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Low capacitance test solution (Proof-of-Concept)

Armando Bonilla Fernandez

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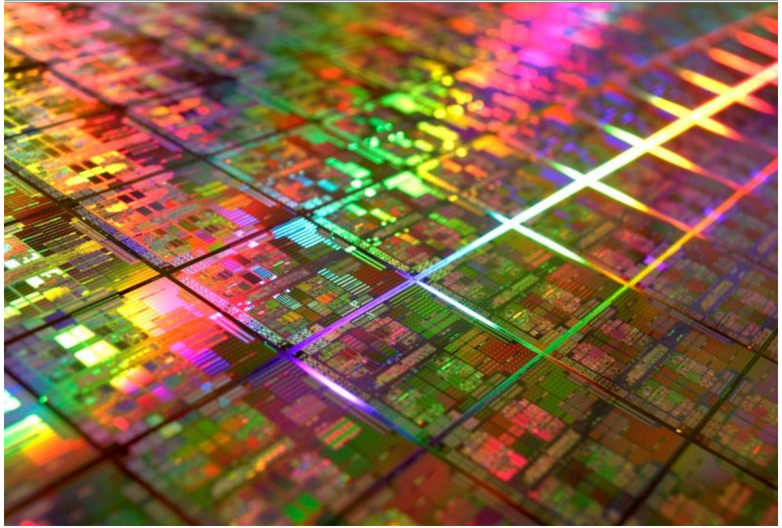
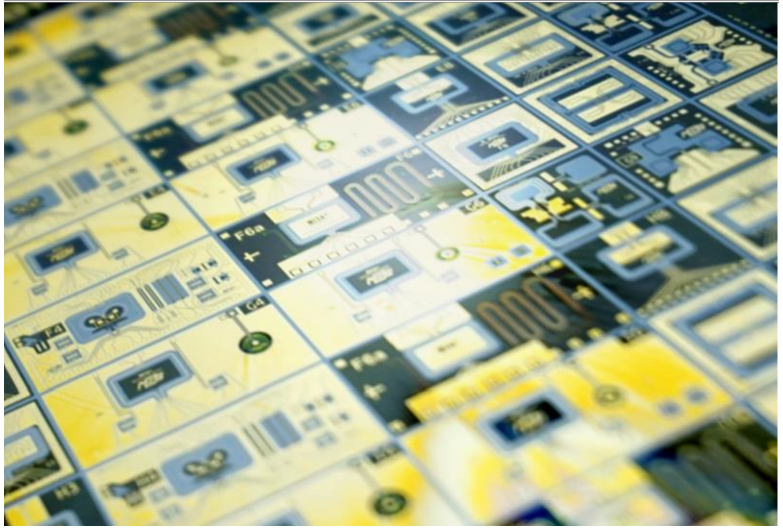
1. Introduction

More than Moore from an engineer's perspective

Integrated circuits



MEMS



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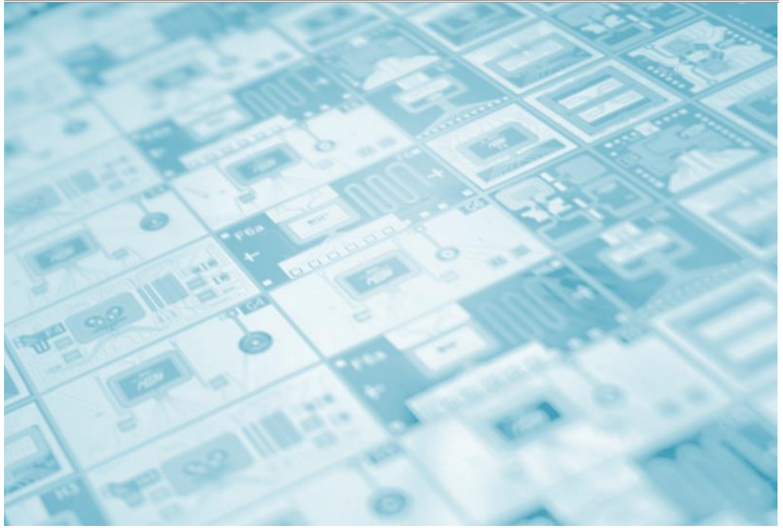
More than Moore from an engineer's perspective

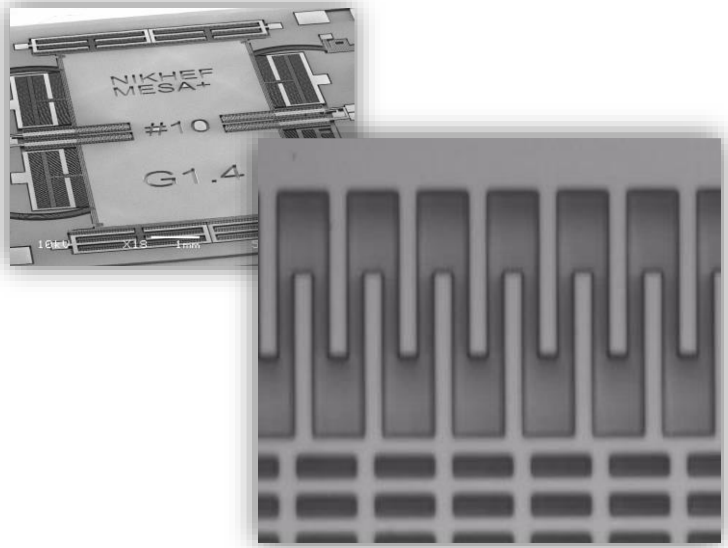
Integrated circuits

- Input: electrical signal.
  Output: electrical signal.
- Designer does not really has to care about fabrication technology.
- A default package usually does the job.
- Testing on an ATE.

MEMS



MEMS: Nano-g accelerometer



- Electrostatically pull the mass.
- Measure the capacitance.
- Impulse response gives information about electrical and mechanical behavior!

📖 B. A. Boom et al., *Nano-G accelerometer using geometric anti-springs*, IEEE MEMS, 2017.
📖 P. Kamp, *Towards an Ultra Sensitive Seismic Accelerometer, MSc thesis, 2015.*

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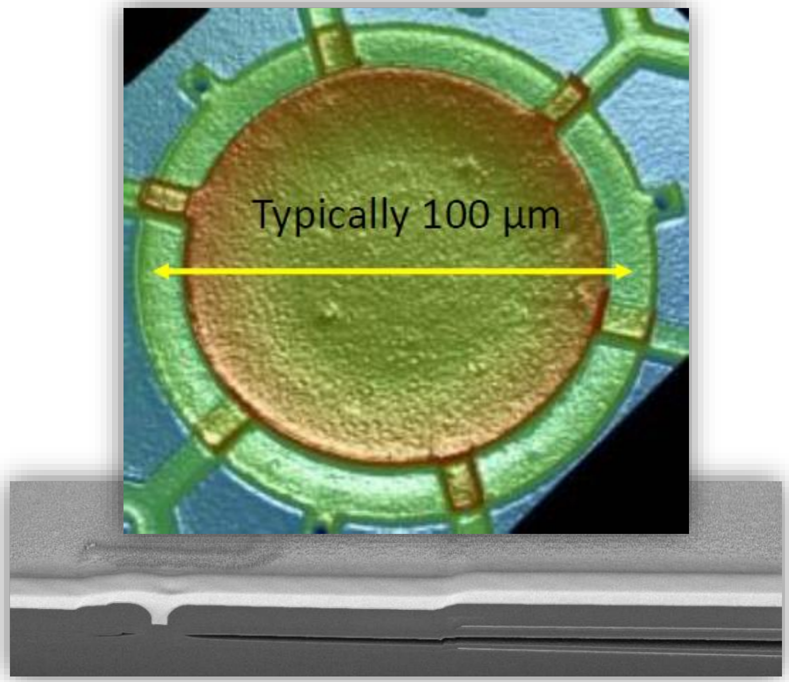
Capacitive microfabricated ultrasone tranducer (CMUT)



- Membrane with an electrode.
- Operates as speaker when electrostatically actuated.
- Operates as microphone when capacitance is measured.

🕮 Philips Innovation Services.

