智能传感与检测技术

Measurement & Instrumentation)

过程参数检测部分

彭黎辉　电话：62773623
Email:lihuipeng@mail.tsinghua.edu.cn

压力测量

❑基本概念

❖定义、单位

❖压力表示方法

绝对压力
大气压力
表压力
真空度
差压

❑压力传感器及检测方法

❖重力平衡法、机械力平衡法、弹性

压力测量

❑压力定义

❖垂直均匀作用于物体单位面积上的力，通常用 p表示。

❑压力单位

❖帕斯卡（帕，Pa）、千帕（kPa）、兆帕（MPa）

❖标准大气压、工程大气压

❖巴

❖毫米水柱、毫米汞柱

压力单位换算表

4° C 状态的水柱高度

0° C 状态的汞柱高度

	Pa 帕	bar 巴	kgf/cm^2	atm	at	mm H_2O	mmHg	Psi
1 Pa 帕	1	0.00001	0.00001	0.00001	0.00001	0.10197	0.0075	0.00014
1 bar 巴	100000	1	1.01972	0.9869	1.01972	10.1972	750.062	14.504
1 kgf/cm^2	98066.5	0.98067	1	0.9678	1	10.000	735.6	14.22
1 atm 标准大气压	101325	1.01325	1.033	1		10.332	760	14.7
1 at 工程大气压	98067	0.98067	1	0.9678	1	10.000	735.6	14.22
H_2O 1mm 毫米水柱	9.8067	0.000098	0.0001	0.0000968	0.0001	1	0.07356	0.00142
1 mmHg 毫米汞柱	133.322	0.00133	0.00136	0.00132	0.00136	13.5951	1	0.01934
1 Psi 磅/寸 ^{2}	6894.76	0.06895	0.07031	0.06805	0.07031	703.07	51.7149	1

填空题 1分

此题未设置答案，请点击右侧设置按钮

设置

在半导体制造过程中，多个环节均涉及到压力测量。例如在刻蚀过程中，需要对压力进行测量和控制。由于涉及的压力较低，通常使用Torr（托）作为单位。1托= [填空1] mmHg（毫米汞柱）=133.3Pa（帕）。单位“托”为纪念完成大气压mmHg实验的意大利物理学家托里拆利而命名。

作答

压力表示方法（一）

❑绝对压力

❖被测介质作用于容器表面积的全部压力，以绝对真空作为基准所表示的压力。

❑大气压力

❖地球表面空气柱重量形成的压力，与地理位置有关。

❖标准大气压：把0° C时，水银比重13.5951克/厘米^3，重力加速度980.665厘米/秒^2,北纬45度海面的大气压定义为1个标准大气压。

❖工程大气压： 1kgf/cm^2

压力表示方法（二）

❑表压力

❖压力测量仪表中的敏感元件通常处于大气中，所测压力为绝对压力与大气压的差，称为“表压”。

❑真空度

❖当绝对压力小于大气压时，表压为负值，其绝对值为真空度。

❑差压

❖两个压力的差简称差压。

压力表示方法（三）

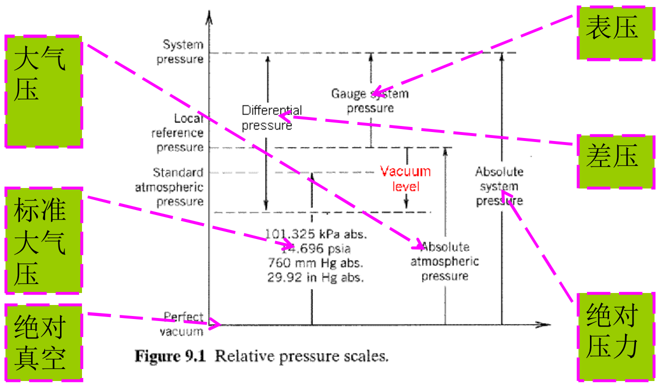


Figure 9.1 Relative pressure scales.

压力测量方法

- ❑重力平衡法 → 液柱式、活塞式
- ❑机械力平衡法
- ❑弹性力平衡法 → 弹性元件
- ❑物性测量方法 → 压电式、压阻式、电容式

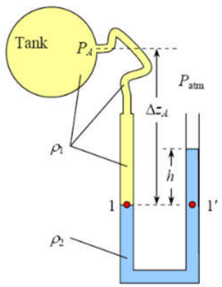
压力测量方法（一）

❑重力平衡法

❖液柱式压力计：被测压力和一定高度的液体产生的重力相平衡，简单、直观、价格低廉、信号不易远传。如U型管压力计。

❖负荷式压力计：基于重力平衡原理，如活塞式压力计，被测压力与活塞及活塞上承载的砝码重量相平衡，精度高、常用于压力表校验。

液柱式压力计



$$P_1 = P_A + \rho_1 g \Delta z_A$$

$$P_{1'} = P_{atm} + \rho_2 g h$$

$$P_A = P_1 - \rho_1 g \Delta z_A$$

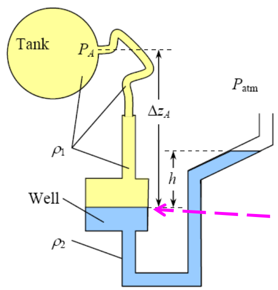
$$P_A = P_{atm} + \rho_2 g h - \rho_1 g \Delta z_A$$

