AZD110 – WEAR DETECT IN WATCHES AND FITNESS BANDS

In this document wear detect design elements are introduced. “Wear detect” is a term used for proximity, touch or wear triggers that remain for a long time under various conditions.

1 Wear detect definition

Detection of the wear (donned/”put on”) state of a wearable device for a long period of time as well as the successful release detection upon termination of use or the removal of the device from a person’s body.

2 Wear detect design

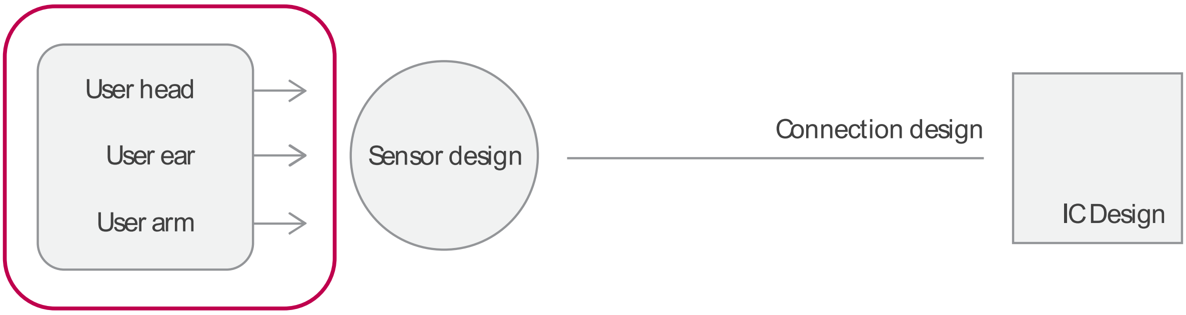


Figure 2.1 Sensor system design topics

2.1 Capacitance values of wear detect

Typical "wear detect" applications need to distinguish **very small differences in capacitive measurement** due to the sensor size and characteristic influence of touch and proximity activations. Below table lists some known wear examples and capacitive values associated with each.

Table 2.1: Typical sensor size and capacitance change values for the different wear detection applications

Application	Sensor size (mm^2)	Typical Wear signal	Typical Proximity signal	Unique considerations
User arm	75 – 150	200fF – 800fF	<50fF (3mm)	Loose wearing, sweat & water

2.2 Capacitance threshold vs total system capacitance

Due to the small capacitive signal changes, observed for wear detect applications, it is most often required for a system design to have **even smaller threshold values**. These thresholds tend to be fractionally insignificant to the total sensor load. Environmental change can account for similar or even larger proportions of capacitances and this pose a high risk to wear detect signal integrity.

Table 2.2: Typical sensor size and capacitance change values for the different wear detection applications

Application	Sensor load (layout dependent)	Touch %	Proximity %	Wear Threshold %
User ear/arm best	4pF	5% (200fF)	1.25% (50fF)	0.75% (25fF)
User ear/arm worst	10pF	2% (200fF)	0.5% (50fF)	0.25% (25fF)

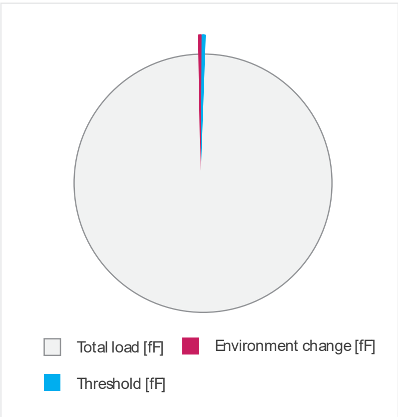


Figure 2.2 Typical bench test situation

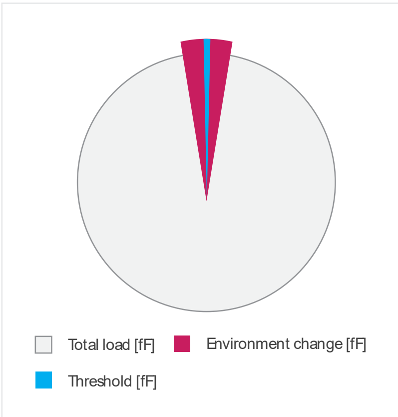
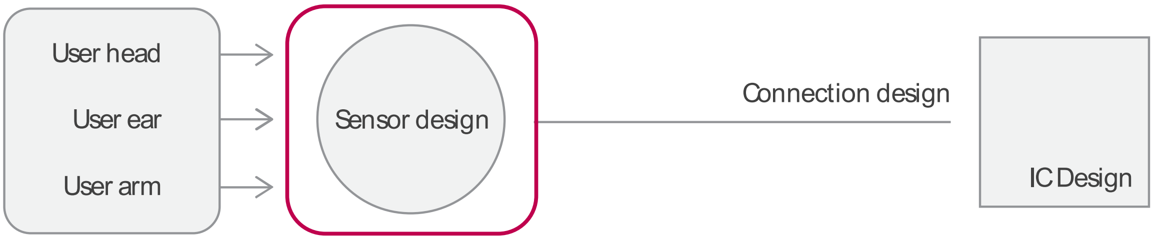


Figure 2.3 Typical use case may easily show 250fF under heating/cooling

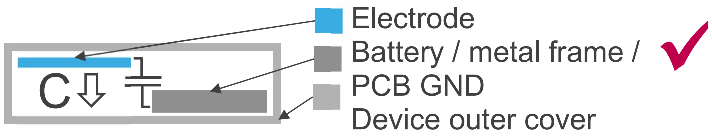
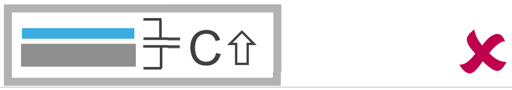
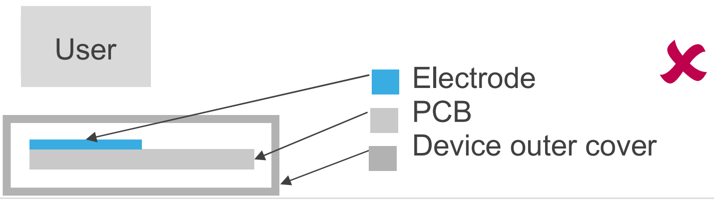
3 Sensor pad design



3.1 Area & GND reference

The sensor area and reference towards the system ground potential will directly impact the self-capacitance sensitivity of a wear detect sensor. This detectable range is commonly referred to as proximity sensitivity. Engineers should evaluate the sensor to ground relation and ensure the electrode can produce reasonable electric field distributions to be sensitive in the correct area or distance as required.