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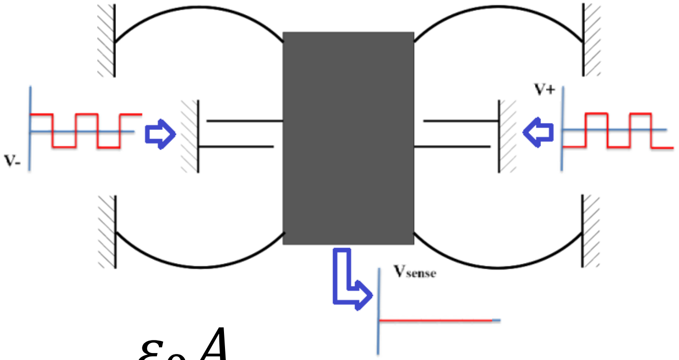
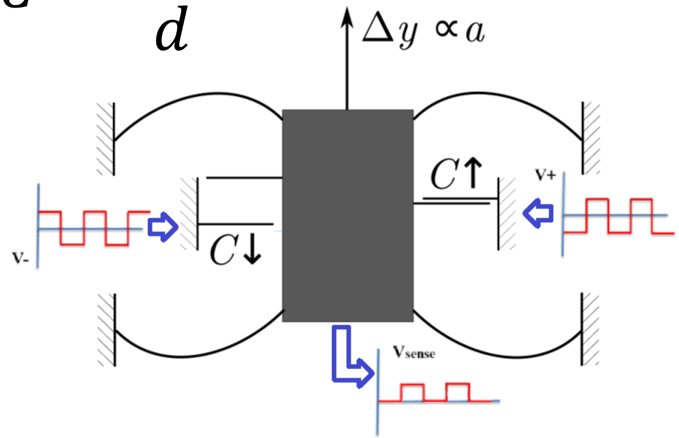
Capacitive Read-out

- The use of MEMS is growing.
- One of the biggest applications: Sensing.



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



Capacitive Read-out offers:

Low

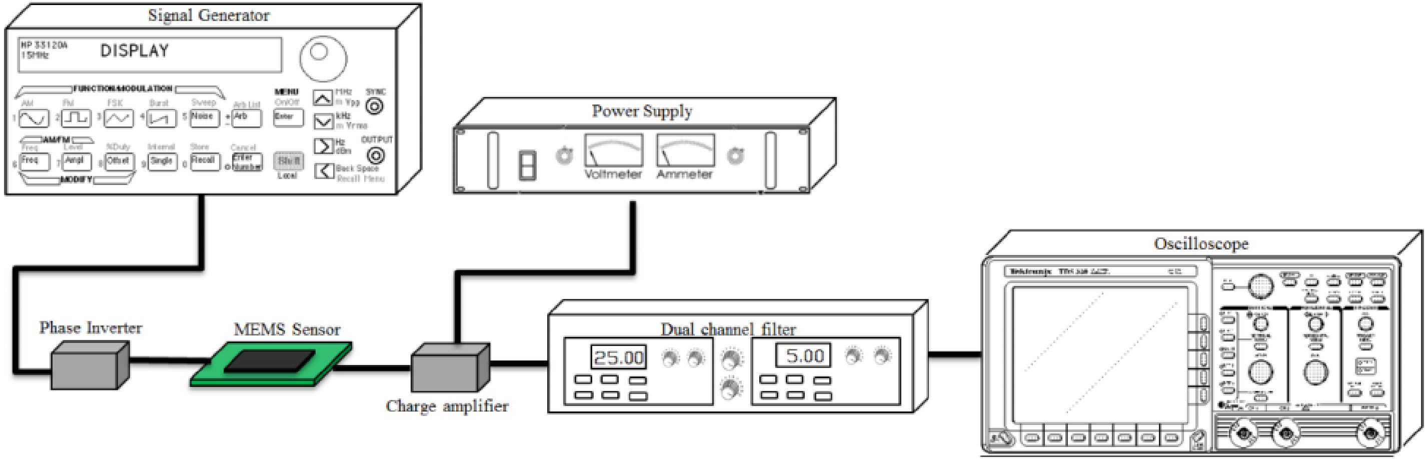
- ➢ *Temperature Coefficients*
- ➢ *Power Dissipation*
- ➢ *Noise*
- ➢ *Fabrication Cost*

2. Motivation

Our motivation

- Due to the advantages and widespread use of Capacitive read-out, we want to create a measurement system that is:

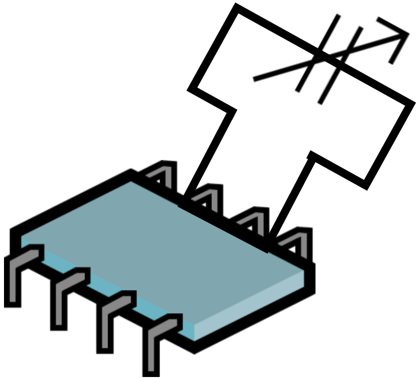
▶Accurate
▶Repetitive
▶Small Footprint
▶ Suitable for ATE



