* HW#1 will be posted tomorrow

SOI MEMS

Fixed

Released

Box $\text{SiO}_2$

Design Rule (Assume 250 nm litho resolution)

1. Line width $\geq 300$ nm
2. Spacing $\geq 300$ nm
3. Fixed structure $\geq 20 \mu$m
4. Released " $< 8 \mu$m

Accelerometer

Proof mass

Layout (Top View)
Diagonal distance = \((s-h)\sqrt{2}\)

\[
\frac{(s-h)\sqrt{2}}{2} \leq 4 \text{\(\mu\)m}
\]

\[
s-h \leq \frac{8}{\sqrt{2}} \approx 5.6
\]

\[
h \text{ is limited by aspect ratio } = AR
\]

\[
AR = \frac{\text{Thickness of SOI}}{h} = \frac{40 \text{\(\mu\)m}}{h} \leq AR = 20
\]

\[
h > 2 \text{\(\mu\)m}
\]

\[
S \leq h+5.6 = 7.6 \text{\(\mu\)m} \quad \Rightarrow \text{choose } S = 7 \text{\(\mu\)m}
\]

**Hand Calculation**

\[F = ma = k \cdot \Delta x\]

\[
\uparrow \quad \text{spring const}: \quad \frac{F}{\Delta x} = \left[\frac{N}{m}\right]
\]

\[
k = E \frac{w^3L}{4L^3}
\]

\[
E = \text{Young's Modulus} \quad \text{for } S_c = 170 \text{ GPa} \quad \frac{F}{A}
\]

\[
= 170 \times 10^9 \left[\frac{N}{m^2}\right]
\]
\(k = \frac{E \cdot W^3 t}{4L^3}\)

\(W = 2 \text{ µm}\)
\(L = 100 \text{ µm}\)
\(t = 40 \text{ µm}\)
\(E (\text{Se}) = 170 \text{ GPa}\)

\[k = \frac{170 \times 10^9 \cdot (2 \times 10^{-6})^3 \cdot (4 \times 10^{-5})}{4 \cdot 10^{-4)^3}} = 1.7 \times 10^{11-18-5+12}\]

\[= 15 \frac{\text{N}}{\text{m}} = 15 \frac{\text{mN}}{\text{um}} = 15 \frac{\text{nN}}{\text{nm}}\]

\(m = \rho \cdot L^2 \cdot t \quad \rho \text{ of Se} = 2300 \frac{\text{kg}}{\text{m}^3}\)

\[= (2.3 \times 10^3) \cdot (10^{-4})^2 \cdot (4 \times 10^{-5})\]

\[= 10 \times 10^3 \cdot 8^{-5}\]

\[= 10^{-9} \text{ kg} = 1 \mu\text{g}\]

Measure \(a\) by gravity \("g"\)

\("g" = 9.8 \text{ m/s}^2\)
\[ F = m \cdot g = 10^9 \cdot 10 = 15 \cdot \Delta x \]
\[ \Delta x = \frac{2}{3} \times 10^{-9} \quad \text{m} = 0.6 \quad \text{nm} = 6 \AA \]

\[ \Delta C = C \cdot \Delta x \]

\[ \text{gap spacing} \]

\[ C = \varepsilon_0 \cdot \frac{t \cdot L}{g} = 8.8 \times 10^{-12} \cdot \frac{4 \times 10^{-5} \times 10^{-4}}{2 \times 10^{-6}} \]

\[ \left[ \frac{F}{m} \right] \left[ m \right] \]

\[ = 18 \times 10^{-12-5-4+6} = 18 \times 10^{-15} \quad F = 18 \ \text{fF} \]

\[ \Delta C = C \cdot \Delta x \]

\[ = (18 \ \text{fF}) \cdot \frac{0.6 \times 10^{-9}}{2 \times 10^{-6}} = 5 \times 10^{-15-3} \]

\[ = 5 \times 10^{-18} \quad F = 5 \ \text{aF} \]

How many electrons do we move in/out of \( C \)?

\[ \Delta Q = \Delta C \cdot V = 5 \ \text{aC} \]

\[ \frac{\Delta Q}{e} = \frac{5 \times 10^{-18}}{1.6 \times 10^{-19}} = 30 \ \text{electrons} \]
24-Bit Capacitance-to-Digital Converter
with Temperature Sensor
AD7745/AD7746

FEATURES
Capacitance-to-digital converter
New standard in single chip solutions
Interfaces to single or differential floating sensors
Resolution down to 4 aF (that is, up to 21 ENOB)
Accuracy: 4 fF
Linearity: 0.01%
Common-mode (not changing) capacitance up to 17 pF
Full-scale (changing) capacitance range: ±4 pF
Tolerant of parasitic capacitance to ground up to 60 pF
Update rate: 10 Hz to 90 Hz
Simultaneous 50 Hz and 60 Hz rejection at 16 Hz
Temperature sensor on-chip
Resolution: 0.1°C, accuracy: ±2°C
Voltage input channel
Internal clock oscillator
2-wire serial interface (I²C®-compatible)
Power
2.7 V to 5.25 V single-supply operation
0.7 mA current consumption
Operating temperature: −40°C to +125°C
16-lead TSSOP package