The minimum recommended electrode conductor area size for a proximity sensor is: $100mm^2$

Case	Picture	Description
1		Maximize distance between GND reference and sensing pad. Keep capacitance load low in sensing area
2		Keep parasitic capacitance minimum, especially in the sensing area
3		Avoid moving parts that may change the parasitic capacitance
4		Performance is limited when sensing through an air gap
5		Performance is optimized when closing the air gap. Performance is optimized when “extending” the sensing away from the main PCB (away from GND reference)

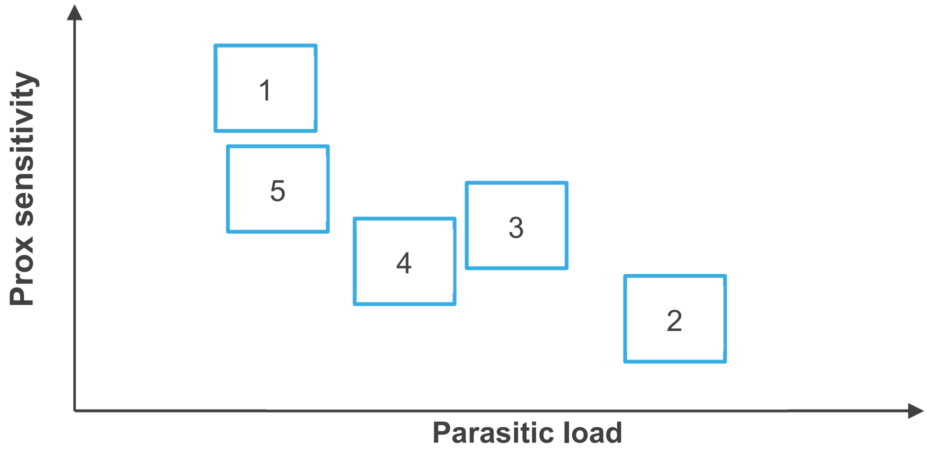


Figure 3.1 Proximity sensitivity trade-off with parasitic loads for the parallel plate examples illustrated in Figure 3.1

3.2 Sensing pad on battery

- Sensing pad is often place directly on the battery
- Performance is often better than expected, as explained in the following bullet points

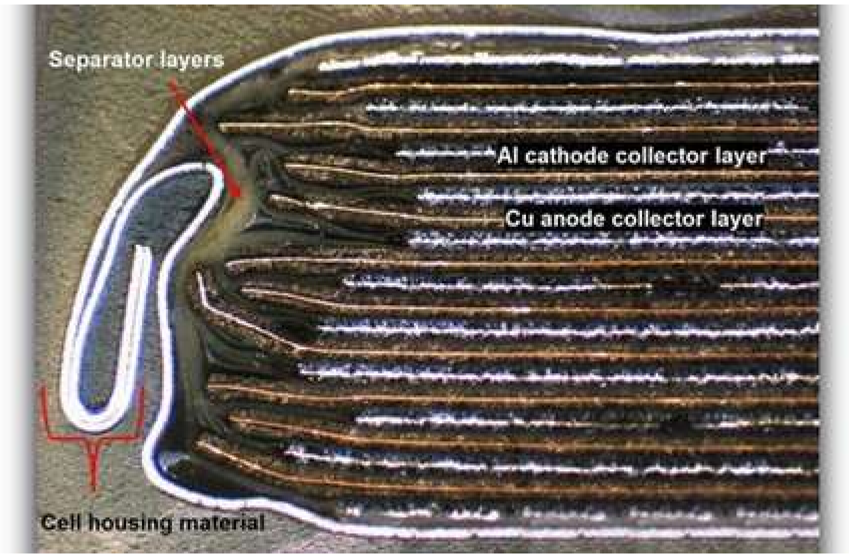


Figure 3.2 The side-profile of a lithium-ion battery showing housing material and other non-conductive layers

- Battery "housing" (material on the outside) is typically a combination of non-conductive and conductive material

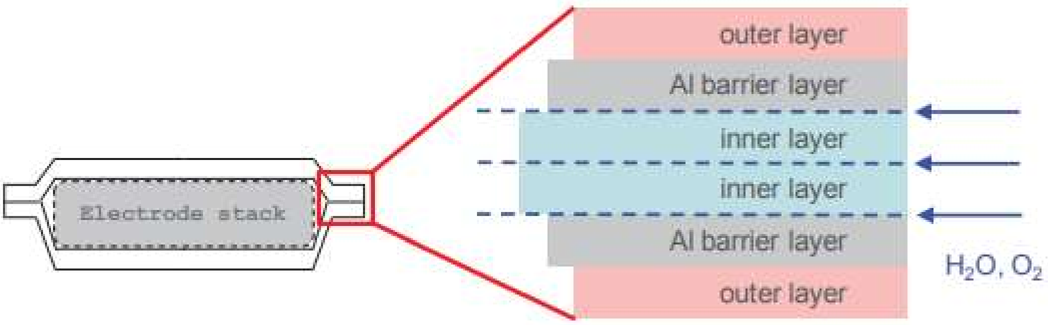


Figure 3.3 Battery side profile showing non-conductive layers and conductive layers (Aluminium barrier layer)

- The "Aluminium barrier layer" is a floating metal capacitively coupled to both the sensing pad and battery GND

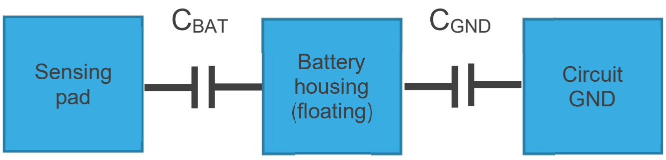


Figure 3.4 Battery housing effects on the sensor capacitance

- In such case, the battery housing itself is also part of the sensor, being charged and discharged indirectly by the sensor IC
- If C_{BAT} or C_{GND} can change during use or drop test, it will affect the wear detect performance

3.3 Shielding

According to Figure 3.4 it is recommended to minimize C_{BAT} by placing a coarsely hatched GND shield between the sensing pad and the battery.

Design guidelines:

1. Evaluate the total sensor pad area (in mm^2) required according to the examples provided in the next section. Keep in mind that the hatched GND shield will reduce the prox distance based on the parasitic load amount – keep this to a minimum for best sensitivity results.
2. Place a hatched pour on the opposite layer connected to the same GND as the IQS sensor.
3. Use the thinnest possible trace/track width as defined by the etching process' minimum limitation for the manufacturer (usually 0.15mm trace width for most FPC processes).
4. Use the formula: $\frac{\text{track width}}{(\text{grid size} + \text{track width})} \times 100\% = hatched\ GND\ \%$
5. Adjust the grid size parameter to manipulate the hatched GND percentage required.