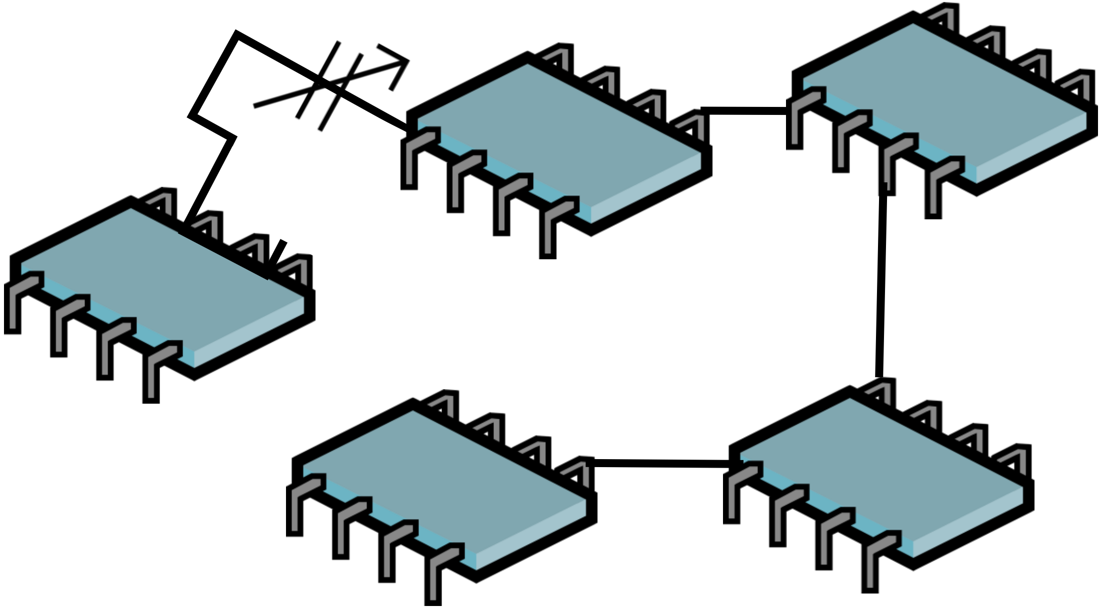
3. Design

The design options

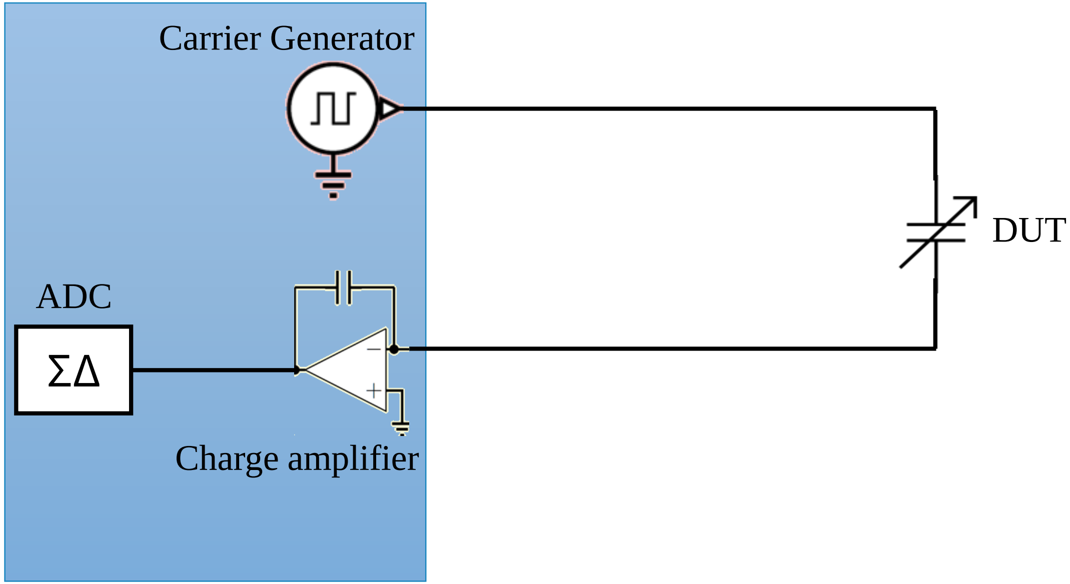
- *Single chip*



- *Multichip*

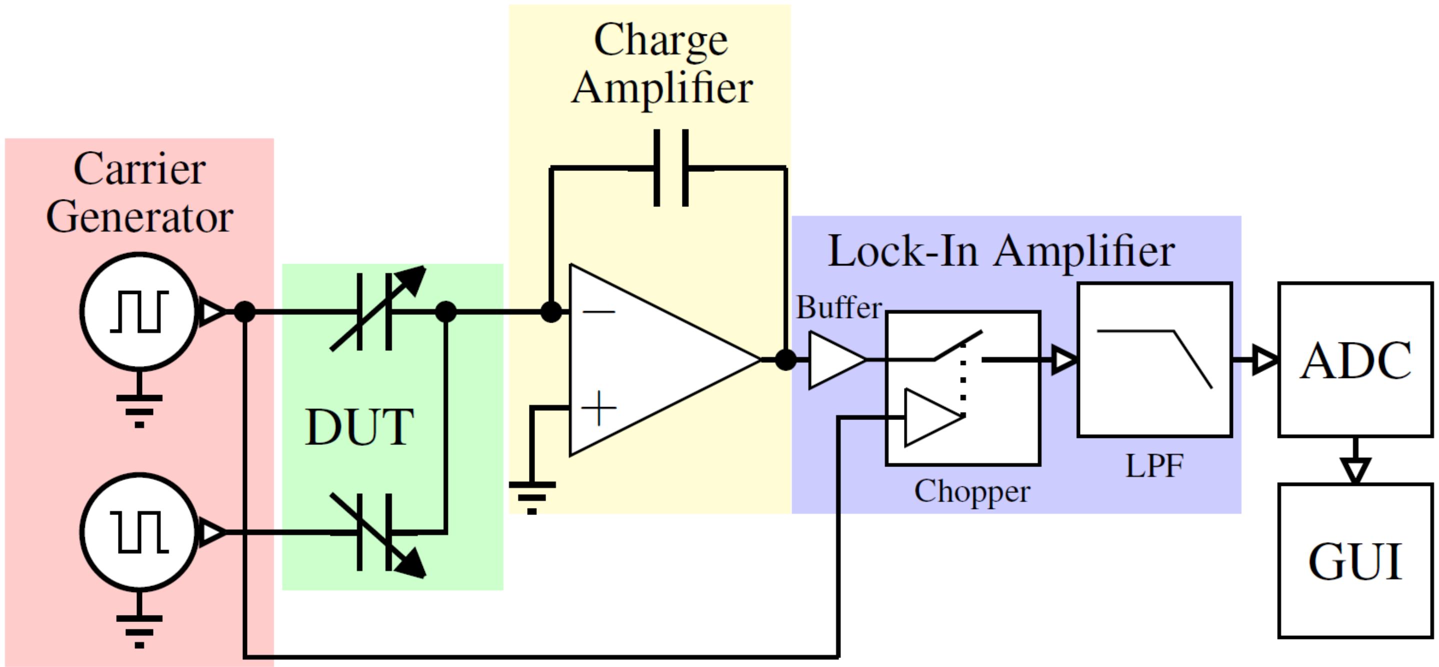


Single Chip Design Overview



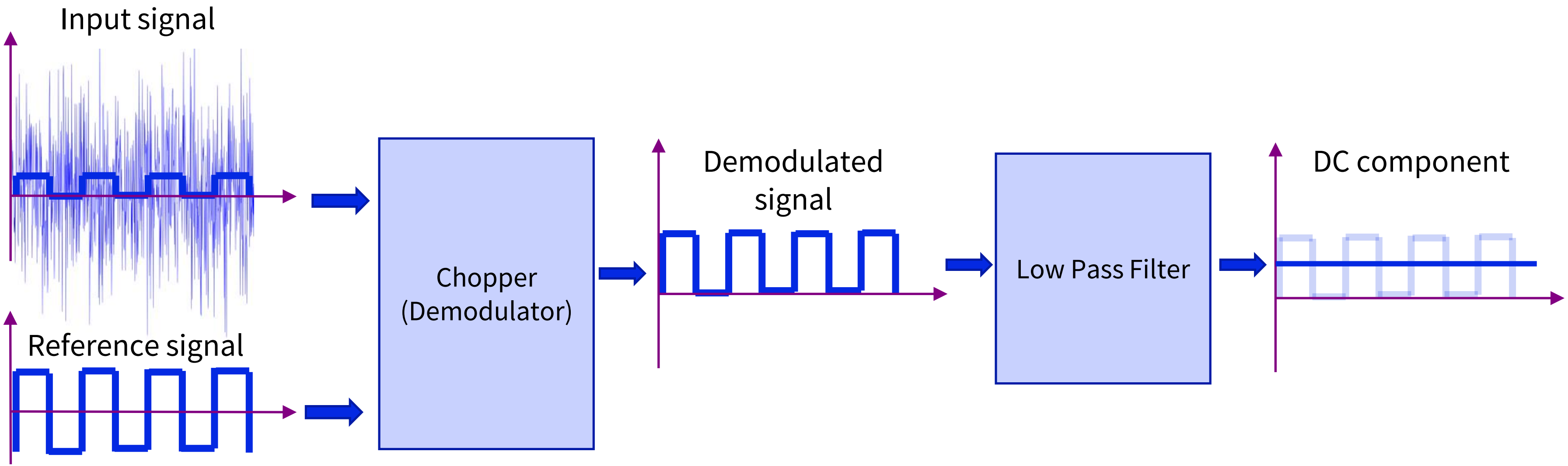
Block diagram showing the main components of the *single chip* capacitance measurement system.

Multichip Design Overview



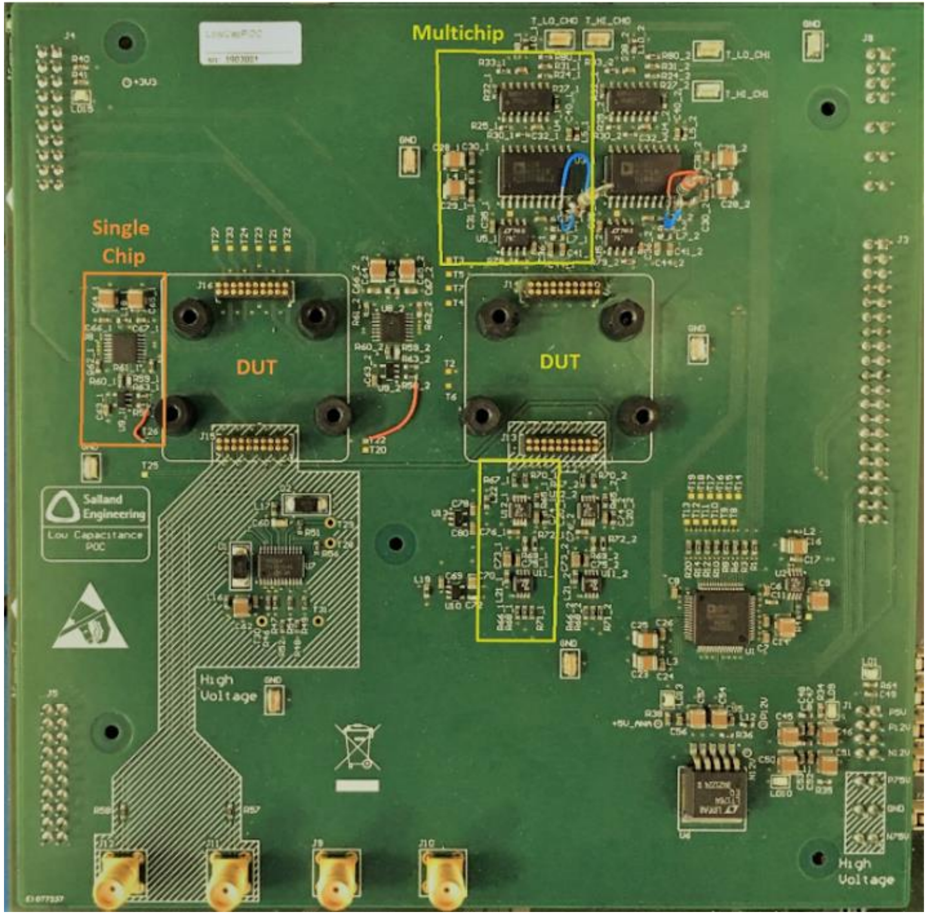
Block diagram showing the main components of the *multichip* capacitance measurement system.

Measurement concept: Lock in amplifier



PoC PCB

- PCB with 2 single-chip channels, 2 multi-chip channels and a high voltage MEMS driver.



