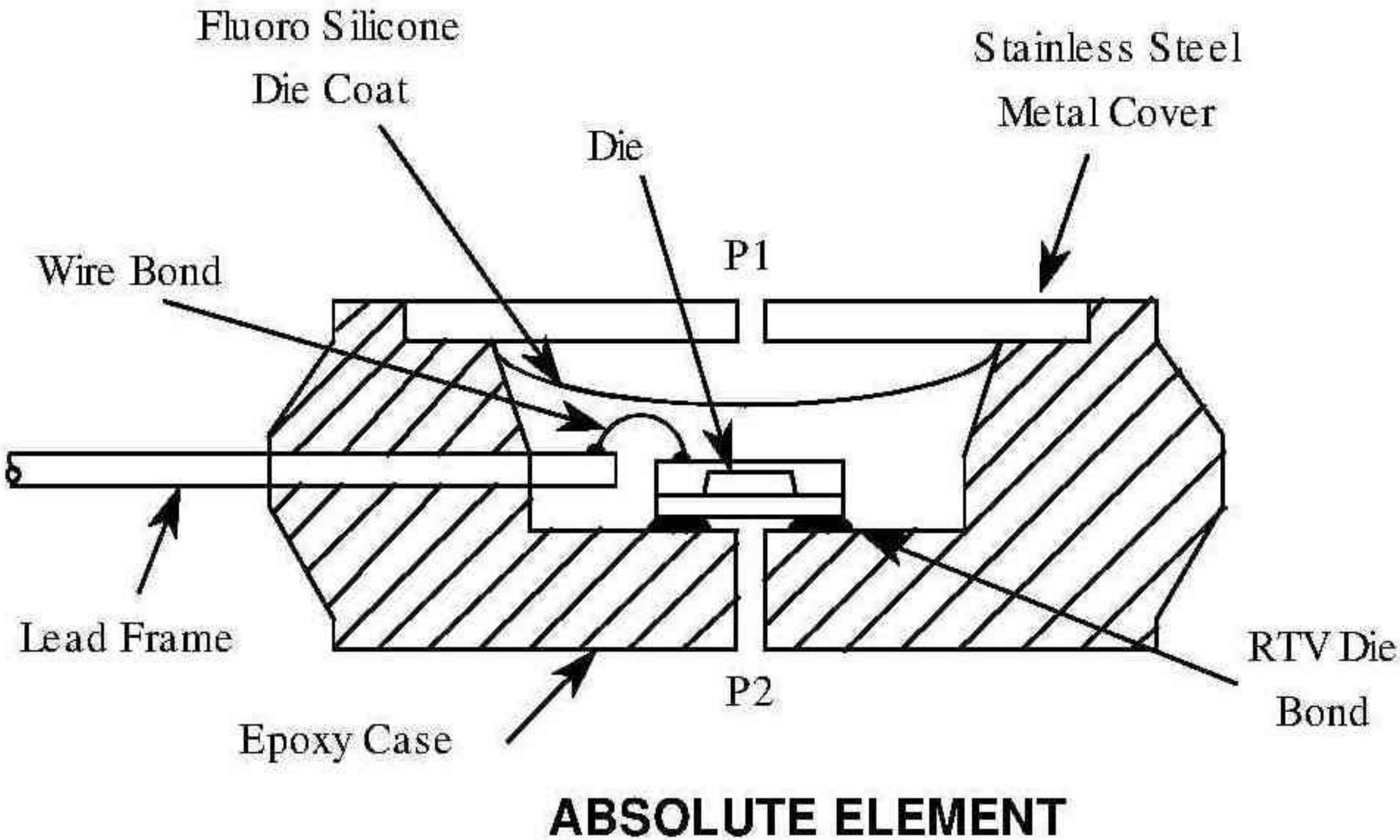


Cross-Sectional Diagram of MEMS for Differential/Gauge Pressure Sensing



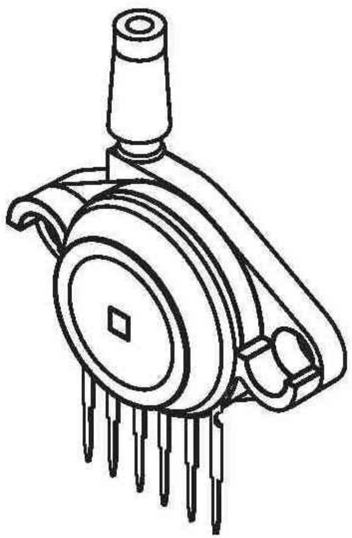
(Source: Data sheet of MPX5700)

Cross-Sectional Diagram of MEMS for Absolute Pressure Sensing

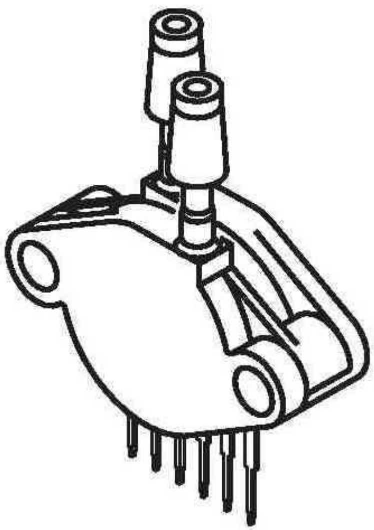


(Source: Data sheet of MPX5700)

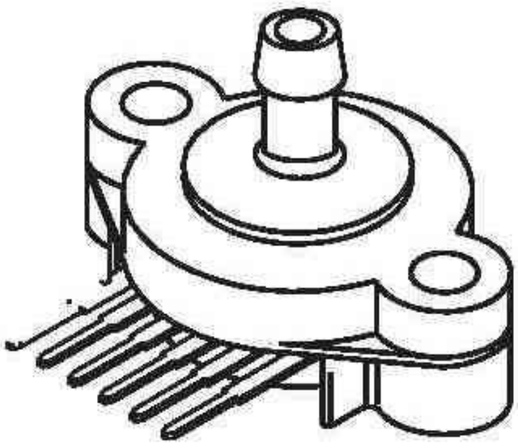
Packages and Pins



MPX5700AP/GP/GP1
CASE 867B-04



MPX5700DP
CASE 867C-05



MPX5700ASX
CASE 867F-03

PIN 1: VOUT	PIN 2: GROUND	PIN 3: VS
PIN 4: NC	PIN 5: NC	PIN 6: NC

(Source: Data sheet of MPX5700)