with density $\rho_1 < \rho_2$

$$\Delta p = \rho_2 g h$$

"U tube"　参考点"1"不固定

液柱式压力计



$$P_A = P_{atm} + \rho_2 g h - \rho_1 g \Delta z_A$$

with density $\rho_1 < \rho_2$

$$\Delta p = \rho_2 g h$$

参考点可近似认为固定，读数更方便

Well-type　$\Delta p = \rho_2 g h$

单选题 1分 设置

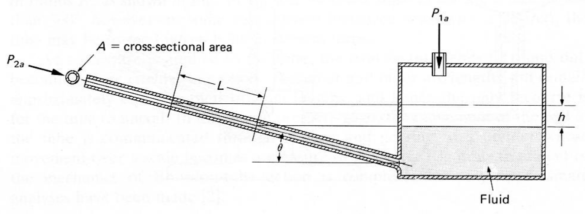
“井”式U型管压力计读数时近似认为读数参考液面恒定，因此获得的液柱高度读数比理论值

- A 偏小
- B 偏大

提交

液柱式压力计

Figure 14.6 Inclined-type manometer

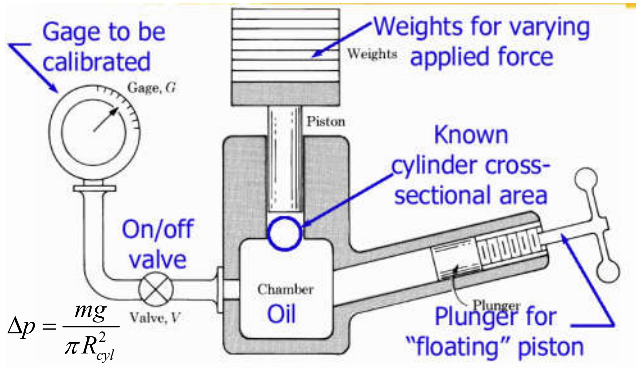


$\Delta p = \rho g h = \rho g L \sin\theta$ 斜管式

液柱式压力计

- ❑思考题1：试推导“U”型管式压力计及斜管式压力计的灵敏度公式。并回答斜管式压力计相比“U”型管式压力计有何优点？
- ❑思考题2：试定量分析“井”式“U”型管式压力计因近似认为读数参考液面保持不变所带来的测量误差。（注：设“井”部直径为D，右侧U管直径为d）