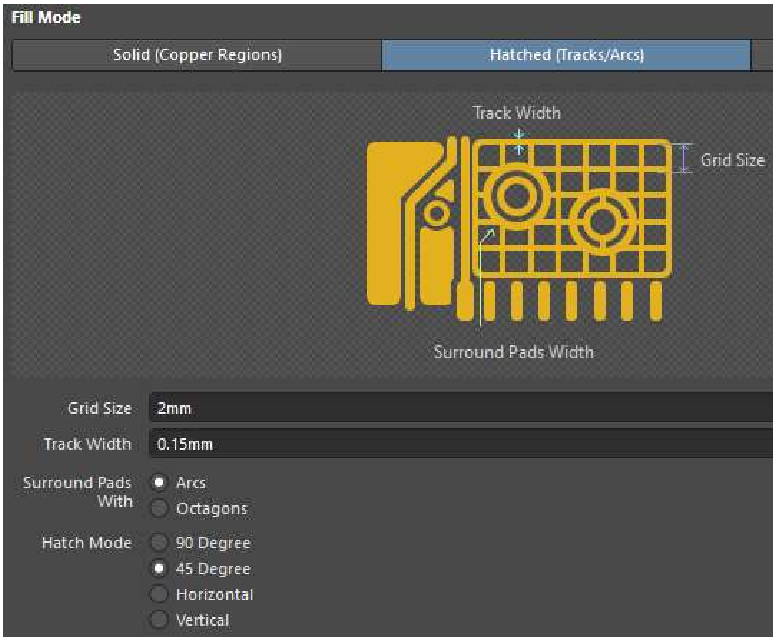


Figure 3.1 *Typical PCB design tool for placing a hatched GND pour shield over defined sense regions*

6. Evaluate the shape of the sense pad to use an appropriate hatched mode (45° / 90° / Horizontal / Vertical) depending on which mode best cover the sense pad uniformly over the complete area.
7. The following hatched GND percentages should provide acceptable results on a ±100mm^2 sense pad:
    a. 7% hatched GND – maximum shielding, highest parasitic load
    b. 5% hatched GND – average shielding, average parasitic load
    c. 3% hatched GND – minimum shielding, lowest parasitic load

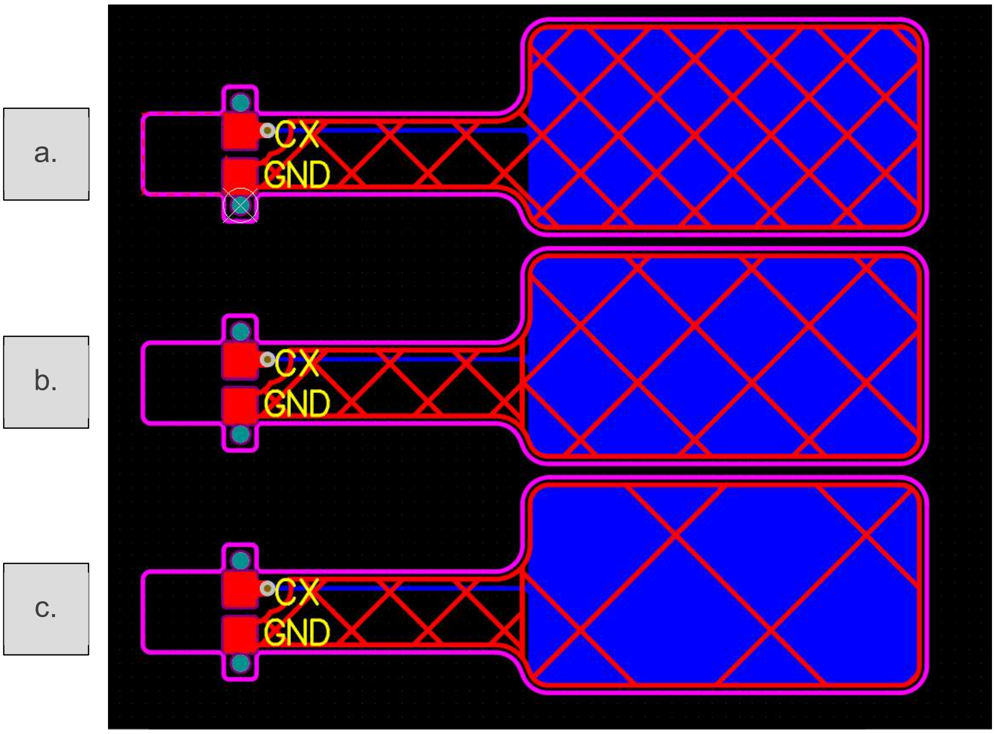


Figure 3.2 *From top to bottom: a. 7% hatched GND; b. 5% hatched GND; c. 3% hatched GND shields*

8. Decrease the hatched GND % to the minimum that can still successfully shield the sensor without false triggering during drop test and other battery movement induced use/test cases.
9. Evaluate sensor signal stability over temperature and long term activation.