4. Specifications

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Salland’s Low Capacitance Measurement solution

Target Specifications

- Target to a 8 channel Low capacitance PXIe instrument
  - ▶ Range: sub pF (extendable to nF)
  - ▶ Accuracy: ≈ fF, Resolution: aF
  - ▶ Frequency up to 2MHz
- Suitable for high volume
  - ▶ High parallel => many channels, small =footprint, “immune for long wires”
  - ▶ Efficient => Fast measurements and high Parallel efficiency
- Develop the technology to use it in several formats
  - ▶ PXIe (8 ch), Modules, ATE, etc.
  - ▶ MEMS, IoT Market, etc.

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Salland specifications vs equipment available in the market

	Salland PoC Specifications	Salland (Instrument Target spec)	Keysight	Solidus	Target
Capacitance Range	±7.5pF	±5pF (0fF to 5000 fF diff.)	0 to 1pF	±4pF	±4pF
Settling time	3ms	3ms			-
Accuracy	~4fF	~4fF	10fF		4fF
Resolution	18 bit (≈ 40 aF)	18 bit (≈ 40 aF)		24 bit	-
Carrier Frequency	100kHz to 300kHz	30kHz to 2MHz	1MHz	1MHz	≈2MHz
Carrier Waveform	Square	Square			
Carrier Amplitude	1.8 V rms	0.5V, 1V, 1.5V, 2V (rms)	0 to 2V	±5V	-
Noise	±4fF	±4fF			-
V DC Bias	External up to 75V	±15V	+20V	±8V	-
No. of DC Bias Ch.	1	8	1	1	1
Number of Meas. Ch.	2	8	16	4	≥8
Phase Angle Meas.*	Not Supported	Not Supported	Yes	Yes	-
Max. cable length	Tested up to 1.6m	1.0m	0, 1, 2 or 4m		1.0m

*Resonance frequency and Q factor can be calculated with Amplitude vs Frequency.

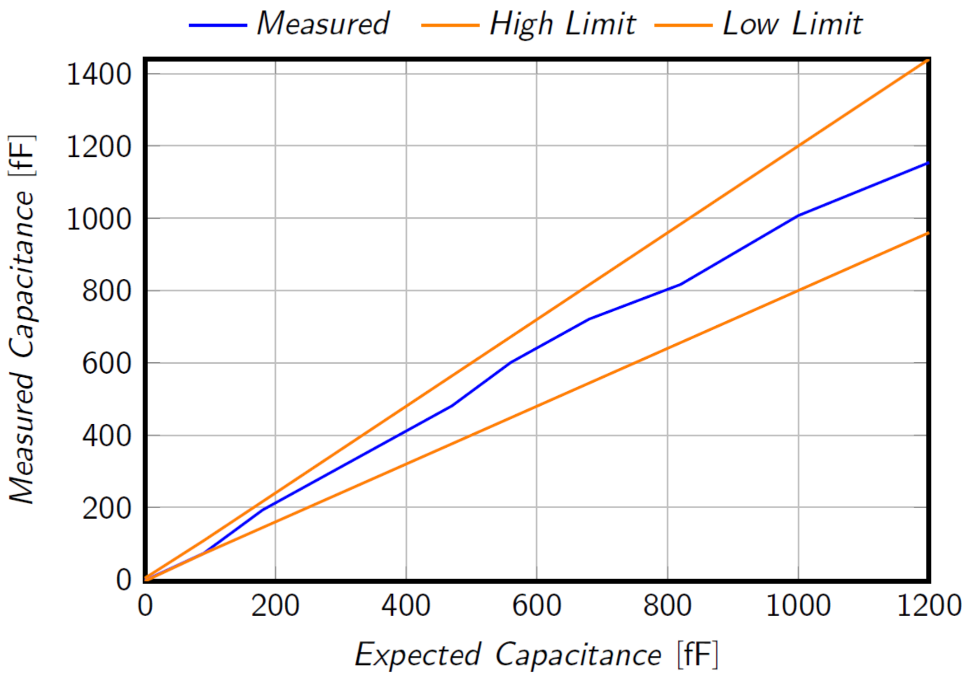
5. Results

POC Results: Accuracy of low capacitance meter

Measured Capacitance	Single Chip		Multichip		Noise Multichip (fF)
	Ch1 (fF)	Ch2 (fF)	Ch1 (fF)	Ch2 (fF)	
0.0pF (Open circuit)	0.4	0.4	-2.35	-0.15	±3
0.47 pF ± 0.25pF (N_Inv)	-	529.29	-	527.37	±2
0.56 pF ± 0.25pF (Inv)	-	-604.71	-	-600.96	±2
0.47pF - 0.56pF	-	-73.06	-	-71.83	±3
1pF ± 0.25pF (N_Inv)	1006.12	-	1007.30	-	±4
0.82pF ± 0.25pF (Inv)	-821.42	-	-816.93	-	±4
1pF-0.82pf	186.64	-	192.62	-	±3
0.47pF – 0.47 pF	-2.21	-	-1.99	-	±1
1.2pF ± 0.25pF (N_Inv)	Measurements of known capacitance on DUT board.			1153.12	±4

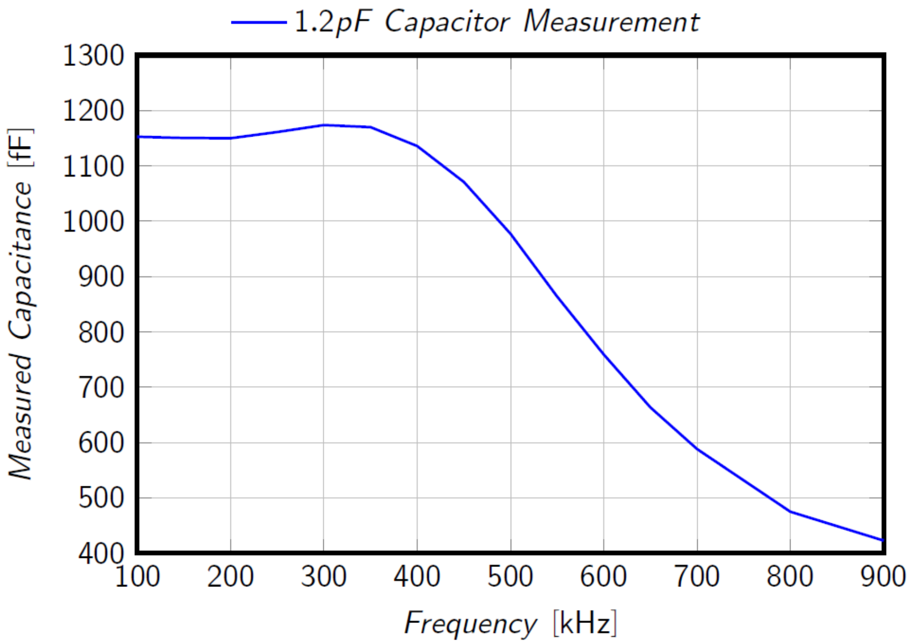
Accuracy of low capacitance meter

- ➢The expected capacitance is measured from capacitors with ±20% tolerance.
- ➢ Measurements executed on 0, 90, 180, 470, 560, 680, 820, 1000 and 1200fF.



Effect on measured capacitance from carrier frequency

- These measurements where taken with the current hardware of the Low Capacitance POC.
- The bandwidth of the system can be increased by changing some components.