活塞式压力计

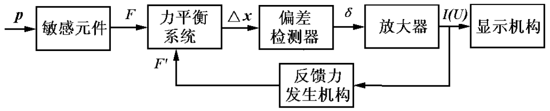


$$\Delta p = \frac{mg}{\pi R_{cyl}^2}$$

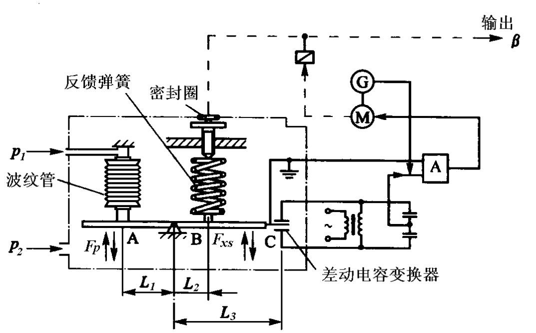
压力测量方法（二）

❑机械力平衡法

❖将被测压力转化为一个集中力，然后用外力与之平衡，通过测量平衡时的外力从而测得被测压力。如力平衡式差压变送器。



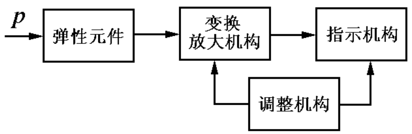
压力测量方法（二）



压力测量方法（三）

❑弹性力平衡法

❖被测压力使得弹性元件产生形变，弹性形变产生的弹性力与被测压力平衡，通过测量弹性元件弹性形变的大小从而测得被测压力。在实际中使用最为广泛。



常用弹性元件

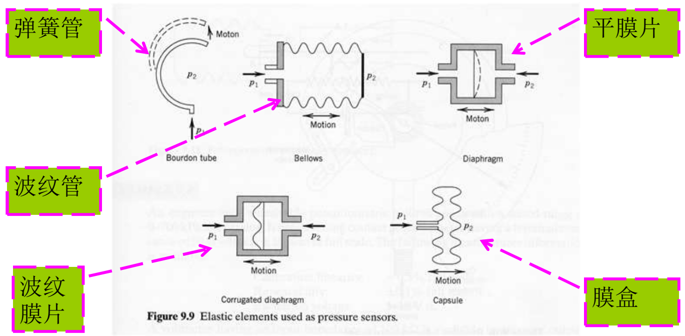
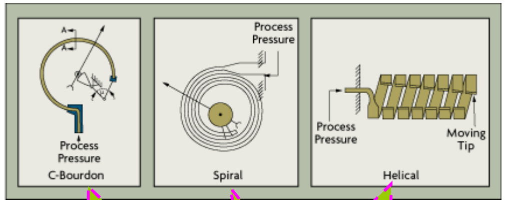


Figure 9.9 Elastic elements used as pressure sensors.

常用弹性元件

❑弹簧管



“C”型（单圈式）

盘式

螺旋式

常用弹性元件

❑弹簧管

常用弹性元件

❑弹簧管压力计

1-弹簧管；2-连杆；

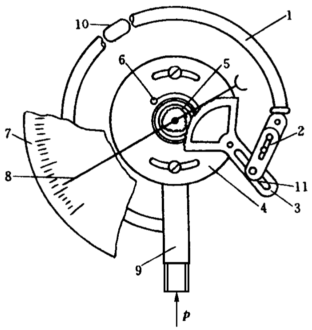
3-扇形齿轮；4-底座；

5-中心齿轮；6-游丝；

7-表盘；8-指针；

9-接头；10-横断面；

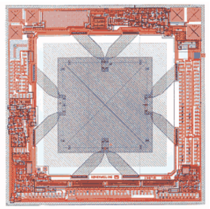
11-灵敏度调整槽

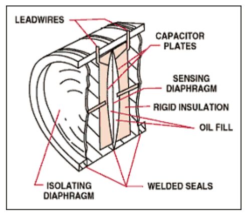


压力测量方法（四）

❑物性法

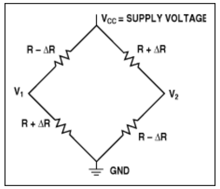
❖采用压电、压阻、光纤等传感器，将被测压力转换为其他物理量来测量。

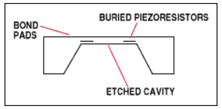


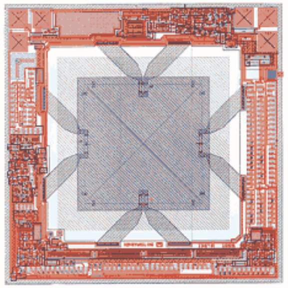


压力测量方法（四）

❑物性法：应变式和压阻式

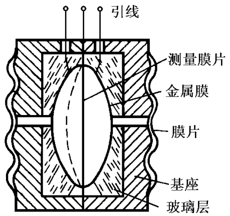






压力测量方法（四）

❑物性法：电容式



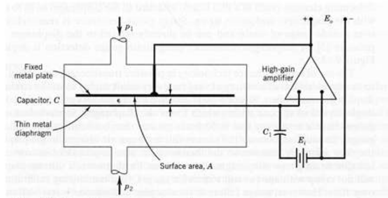


Figure 9.14 Capacitance pressure transducer.

压力测量方法（四）

❑物性法：

电容式

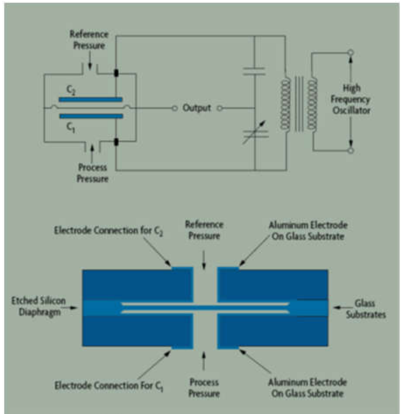


Figure 3-5: Capacitance-Based Pressure Cell

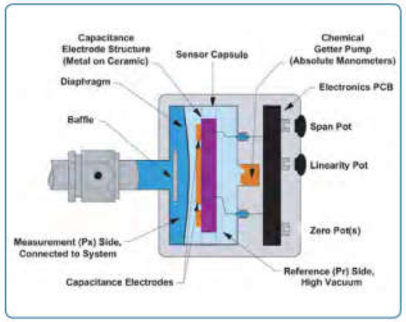
Pressure Measurement in Semiconductor Manufacturing Process

Capacitance manometers are mechanical gauges that sense the deflection caused by the pressure difference between the chamber to be measured and a reference volume. These devices detect the movement of a thin metal diaphragm to do so. Although they can be used to detect pressures as low as 1 mTorr, they are also often used to measure pressures as high as 1 Torr.