3.4 Sensor pad size vs proximity detection distance

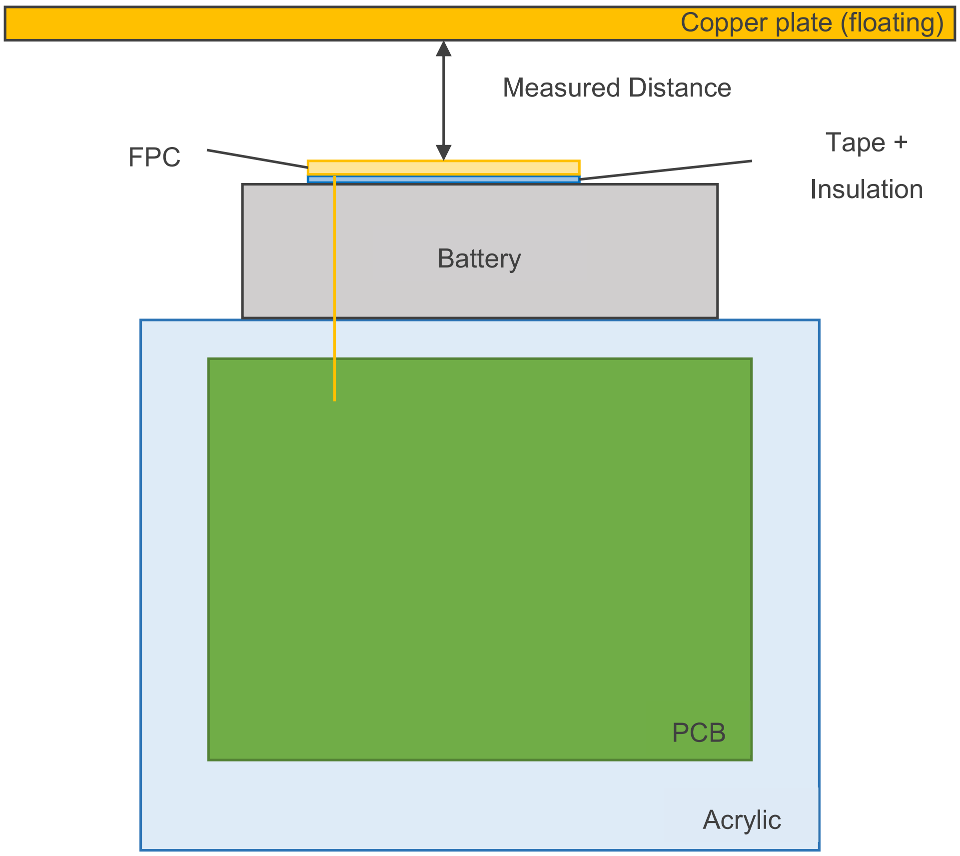
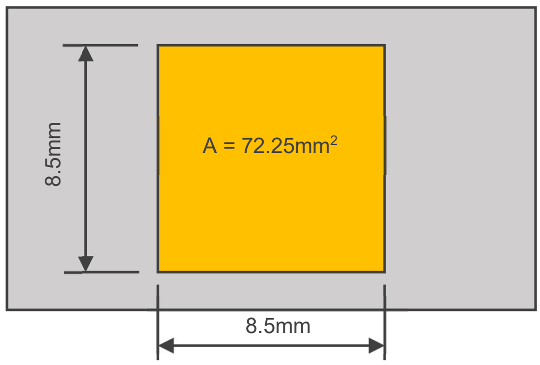
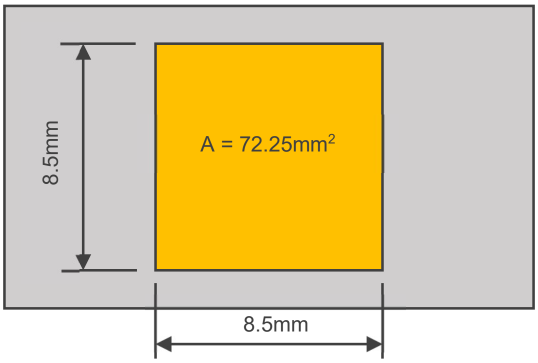
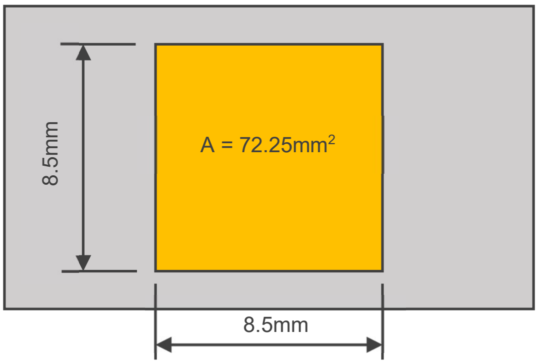
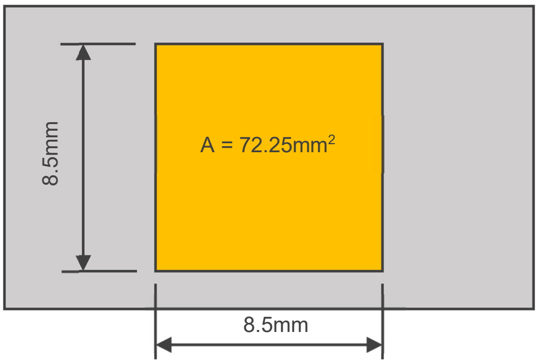
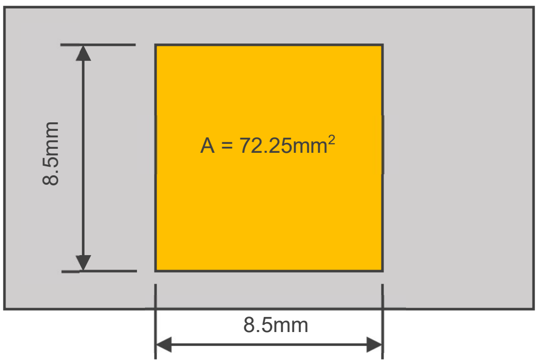
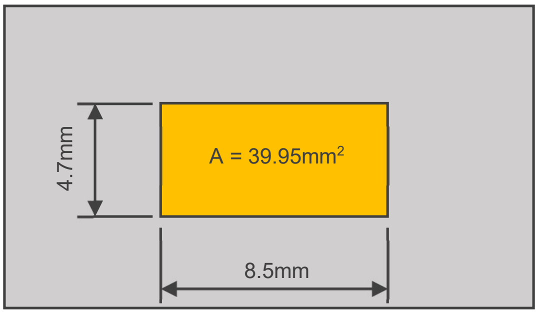
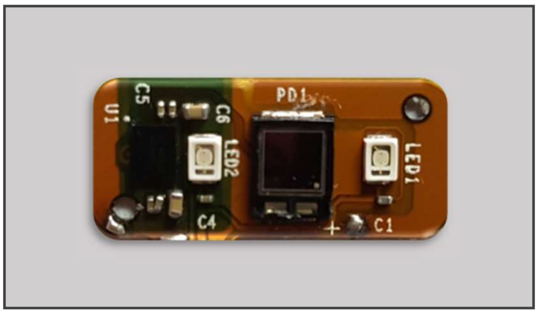
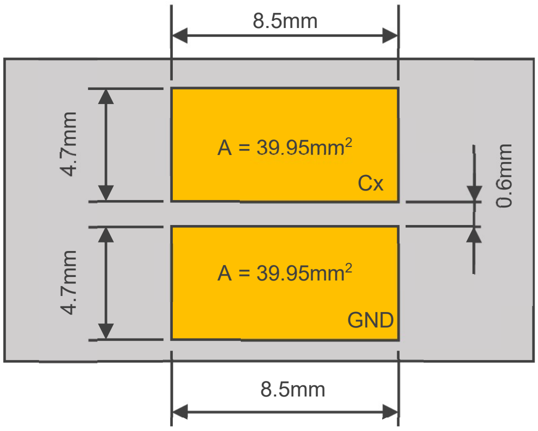


Figure 3.5 Test setup used to adjust the measurement distance for prox trigger (similar to a wearable use case)

Table 3.1 Test case examples sense pad sizes and layouts with resultant prox distance achieved

Test case	Picture	Result
Length = 8.5mm Width = 8.5mm A = 72.25mm^2 1 x Tape (0.1mm)		Prox Distance = 5mm

Length = 8.5mm Width = 8.5mm $A = 72.25mm^2$ 2 x Tape (0.2mm) 1 x Insulation (0.25mm)		Prox Distance = 5mm
Length = 8.5mm Width = 8.5mm $A = 72.25mm^2$ 3 x Tape (0.3mm) 2 x Insulation (0.5mm)		Prox Distance = 5.5mm
Length = 8.5mm Width = 8.5mm $A = 72.25mm^2$ 4 x Tape (0.4mm) 3 x Insulation (0.75mm)		Prox Distance = 6mm
Length = 8.5mm Width = 8.5mm $A = 72.25mm^2$ 5 x Tape (0.5mm) 4 x Insulation (1mm)		Prox Distance = 7mm

Length = 8.5mm Width = 4.7mm A = 39.95mm^2 1 x Tape (0.1mm)		Prox Distance = 2mm
Total Cx: A = ±40.00mm^2 1 x Tape (0.1mm) 1 x Stiffener (0.3mm)		Prox Distance = 2mm
Cx: Length = 8.5mm Width = 4.7mm A = 39.95mm^2 GND: Length = 8.5mm Width = 4.7mm A = 39.95mm^2 1 x Tape (0.1mm)		Prox Distance = 2mm

3.5 Placement & coverage

- Fitness band example: Two separate electrodes provides a larger coverage for different user bodies and loose wearing.

Figure 3.6 Example sensor placement in a typical fitness band employing dual sensor pads.

Fitness band example: With limited space on FPC/PCB for wear detect, fitness bands may benefit significantly by printing the sensor design onto the plastic body. This solves coverage issues along with being most stable sensor material choice. Choosing this process also enables the integration of Bluetooth & NFC antenna into the plastic casing.