GENERAL DESCRIPTION
The AD7745/AD7746 are a high resolution, Σ-Δ capacitance-to-digital converter (CDC). The capacitance to be measured is connected directly to the device inputs. The architecture features inherent high resolution (24-bit no missing codes, up to 21-bit effective resolution), high linearity (±0.01%), and high accuracy (±4 fF factory calibrated). The AD7745/AD7746 capacitance input range is ±4 pF (changing), while it can accept up to 17 pF common-mode capacitance (not changing), which can be balanced by a programmable on-chip, digital-to-capacitance converter (CAPDAC).

The AD7745 has one capacitance input channel, while the AD7746 has two channels. Each channel can be configured as single-ended or differential. The AD7745/AD7746 are designed for floating capacitive sensors. For capacitive sensors with one plate connected to ground, the AD7747 is recommended.

The parts have an on-chip temperature sensor with a resolution of 0.1°C and accuracy of ±2°C. The on-chip voltage reference and the on-chip clock generator eliminate the need for any external components in capacitive sensor applications. The

Resolution in "g" = \frac{5aF}{4aF} \approx 1 "g"

Full range = \frac{\pm 4pF}{5aF} = \pm 10^6 "g"
Increase $\frac{\Delta C}{C}$ by increase width of proof mass.

\[ L \rightarrow 1 \text{ mm} \quad 10 \times \uparrow \]

\[ N_{\text{max}} = \frac{1 \text{ mm}}{10 \mu\text{m}} = 100 \]

\[ C \uparrow 100 \times \]

\[ F = ma = m \cdot g \quad \uparrow 10 \times \]

\[ L \rightarrow 10 \times \uparrow \]

\[ \Delta x = \frac{F}{k} \uparrow 10 \times \]

\[ \Delta C \uparrow 100 \times 10 = 1000 \times \Rightarrow 5 \text{ fF for } g \]

\[ \text{Resolution} = \frac{4 \text{ aF}}{5 \text{ fF}} = 10^{-3} = 1 \text{ m"g"} \]

* Full scale $= \frac{\pm 4 \text{ pF}}{5 \text{ fF}} \approx \pm 10^3 \text{ "g"} = \pm k\text{"g"} $

Resonance frequency $100 \text{ nm}$-wide.
\[ \omega = \sqrt{\frac{k}{m}} = \sqrt{\frac{15}{10^9}} = \sqrt{1.5 \times 10^{-10}} = 1.2 \times 10^5 \text{ rad/s} \]
\[ f = \frac{\omega}{2\pi} = 2 \times 10^4 \frac{1}{s} = 20 \text{ kHz} \]

1 mm wide
- K same
- \( m \uparrow 10x \)

\[ f \propto \sqrt{10} = 3 \times \approx 6 \text{ kHz} \]

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Issues of this simple accelerometer.

- Lots of parasitic capacitance
- Nonlinearity

\[ \Delta C = \frac{dC}{dg} \Delta x \text{ Linearized} \]

\[ C = \frac{\varepsilon A}{g - \Delta x} \text{ Nonlinear} \]

\[ = \frac{\varepsilon A}{g} \left( 1 - \frac{\Delta x}{g} \right) \]
Differential capacitive sensing

\[
V_{\text{out}} \quad \begin{array}{c}
\overset{\uparrow}{C_1} \quad \overset{\downarrow}{1} \\
\frac{1}{1 + \frac{\Delta X}{g}} \\
\overset{\uparrow}{C_2} \quad \overset{\downarrow}{1} \\
\end{array}
\]

\[
C_1 = C_0 \cdot \frac{1}{1 - \frac{\Delta X}{g}} \\
C_2 = C_0 \cdot \frac{1}{1 + \frac{\Delta X}{g}}
\]

\[
Z_1 = \frac{1}{j\omega C_1} \\
Z_2 = \frac{1}{j\omega C_2}
\]

\[
V_x \\
\quad \overset{\uparrow}{C_1} \\
\quad \overset{\downarrow}{V_{\text{out}}} \\
\quad \overset{\uparrow}{C_2}
\]

\[
V_{\text{out}} = V_x \cdot \frac{Z_2}{Z_1 + Z_2} = V_x \cdot \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}}
\]

\[
= V_x \cdot \frac{1 + \frac{\Delta X}{g}}{(1 - \frac{\Delta X}{g}) + (1 + \frac{\Delta X}{g})}
\]

\[
= \frac{1}{2} \left(1 + \frac{\Delta X}{g}\right) \cdot V_x
\]

\[\text{Linear}\]