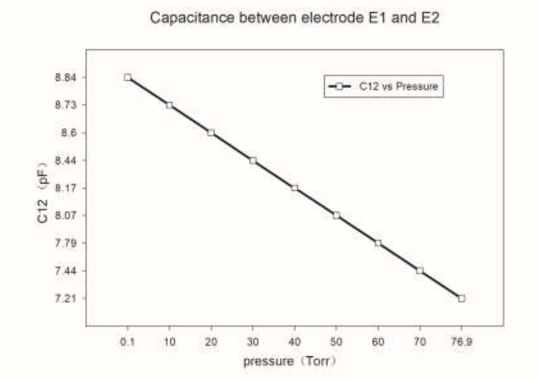
Gary S. May, Costas J. Spanos, Fundamentals of Semiconductor Manufacturing and Process Control, Wiley-Interscience, 2006.

压力测量方法（四）

❑物性法：电容式

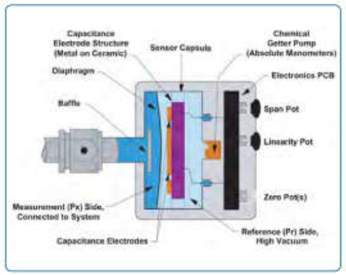


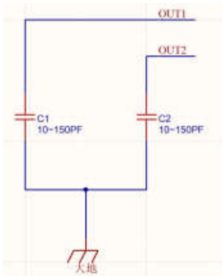
压力测量方法（四）



压力测量方法（四）

❑物性法：电容式

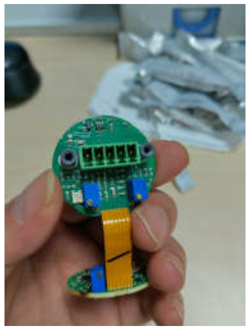




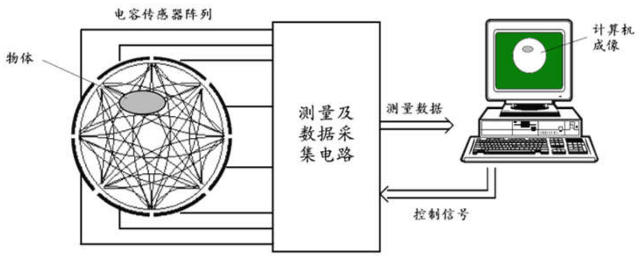
电容C1、C2:（10pF~150pF）；Y=C1-C2, Y（0-0.3pF）

压力测量方法（四）

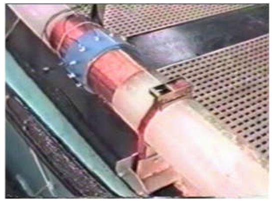
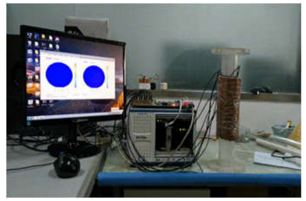
❑物性法：电容式

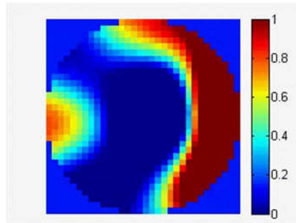


Electrical Capacitance Tomography



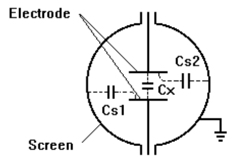
Eletrical Capacitance Tomography

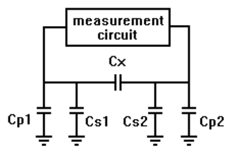





Capacitance Measurement Electronics

- Requirements of measurement electronics:



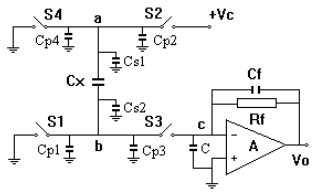


Stray-immune: Cx is only several pico Faraday, but stray capacitance is about 150 pico Faraday

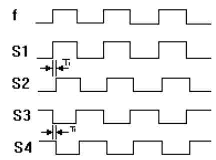
High dynamic range: the largest capacitance is several 10 times of the smallest one

High SNR and high speed: for real time application

Capacitance Measurement Electronics



(a) charge/discharge circuit

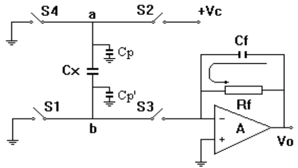


(b) control clock

f : frequency, if $fR_fC_f >> 1$, $V_o = V_c fR_f C_x$, ripple: $V_c \dfrac{C_x}{C_f}$

S. Huang, R. G. Green, A. Plaskowski, M .S. Beck, A high frequency stray-immune capacitance transducer based on the charge transfer principle, IEEE Transactions on Instrumentation and Measurement, 1988, 37(3): 368-373.