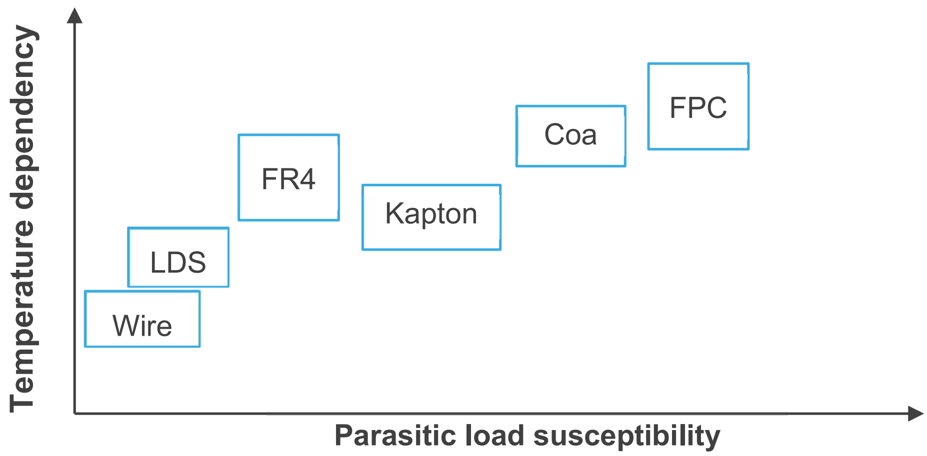
Figure 3.7 An example of a pattern placed on plastic

3.6 Material

Circuit and substrate material properties for capacitive sensors can vary significantly. Capacitive sensor conductor & PCB/FPC substrate types include copper tape, printed ink on plastic, traditional FR4, FPC variations, and simple insulated wire. Below are commonly used examples with preferred suitability for capacitive sensor use.

Table 3.1: Typical substrate materials and suitability for use as sensor conductor carriers

Material	ε_r @1MHz	Parasitic load susceptibility	Temperature stability
FR4 (N4000-29)	4.5	✓	✗
FPC (PET)	3.4 - 3.5	✗	✗
PI (Kapton)	3.4 – 3.8	✗	✓
Printed ink (on ABS) Or LDS technology	2.8	✓	✓
Co-axial (PTFE dielectric)	2.1	✗	✗
Insulated wire	≈1.0	✓	✓



3.7 Temperature

Body heat transferred to wearable devices (such as smart watches, fitness trackers & headphones which remain in close body contact for long periods) can impact the capacitive sensor measurements during long wear detect states.

> Electrodes in direct/indirect contact with a person's skin, ear or head is heated first and more significantly than the rest of the system design.
> Differential changes to a sensor IC and sensing electrode cannot be accounted for with only an internal compensation method (an external reference channel is also required).
> Substrate materials' thermo-dynamic properties plays a significant role and the effect is most drastic in thin FPC designs.

Please refer to the next section for detail discussions regarding this topic.

3.8 Water immunity

Most wearable devices are waterproof or -resistant with complex mechanical design to seal off housings containing electronic parts.

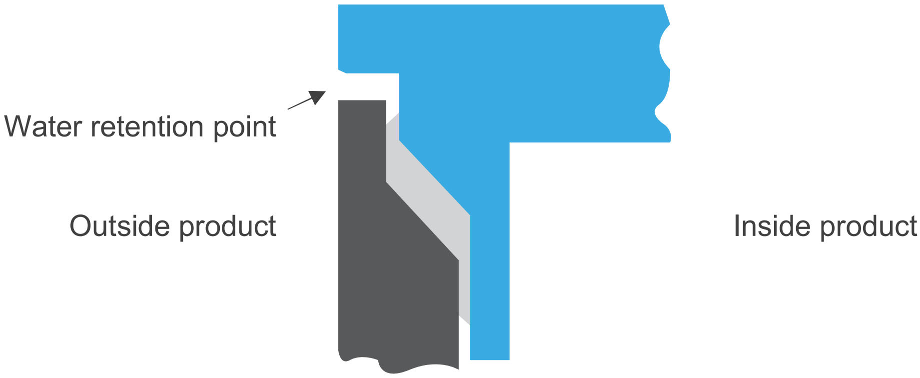


Figure 3.8 Ultrasonic weld with the risk of water retention

> Joins in plastic molded housings (with seams/gaps/cavities/junctions) can still retain moisture outside the housing. If this moisture is situated/captured near or on-top of a capacitive sensor it will affect the capacitive sensor reading & performance significantly. This can result in incorrect wear detect outcomes.
> Change in environmental conditions due to humidity, condensation & evaporation can sometimes

lead to inaccurate wear detection/release states. Early design phase testing is recommended to identify problem areas.

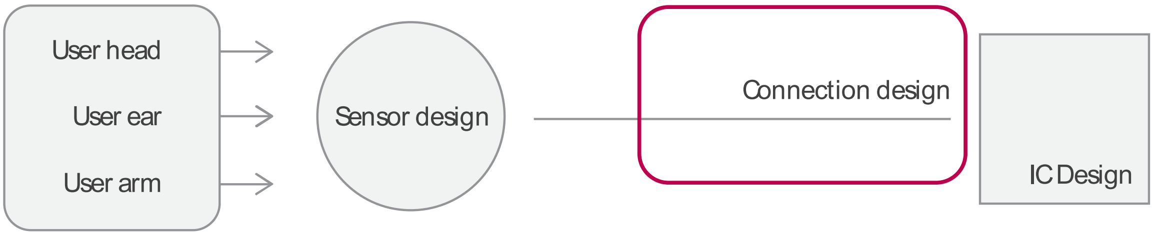
3.9 Moisture

If a design is highly susceptible to moisture changes (typical for devices that are not waterproof) – please refer to the next section discussing substrate material & moisture absorption influences.

As example, over-ear headphones with sensing pads in the ear cup have an increased risk for moisture effects. Moisture increase and moisture retention during wear will typically result in a failure to release (or significant release delay) when removed from the head.

Avoid these effects by using materials that are not sensitive to moisture like LDS (plastic printed sensing pads) on the reverse side of the area that is moisture sensitive.

4 Connection design



4.1 Length & Area

When sensor lines need to be routed from the IC towards the intended sensor pad/area, a proper connection design is required. Please take note of the following concerns:

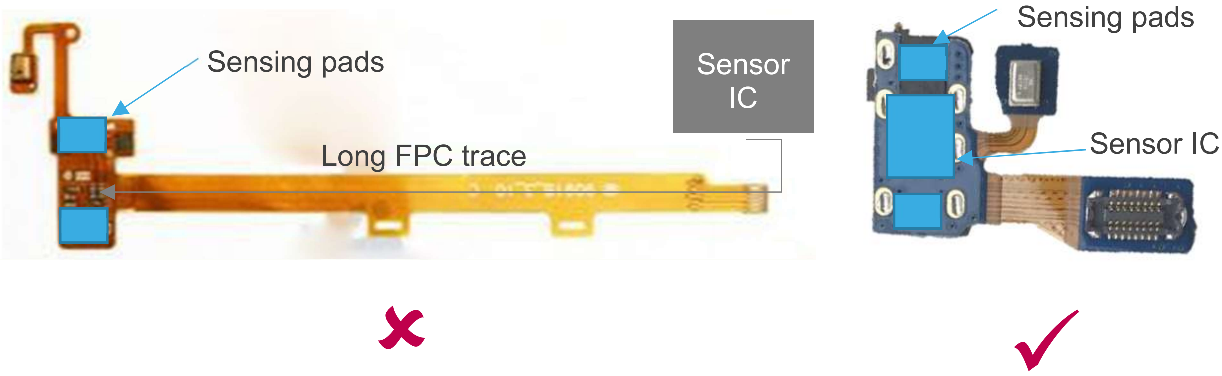


Figure 4.1 Longer routing of sensing line complicates the design and limits performance, while short routing simplifies design and optimizes performance