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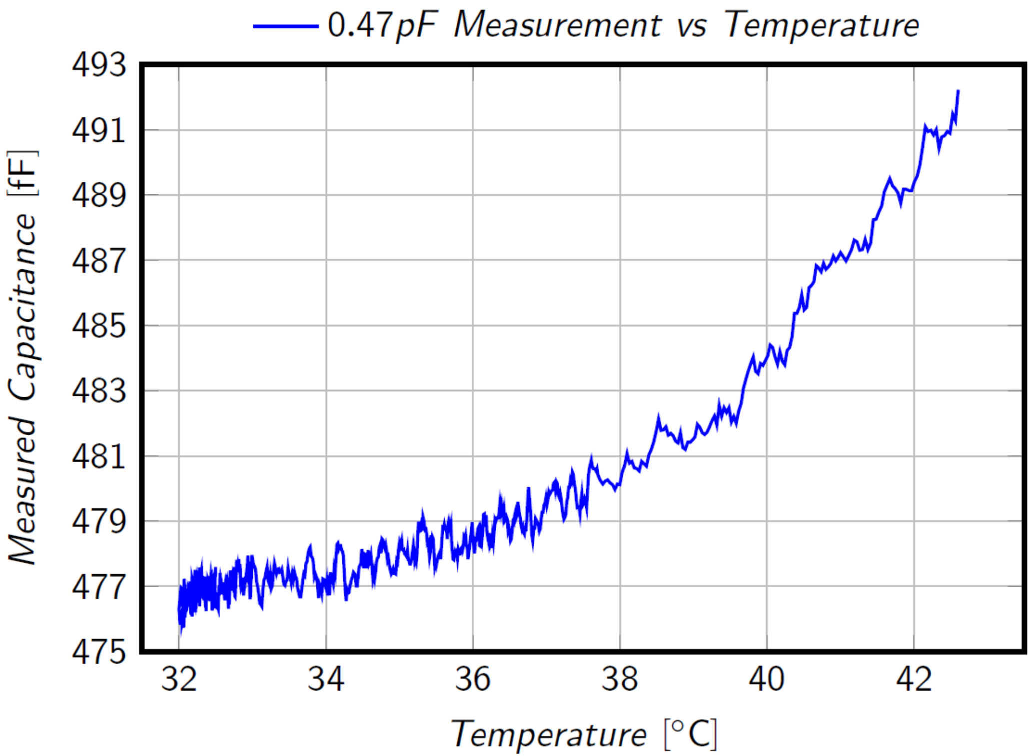
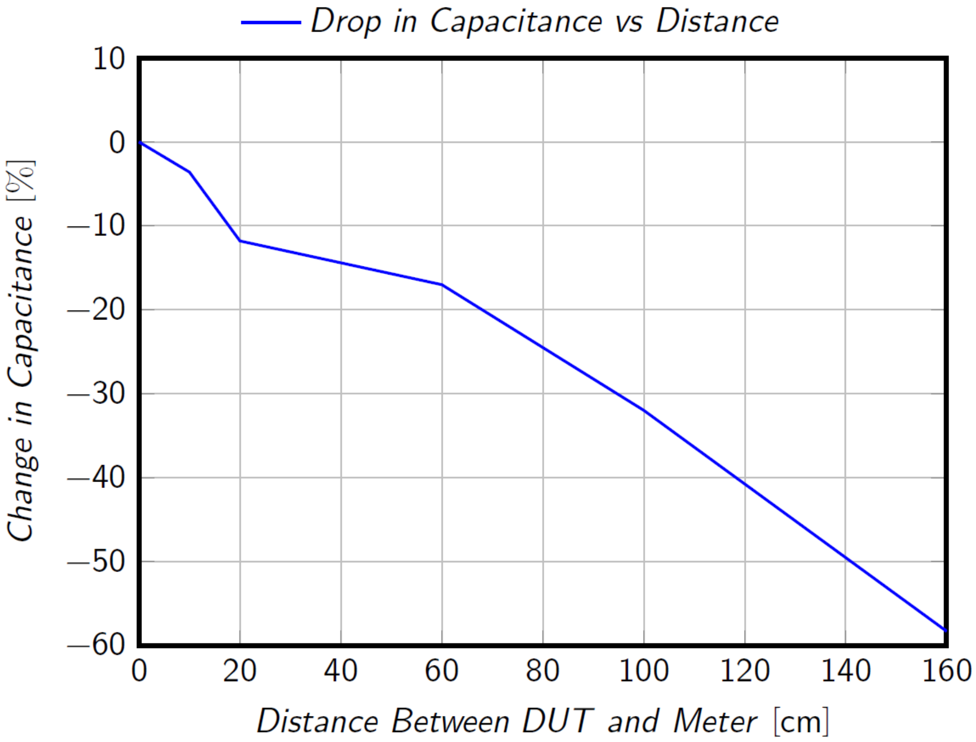
Temperature influence in capacitance measurement



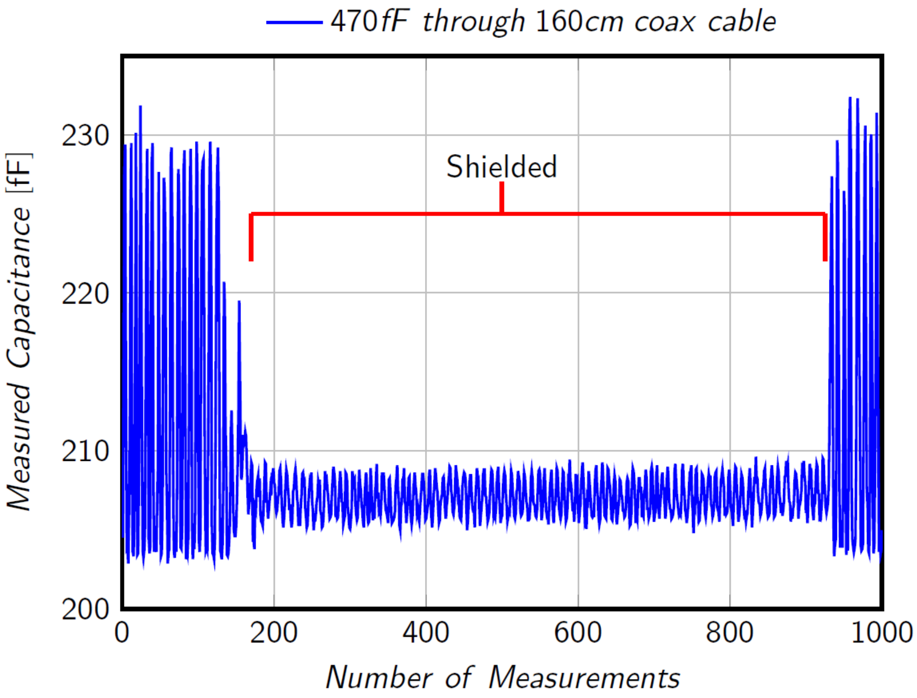
Influence of distance from DUT to readout circuit.

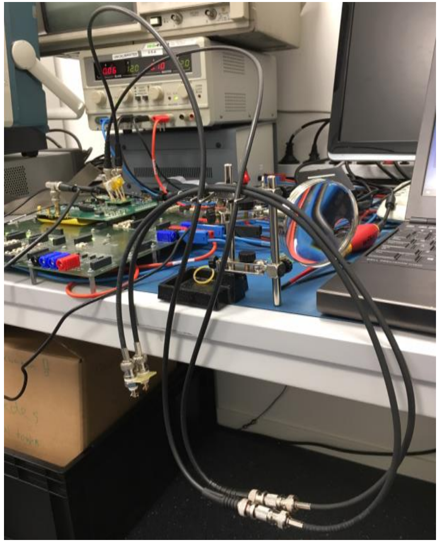


The reason of the jump from 10 cm to 20 cm and from 20cm to 60 cm is caused by using different cable types,