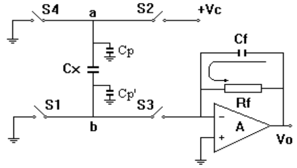
Capacitance Measurement Electronics



$$R_1(t) = \begin{cases} R_{on} & 2nT_f < t \le (2n+1)T_f \\ R_{off} & 2(n+1)T_f < t \le 2(n+1)T_f \end{cases} \qquad n = 0,1,\cdots\infty$$

$$R_3(t) = \begin{cases} R_{off} & 2nT_f < t \le (2n+1)T_f \\ R_{on} & 2(n+1)T_f < t \le 2(n+1)T_f \end{cases} \qquad n = 0,1,\cdots\infty$$

Capacitance Measurement Electronics



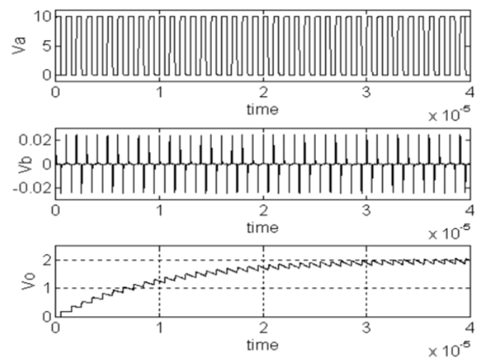
$$\begin{cases} \dfrac{V_c - V_a}{R_2(t)} = C_p \dfrac{dV_a}{dt} + \dfrac{V_a}{R_4(t)} + C_x \dfrac{d(V_a - V_b)}{dt} \\ C_x \dfrac{d(V_a - V_b)}{dt} = \dfrac{V_b}{R_1(t)} + \dfrac{V_b}{R_3(t)} + C_p{}' \dfrac{dV_b}{dt} \\ \dfrac{V_b}{R_3(t)} = -\dfrac{V_o}{R_f} - C_f \dfrac{dV_o}{dt} \end{cases}$$

Electrical Capacitance Tomography

$$\begin{cases} \dfrac{dV_a}{dt} = \dfrac{1}{\alpha}\left\{ \dfrac{(C_p{}' + C_x)V_c}{R_2(t)} - \dfrac{[R_2(t)+R_4(t)](C_p{}' + C_x)}{R_2(t)R_4(t)} V_a - \dfrac{[R_1(t)+R_3(t)]C_x}{R_1(t)R_3(t)} V_b \right\} \\ \dfrac{dV_b}{dt} = \dfrac{1}{\alpha}\left\{ \dfrac{C_x V_c}{R_2(t)} - \dfrac{[R_2(t)+R_4(t)]C_x}{R_2(t)R_4(t)} V_a - \dfrac{[R_1(t)+R_3(t)](C_p + C_x)}{R_1(t)R_3(t)} V_b \right\} \\ \dfrac{dV_o}{dt} = -\dfrac{1}{R_4(t)C_f} V_b - \dfrac{1}{R_f C_f} V_o \end{cases}$$

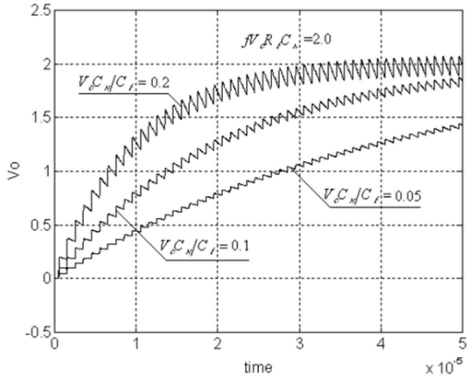
$$\alpha = C_p C_x + C_p{}' C_x + C_p C_p{}'$$

Capacitance Measurement Electronics



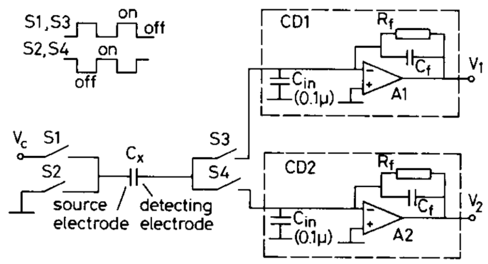
$C_x = 1.0e-12, C_{p1} = 1.5e-10, C_{p2} = 1.5e-10, R_f = 2.0e5, C_f = 5.0e-11,\ T_s = 1.0e-6, T = R_f C_f = 10T_s, T_1 = 0, R_{on} = 100, R_{off} = 1.0e8, V_c = 10$