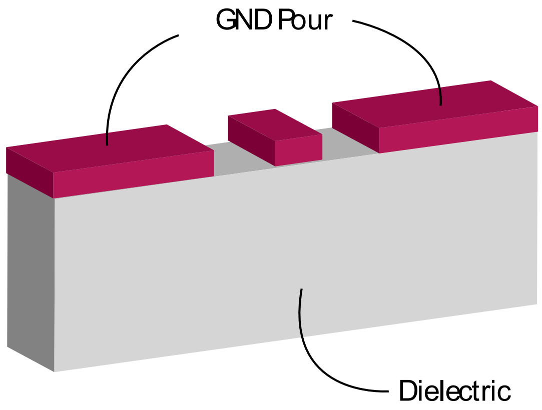
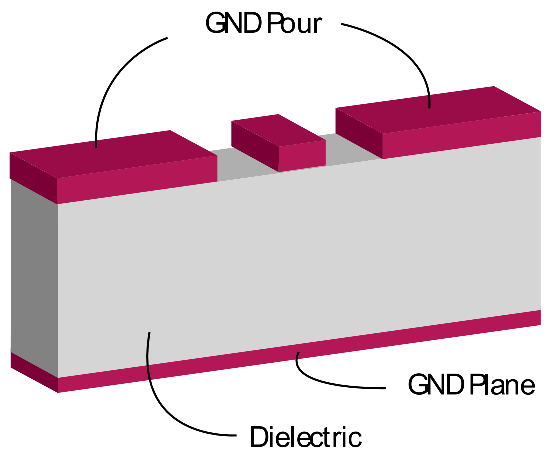
> Longer traces are more susceptible to any form of interference.
> Larger areas are more susceptible to significant capacitance changes as a result of temperature and humidity changes.
> Be careful with stacked areas / layered areas (multi-layer PCBs, thin FPC's etc.)
> Mechanical disturbances can alter the signal when referenced to other conductors/potentials.

4.2 Ground effect & material choice

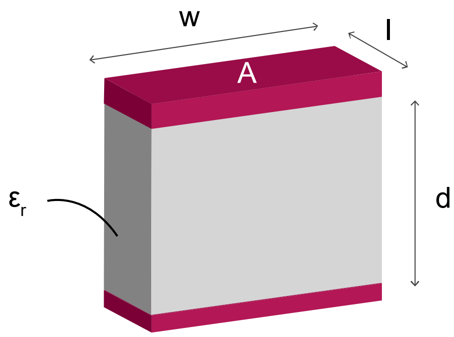
Connection design (i.e. sensor traces/lines) can contribute a significant amount to parasitic capacitance in a sensor.

Substrates between 2 (or more) conductors have significant more parasitic capacitance (C_p) than conductors in the same layer or simply single layer PCB's with other material layers on top / in contact like solder mask, plastic housings etc.

Table 4.1: Single layer vs. overlapping multi-layer trace-to-plane coupling

Single layer copper recommended for sensor connections	GND plane not recommended for sensor connections
 ✓	 ✗

First principle's parallel plate capacitor analogy (Cx – GND):



d

Figure 4.2 Parallel plate capacitor parameters

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

> ε_r: Relative dielectric constant (unitless)
> ε_0: Dielectric constant of air = 8.854 x 10^{-12} F/m
> *A*: Plate area (m^2)
> *d*: Distance of separation between plates (m)

Table 4.2: Commonly used printed circuit substrate materials and their typical range of parasitic capacitance contributions observed for a 1mm^2 area double sided (parallel plate) example

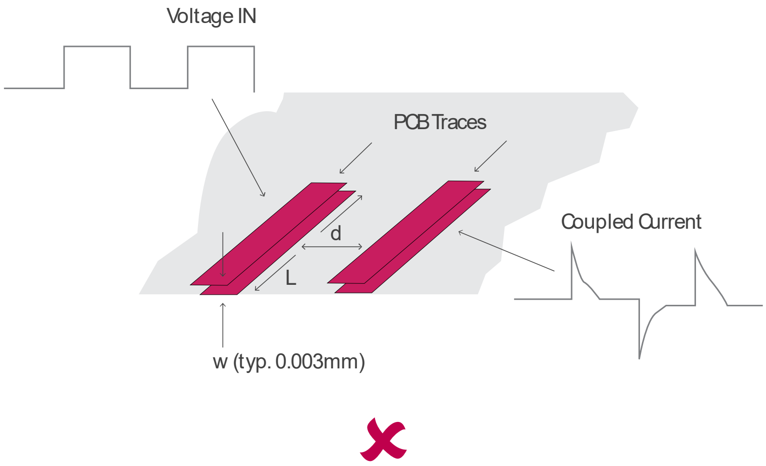
Material	ε_r @1MHz	Typical *d*	$C_{p\text{-}max}$ (per A = 1mm^2)
FR4 (N4000-29)	4.5	0.8mm	0.05 pF
FPC (PET)	3.4	0.025mm	1.2 pF
PI (Kapton)	3.4	0.1mm	0.3 pF
Printed ink (on ABS)	2.8	1mm	0.025 pF
Co-axial (PTFE dielectric)	2.2	0.5mm	0.04 pF

4.3 Interference

Table 4.3: Parallel coplanar vs. orthogonal noncoplanar trace crossing and coupling

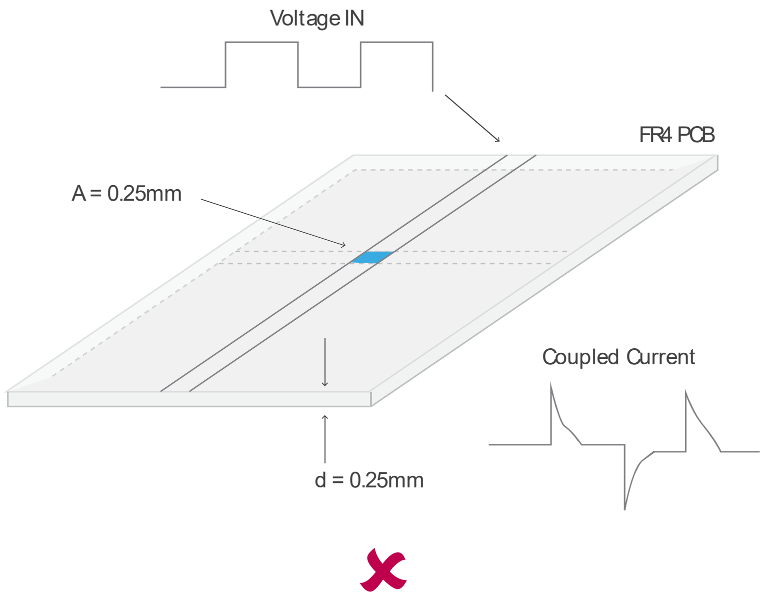
Sensor connections must be shielded against PCB trace coupling.