=> Use good cabling and connectors so that length can be compensated

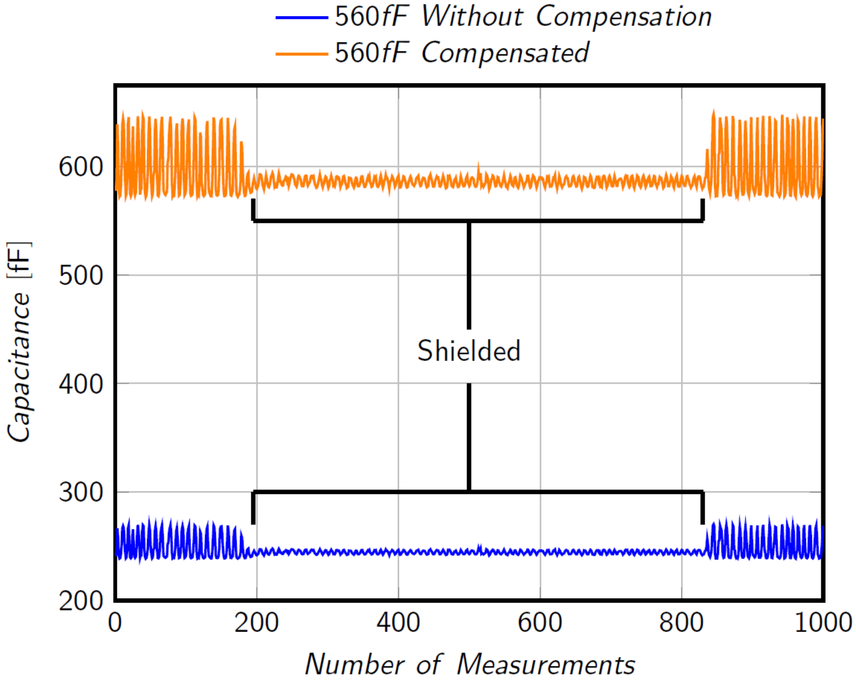
EMI influence in measurements

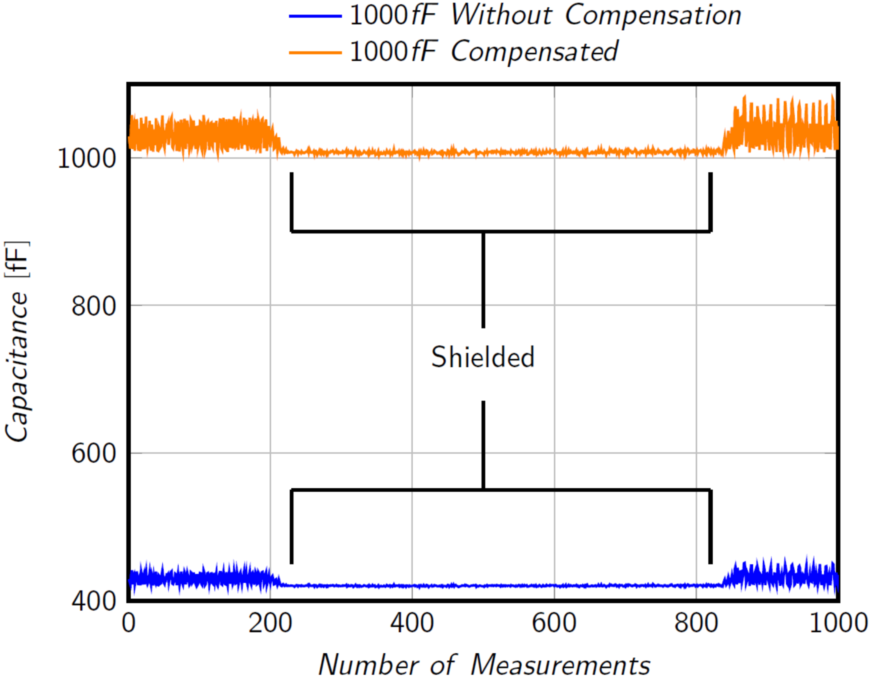




Measurement setup with 1.6m cable between DUT and read-out circuit. DUT shielding with a rolled ESD bag.

Gain compensation for measurements at long distances

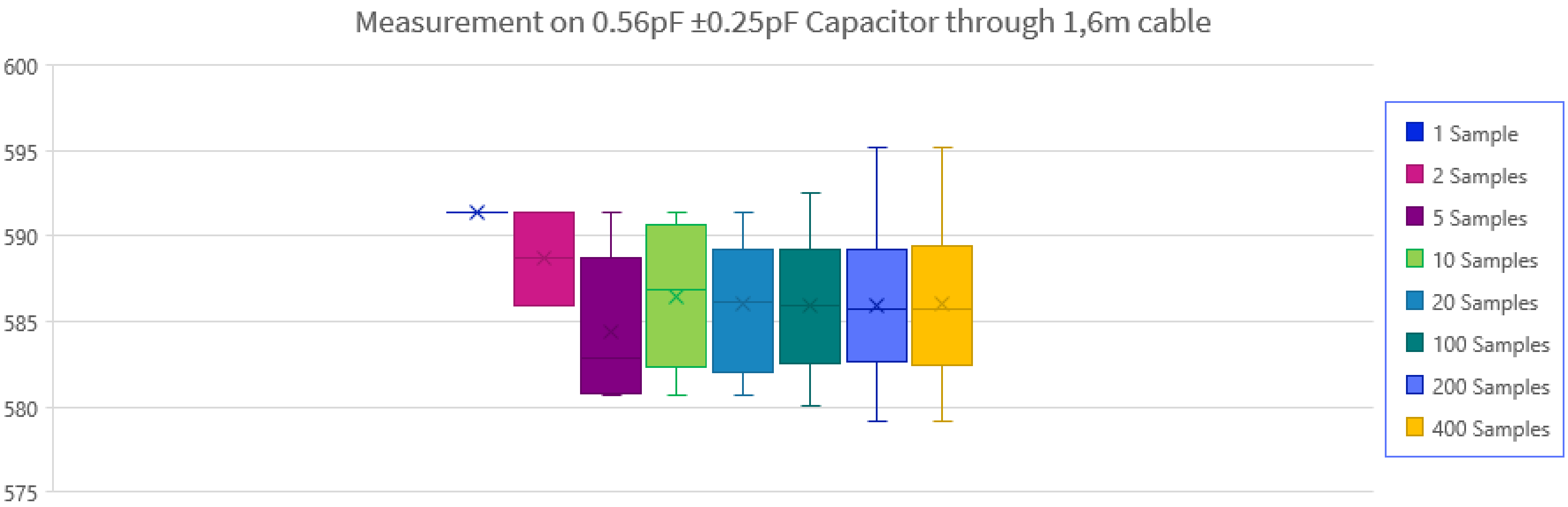




Capacitance measured through 1.6m coax cable without compensation and with gain compensation.

Number of samples vs stability

Improving quasi static measurements



Box plot showing that after 20 samples measurement there is no substantial difference in comparison with taking up to 400 samples to get an average measurement. We will consider 20 Samples = 1 point.

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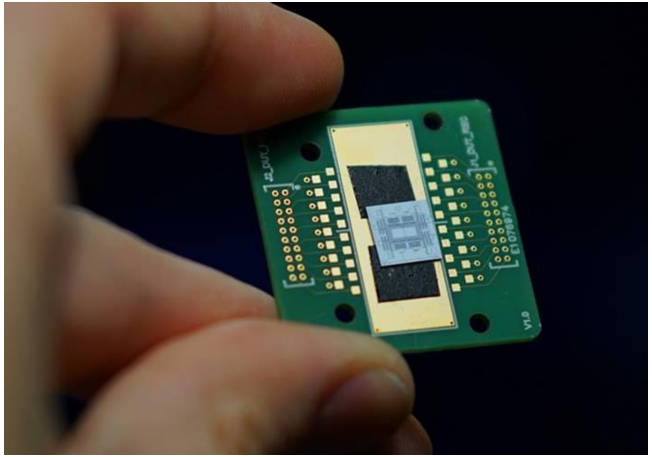
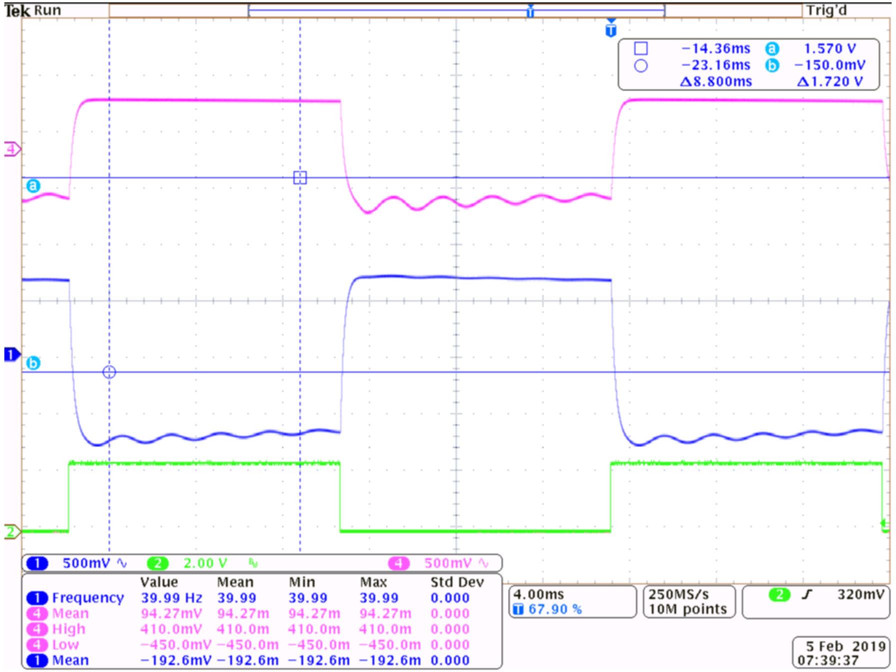
Dynamic measurements

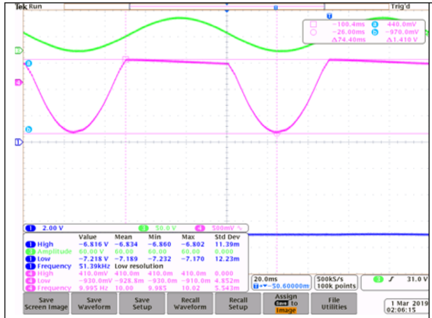


MEMS Device used to test dynamic measurements of the low capacitance meter.