Capacitance Measurement Electronics



$C_x = 1.0e-12, C_{p1} = 1.5e-10, C_{p2} = 1.5e-10, R_f = 2.0e5, T_s = 1.0e-6 \quad T = R_fC_f = 10T_s, T_1 = 0, R_{on} = 100, R_{off} = 1.0e8, V_c = 10$

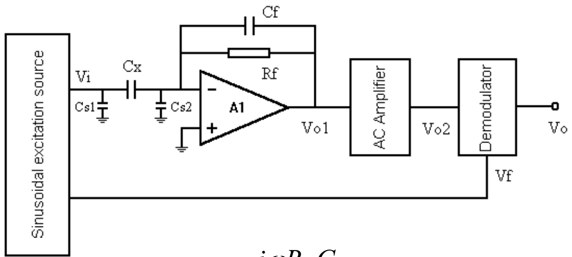
Capacitance Measurement Electronics



$$V_1 = -V_c fR_f C_x + e_1 \quad V_2 = V_c fR_f C_x + e_2 \quad V_2 - V_1 = 2V_c fR_f C_x + \Delta e$$

S. Huang, C. G. Xie, R. Thorn, D Snowden, M. S. Beck, Design of sensor electronics for electrical capacitance tomography, IEE Proceedings-G, 1992, 139(1): 83-88.

Capacitance Measurement Electronics



$$V_{o1} = -\frac{j\omega R_f C_x}{1 + j\omega R_f C_f} \cdot V_i$$

W.Q. Yang, Hardware design of electrical capacitance tomography systems, Measurement Science and Technology, 1996, 7(3): 225-232.

Capacitance Measurement Electronics

if $\omega R_f C_f >> 1$ $\quad$ C_f dominates the feedback

$$V_{o1} = -\frac{C_x}{C_f} \cdot V_i = -\frac{C_x}{C_f} A \sin(\omega t + \alpha)$$

$$V_{o2} = K \cdot V_{o2} = -K \cdot \frac{C_x}{C_f} \cdot A \sin(\omega t + \alpha)$$

$$V_{o3} = V_{o2} \cdot V_f = -K \frac{C_x}{C_f} A \sin(\omega t + \alpha) \cdot B \sin(\omega t + \beta)$$

$$= -K \frac{C_x}{C_f} \frac{AB}{2} \left[\cos(\alpha - \beta) - \cos(2\omega t + \alpha + \beta)\right]$$

Capacitance Measurement Electronics

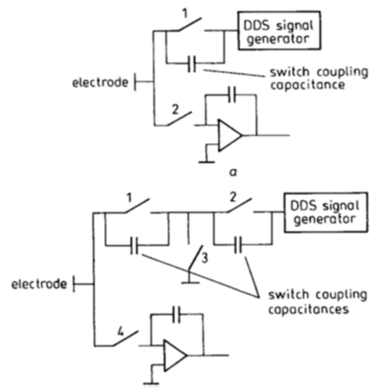
if $\omega R_f C_f << 1$ R_f dominates the feedback

$$V_{o1} = -j\omega R_f C_x \sin(\omega t + \alpha)$$

$$V_{o2} = -j\omega R_f C_x K \sin(\omega t + \alpha)$$

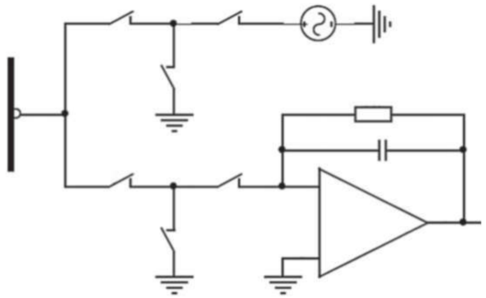
$$V_{o3} = V_{o2} \bullet V_f = -j\omega R_f C_x K \sin(\omega t + \alpha) \bullet B \sin(\omega t + \beta)$$
$$= \frac{-j\omega R_f C_x KB}{2}\left(\cos(\alpha - \beta) - \cos(2\omega t + \alpha + \beta)\right)$$

Capacitance Measurement Electronics



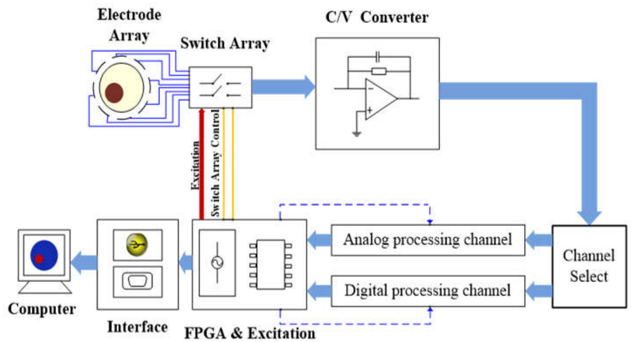
W.Q. Yang, T. A. York, New AC-based capacitance tomography system, IEE Proceedings - Science, Measurement and Technology , 1999, 146(1): 47-53.