This applies to other traces with switching signals or where the DC voltage of the line is changed at some point (GPIO/LED type signals)



Sensor connections must avoid crossing other lines (on a different routing layer) where signal may switch or change voltage level.

If it cannot be avoided, 90-degree crossing is recommended to minimize the coupling area. Minimum trace thicknesses are recommended to reduce the parallel crossing area.



4.4 Moisture absorption

Moisture, absorbed by a substrate, increases the dielectric constant (ε_r) of the material which translates to an increase in parasitic capacitance (C_p) for any parallel conductive sensor plates.

Bare, uncoated laminates have shown higher moisture absorption rates compared to boards covered with solder mask.

Table 4.4: Typical water absorption rates for commonly used PCB/FPC substrates

Substrate material	Water absorption rate (wt.%)	Relative dielectric change (ε_r)
FR4	0.15	±0.04
Polyimide (PI)	0.35	±0.10
Mylar	<0.80	±0.20
PTFE	0.02	±0.01
Hi-Pref FR4	0.50	±0.15
HF Hydrocarbon	0.06	±0.02
Phenolic paper (FR1/FR2)	>0.75	±0.20

From experience, moisture can have an impact in over-ear headphones where a PCB is not enclosed in a housing and an earcup encloses the user's ear and traps moist/humid air together with an increase in temperature due to body heat.

However, the presence of humidity can still impact a capacitive sensor measurement, even when using an appropriate substrate material and enclosure with a low moisture absorption characteristic. The external changes to the airgap in between the user and the sensor plate still can still change dynamically regarding the relative humidity content change. The figure below indicates an example of how drastic effect humidity can have.

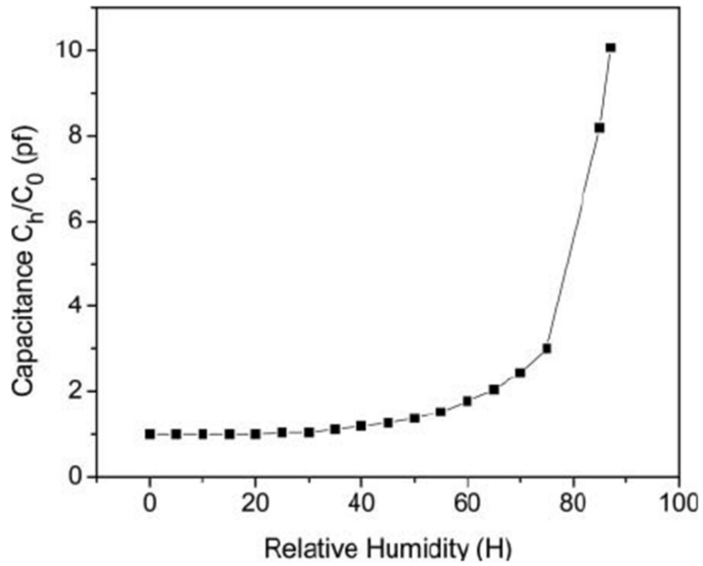
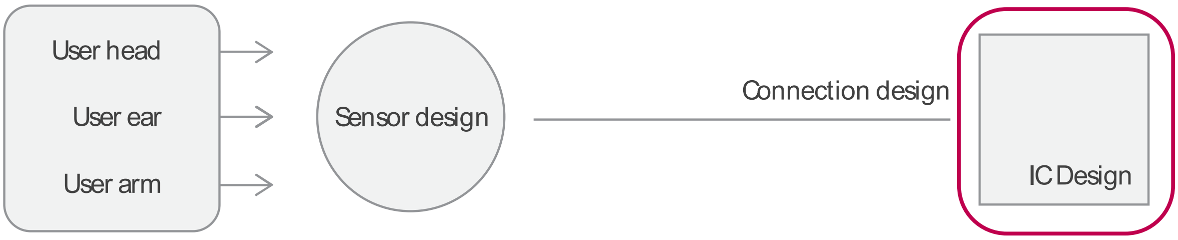


Figure 4.3 Capacitance vs. relative humidity relationship[p for the Al/VOPcPho/Au capacitive sensor based on VOPcPhO

5 IC design



5.1 Choose the device

Decide on a specific IQS device based on the number of channels required and offered.

Wear detect recommended devices:

> IQS620A – 2 CX pins (self-capacitance only); 3 software channels
> IQS269A – 8 CX pins (self & projected capacitance); 8 flexible software channels
> IQS626A – 8 CX pins (self & projected capacitance); 3 flexible software channels

Recommended: Reserve 2 channels (two separate sensor CX pins) for wear detect. See "reference channel" implementation below.

5.2 Optimize settings

Although latest IQS sensors (as recommended above) boast various soft configuration options to adjust sensor performance, it is still of utmost importance to first succeed in a proper hardware design (according to the guidelines above), before settings are selected to fine-tune performance.

Recommend sensor settings for wear detect are as follow:

> Slow charge transfer frequency (500kHz or lower) recommended.
> Base value >= 100 counts and a target ± 1000 counts.

Hardware optimization is critical for mass production success. Verification of sensor parameters (multipliers & compensation) during pre-production & mass production is recommended to limit performance spread and identify and isolate fabrication failures or design flaws.

5.3 Reference channel – internal & external device reference (IC & layout based)

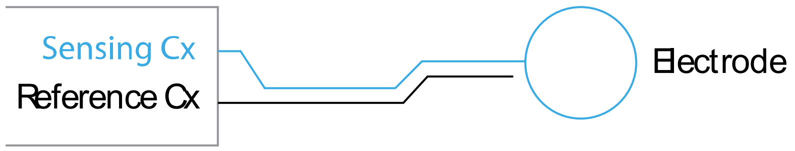


Figure 5.1 Diagrammatical use of a main & reference sensor to account for similar routing parasitic

Advantages of using a "sensing" & "reference" channel:

> Offers the best wear detect performance
> Optimizes sensor integrity in wearable wide operating environments
> Covers environmental changes in IC, PCB & FPC all at the same time