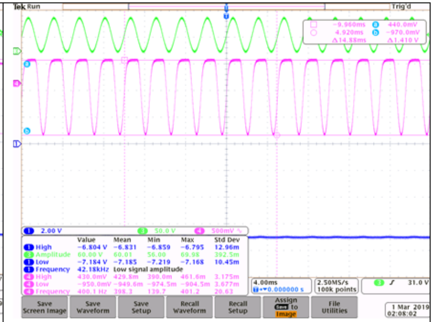


MEMS actuated with square wave 50V at 40Hz.

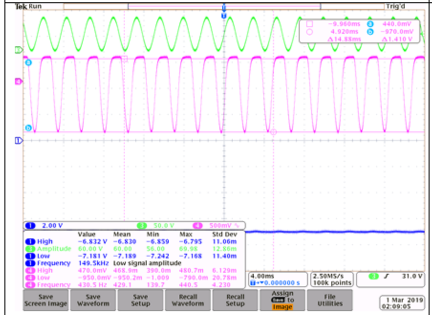
Mechanical resonance frequency



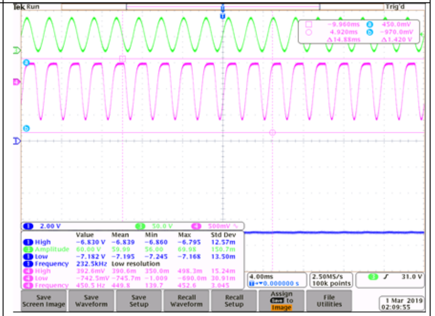
a) MEMS actuated with sine wave 60V at 10Hz.



b) MEMS actuated with sine wave 60V at 400Hz.



c) MEMS actuated with sine wave 60V at 430Hz.

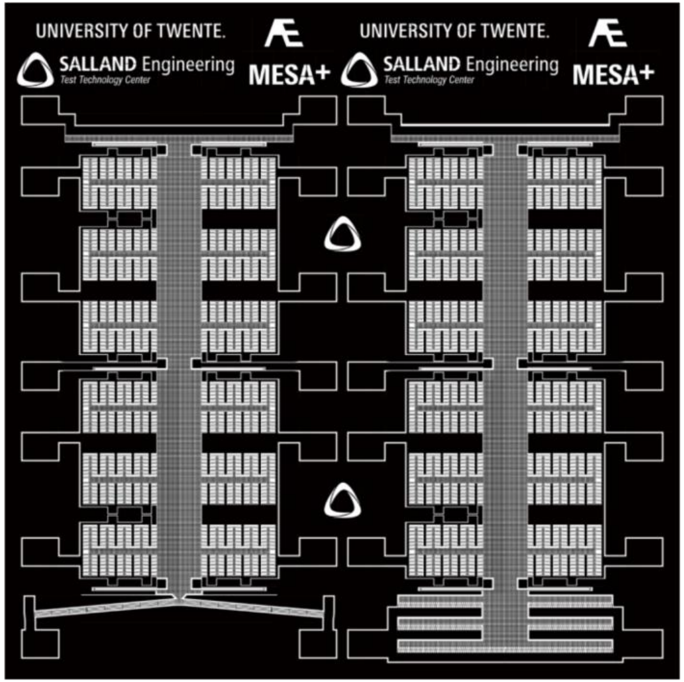


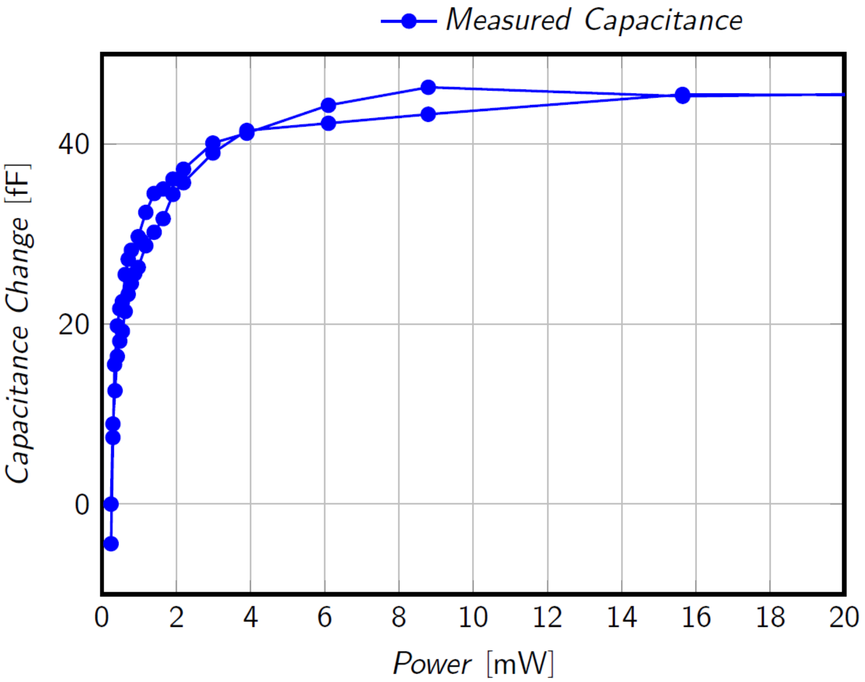
d) MEMS actuated with sine wave 60V at 450Hz.

Variation of amplitude depending on frequency of actuation signal.

High Accuracy Measurements

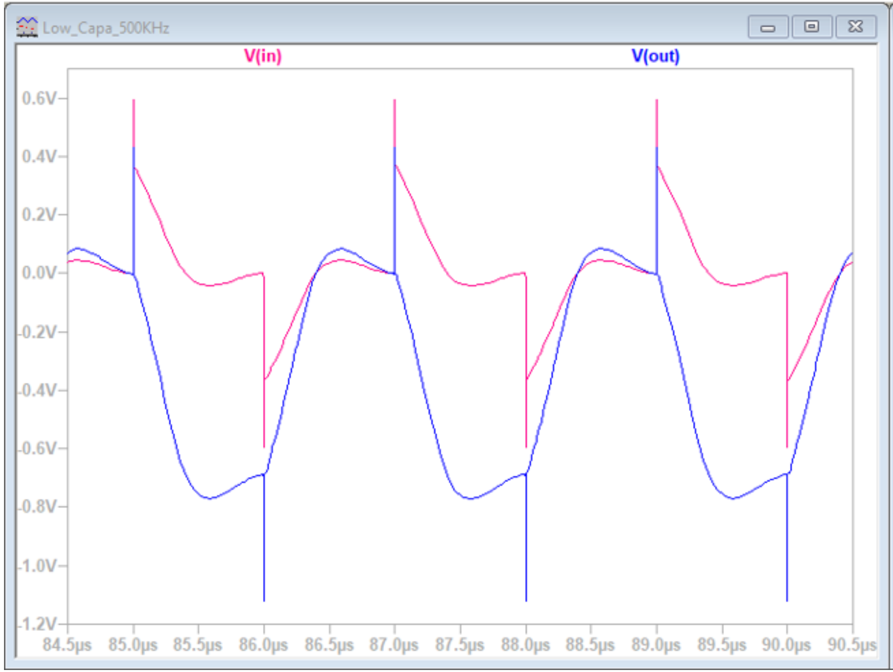
First measurements executed on designed MEMS device.



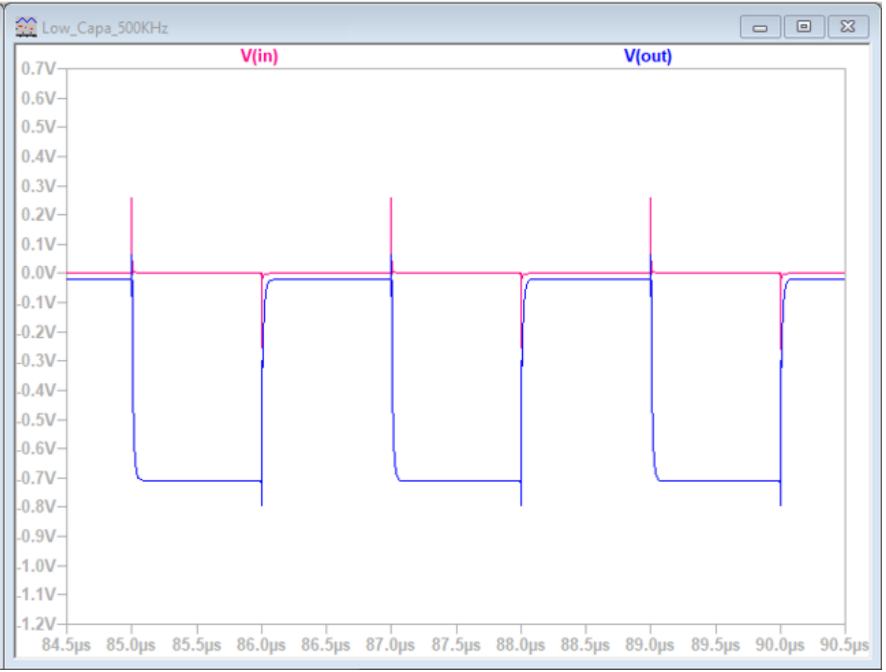


6. Improvements

Increasing bandwidth of charge amplifier (Multichip)