Capacitance Measurement Electronics

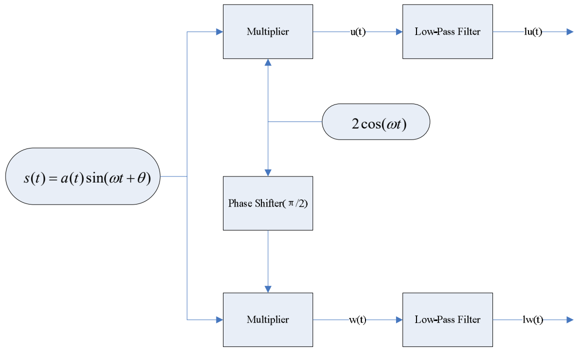


D. Styra D, L. Babout, Improvement of AC-based electrical capacitance tomography hardware, Elektron. Elektrotech, 2010, 103: 47–50.

Capacitance Measurement Electronics

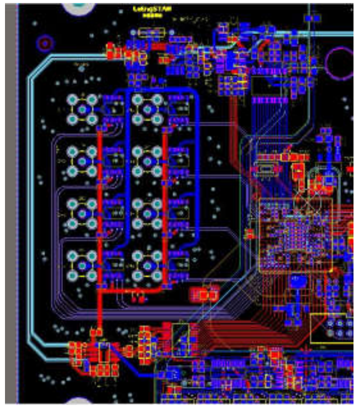


Capacitance Measurement Electronics

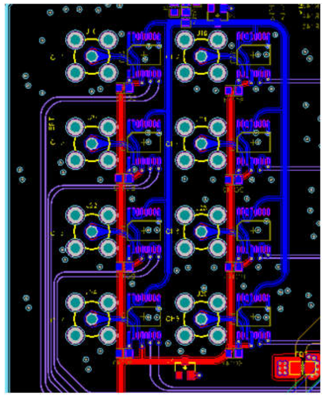


$lu(t) = lpf\,(u(t)) = a(t)\sin(\theta)$ $lw(t) = lpf\,(w(t)) = a(t)\cos(\theta)$

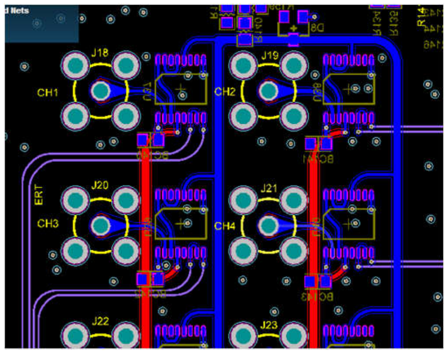
Capacitance Measurement Electronics— PCB Design



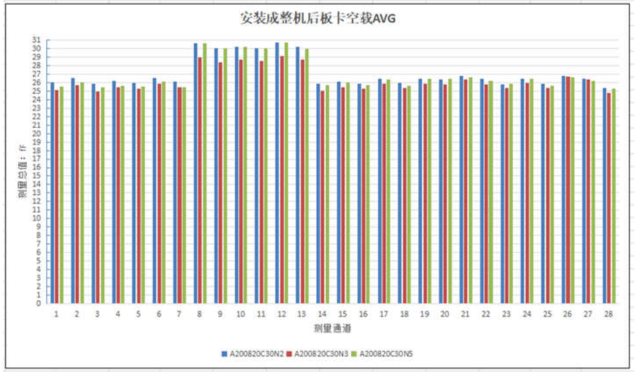
Capacitance Measurement Electronics— PCB Design



Capacitance Measurement Electronics— PCB Design

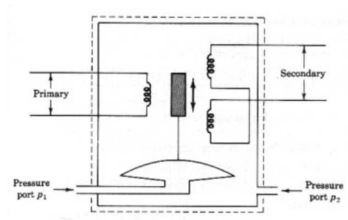


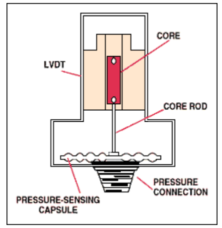
Capacitance Measurement Electronics—PCB Design



压力测量方法（四）

❑物性法：电感式





压力测量方法（四）

❑物性法：压电式

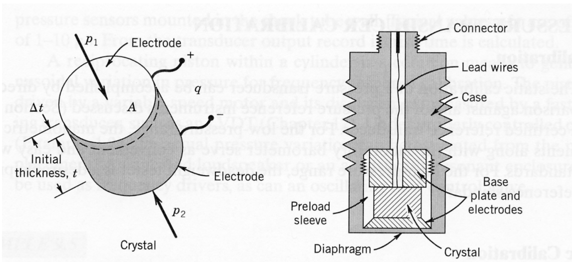


Figure 9.15 Piezoelectric pressure transducer.