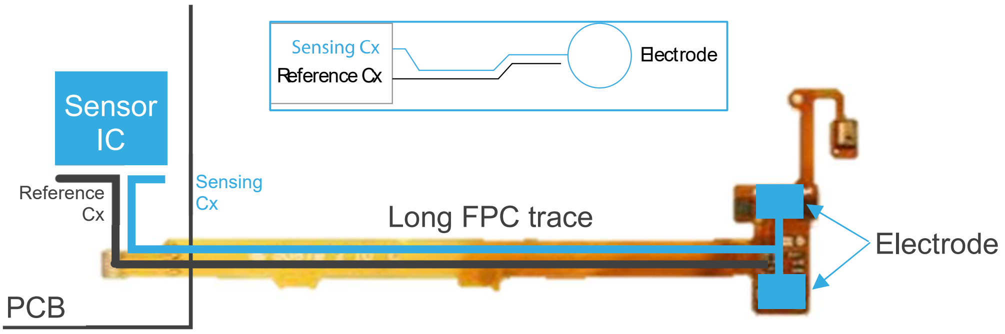


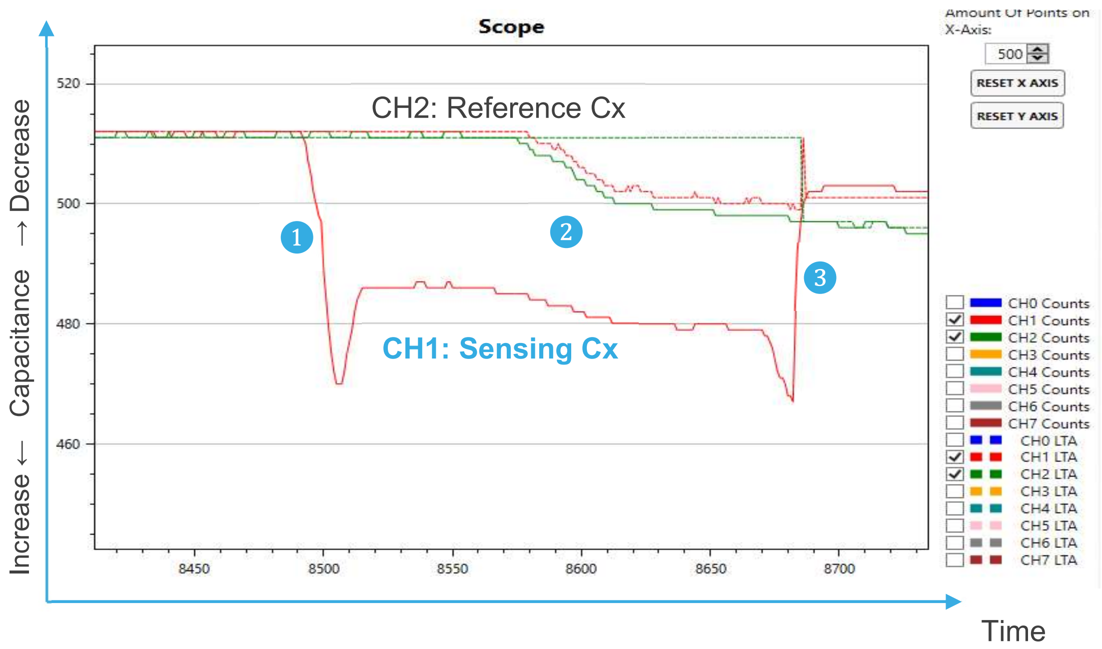
Figure 5.2 An example where sensing is done a distance away from the IC. Here "reference tracking" is required for accurate triggers over a long time

Table 5.1 Typical cases performed on the sensing and reference channel combination

Cx Actions	Sensing Cx	Reference Cx
Electrode – no touch	**LTA[1] slow adapt**	LTA slow adapt
Electrode – proximity / touch	**LTA freeze[2]** **Sensing ∆ ≥ Prox/Touch**	LTA freeze Reference ∆ ≈ 0
Electrode – proximity / touch (+ large temperature change)	**LTA = LTA freeze – Reference ∆** **Sensing ∆ ≳ Prox/Touch**	LTA freeze Reference ∆ >> 0
Electrode – no touch (+ fast temperature shock)	**LTA = Sensing signal** **Sensing ∆ = 0**	LTA freeze Reference ∆ ≥ Prox

[1] Long term average (LTA) is a filtered average of the actual sensing signal.

[2] "LTA freeze" means the LTA is not actively updated while it is used as a reference for the proximity / touch threshold. Typically, the LTA will freeze when a proximity threshold is reached.



Step 1	Step 2	Step 3
Sensing channel trigger. Now reference channel is actively affecting CH1	Heating of PCB. Now, changes on CH2 is applied to reference (LTA) of CH1	Release is successful because the LTA was adapted via the reference channel

5.4 Reference channel – internal device reference (IC based only)

When requiring a more simple and cost-effective option:

> a few good options exist such as the IQS620A & IQS624
> these come with only 2 CX sensors and no on-chip reference channel UI execution
> these can be used for wear detect with careful design

In such cases the following is recommended:

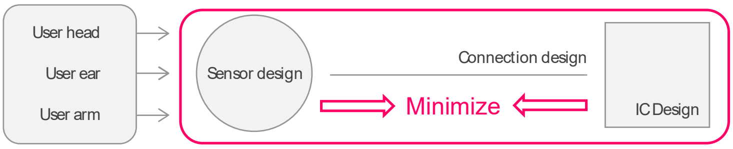
> Use one channel as the main sensor and the other (suitably routed/allocated and perhaps capacitively loaded) as a reference channel.
> The host/master MCU is required to retrieve and process capacitive measurement data to ensure environmental changes are detected and compensated for.
> If both CX's are used for application sensors (touch interface & wear detection):
  > it is possible to enable an internal temperature conversion channel
  > this is to track any temperature changes experienced by the IC itself
  > in this case, the influences experienced by the sensor electrode and IC should be common and in close relation for successful reference adjustment (if necessary).

The above mentioned (internal temperature-based referencing) is not recommended as a fail-safe solution as some designs are more susceptible to complex, dynamic external changes not common experienced/recognized by the IQS IC.

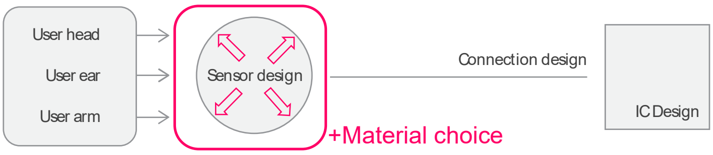
6 Recommended design flow

Follow the steps below to properly prototype, design and evaluate sensor performance for wear detect applications:

1. Place the IQS IC as close as possible to the sensor pad (minimizing the parasitic capacitance load and reducing the area/length of sensor traces exposed to possible noise/environmental changes)



2. Define usable space (sensor conductor area) and suitable materials to be used as carrier substrates and overlays.



3. Choose materials and sense pad size according to the topics discussed in this document.
4. Prototype a design as close as possible to the intended product before fixing mechanics.
   a. Debug a specific design and sensor operating environment with Azoteq tools (evaluate relative counts (delta) changes, measure absolute capacitance changes, ensure decoupled supply evaluations for battery applications etc.).
   b. Test environmental changes (temperature, humidity, mechanical movement etc.) at early design stages.
   c. Employ the use of reference channels where deemed necessary and iterate to ensure suitable reference tracking/blocking is obtained.
5. Fix materials and sense pad size according to the prototype results/optimizations.
6. Confirm final designs to prototype test results through similar/repeated tests and actual user wear tests in different environments (hot, cold, sweat, water, etc.) over long periods of time.

For any additional, detailed enquiries regarding design, debugging and testing please contact Azoteq.

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