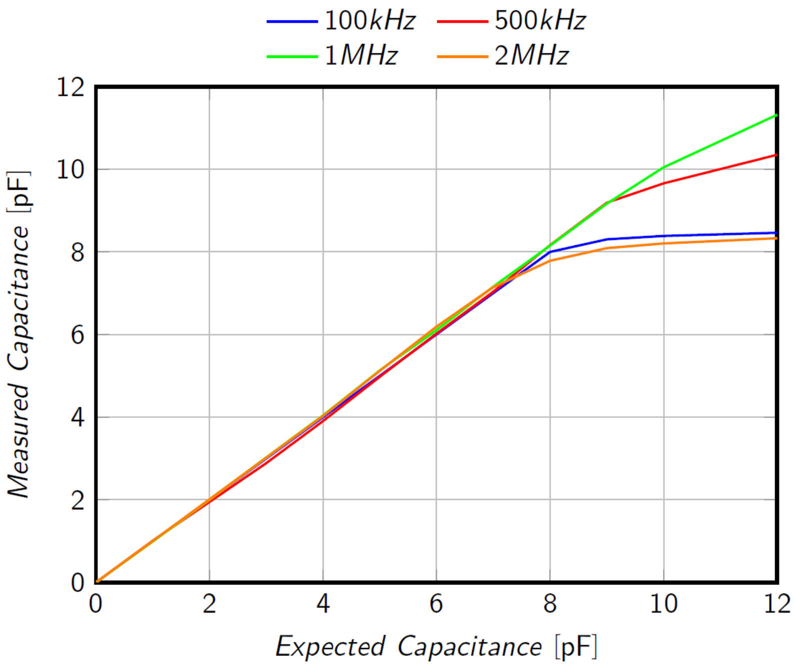


Capacitance meter using current charge amplifier with 500 kHz carrier frequency.



Capacitance meter using new charge amplifier with 500 kHz carrier frequency.

Simulation of improved hardware



Measured Capacitance vs Carrier Frequency

7. Conclusions & Future Work

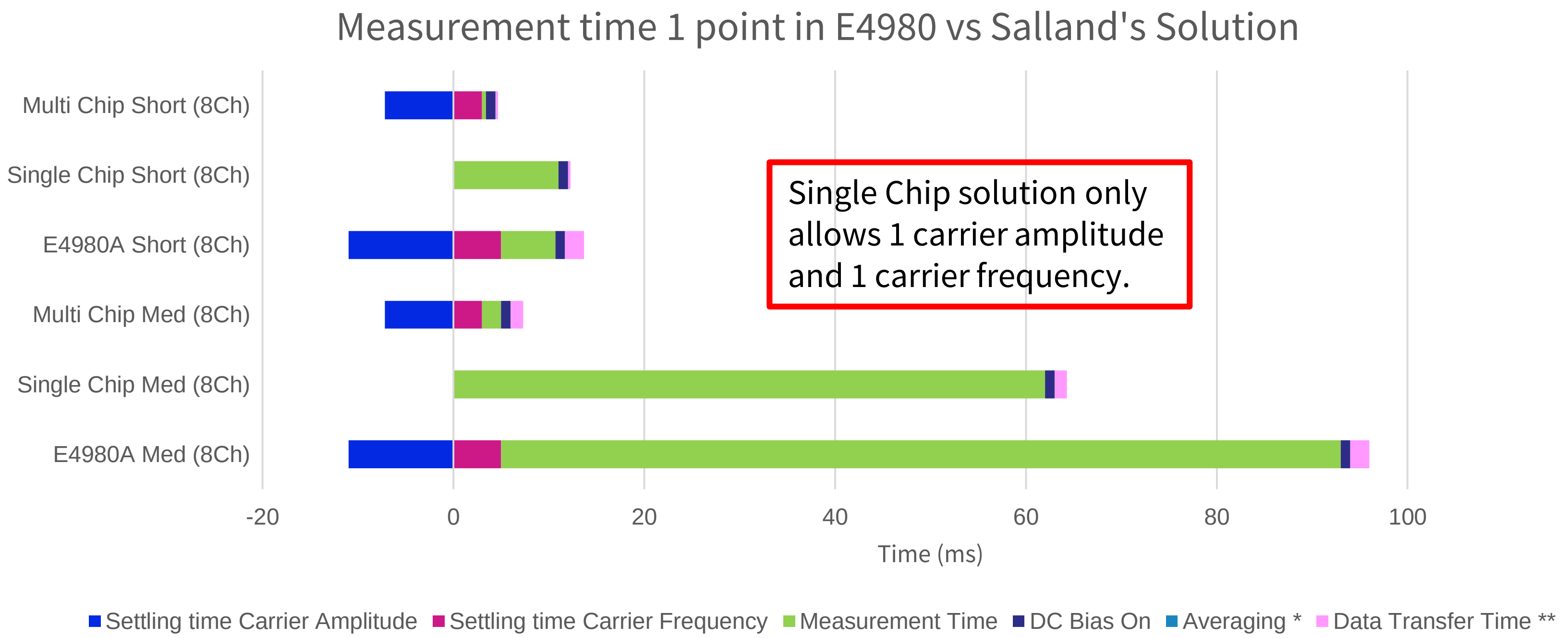
Conclusions

	Multichip	Single Chip
Measurement Range	≈2 fF to ≈5000fF	0pF to ±4pF
Dynamic Range	1:3500	1:100000
Noise	±0.05 % of range*	±1fF
Resolution	40aF	10aF
Advantage summary	✓ Flexibility in Carrier frequency ✓ Avoidance of crosstalk in multichannel environment ✓ Possible to modify to have higher capacitance ranges. ✓ Faster Measurement	✓ Larger Dynamic range ✓ Lower noise

** In the worst case at ±5fF*

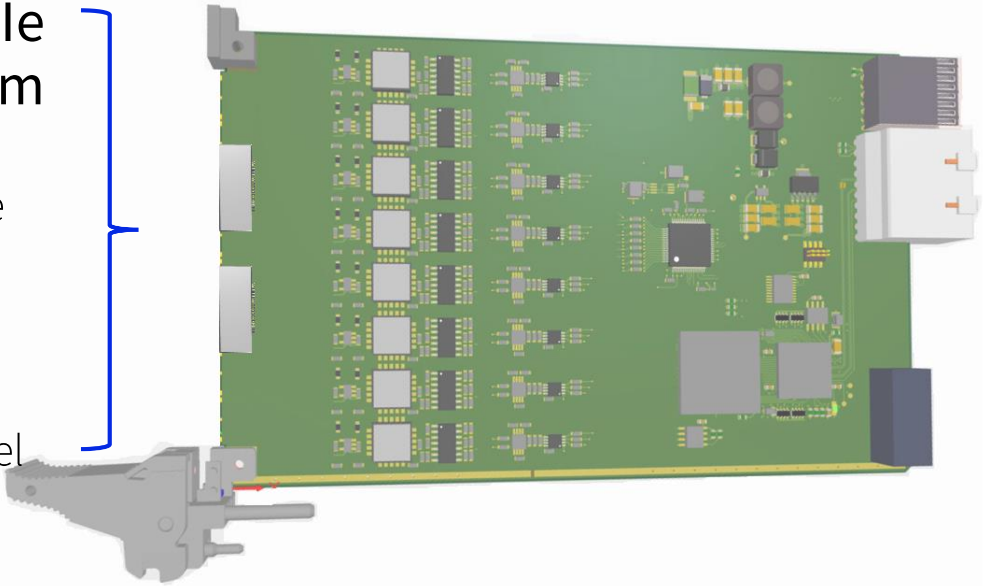
Timer measurement comparison

Both solutions (PXIe) and equipment available in market



Things to be done

- Production of an 8 Channel PXIe Board is in progress, with the aim of:
  - ▶ Implement and test proposed hardware improvements.
  - ▶ Finish characterization of known capacitance MEMS devices with wider range of carrier frequencies.
  - ▶ Test Multichip solution in a multi-channel implementation.
- Improve debug tools.



Acknowledgements

- Salland Engineering.
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