压力测量实例—汽车轮胎胎压监测

Tire-Pressure Monitoring (TPM) System

June 2003

Tire-Pressure Monitoring (TPM) — General Info/ Introduction

- TPM systems help to avoid accidents by warning the driver about tire problems

- Fuel consumption increases by 1% every 0.2 bar the tire is under-inflated.
  - 0.4 bar under-inflation ⇒ 2% increase in fuel consumption
  - 0.6 bar under-inflation ⇒ 3% increase in fuel consumption

- Tire wear increases by 5% every 0.2 bar the tire is under-inflated.
  - 0.4 bar under-inflation ⇒ 10% increase in tire wear
  - 0.6 bar under-inflation ⇒ 15% increase in tire wear

Tire-Pressure Monitoring (TPM) — Indirect & Direct Methods

Indirect TPMS are measuring pressure indirectly, by using information from other vehicle- related sensors (e.g. ABS wheel speed sensor information) and evaluating these signals. Principles are:

- Comparison of wheel speed signals
- Analysis of resonance frequency shifts
- Comparison of wheel speed signals with absolute speed measurements (e.g. from GPS)
- Analysis of correlation patterns between wheel speed signals.
- Analysis of vertical accelerometer signals……

Direct TPMS is based on a UHF receiver in the vehicle and 4 sensor modules mounted on the wheel rim / valve to sense data, to calibrate pressure vs. temperature and to organize the data transmission to the car body.

Tire-Pressure Monitoring (TPM) — Different Phases of Direct Method

Remote TPM

•Based on UHF unidirectional transmitter / receiver system with embedded sensor

Pressure-on-Demand POD

•System consists of a 125 kHz built-in channel for waking up sensor modules in defined duty cycles, improving thus the battery life time

•It remarkbly increases the flexibility of wheel initialization during change of the wheels by reprogramming the memory

•The driver can adjust different modes trough the dashboard

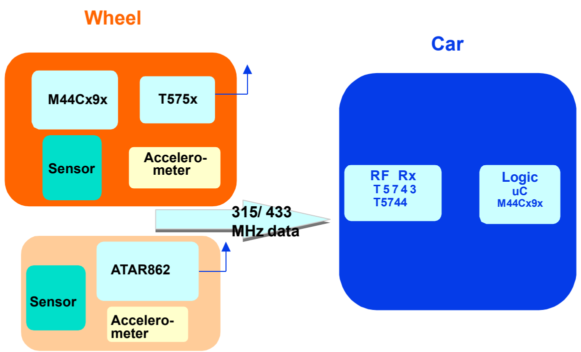
•125 kHz trigger base station and a low-current receiver in the sensor module are today in introduction.

Batteryless System

•System that has no battery in the sensor module but a sensor tag inside the tire

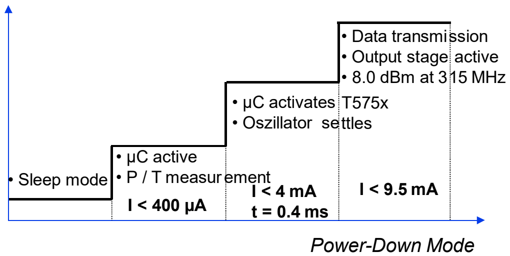
•Allows to merge RFID and pressure measurement functions in the future

Tire-Pressure Monitoring (TPM) — Direct Method



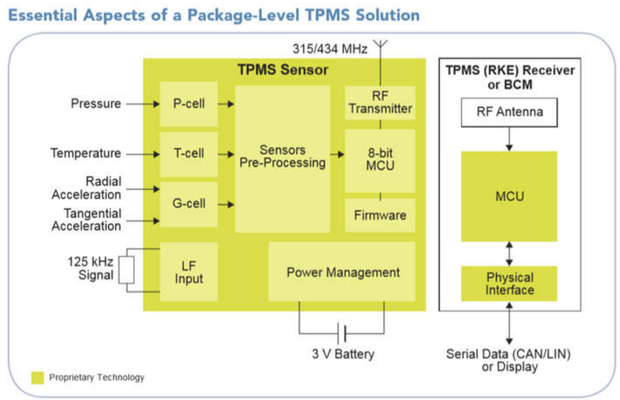
ATAR862 Typical Current Values in Different Power Modes

Battery current



I = typically 0.1 µA (Oscillator OFF; 25⁰ C)

Tire-Pressure Monitoring (TPM) — Pressure on Demond



汽车轮胎胎压监测—— External Type

汽车轮胎胎压监测—— Internal Type