A Fast-Readout Mismatch-Insensitive Magnetoresistive Biosensor Front-End Achieving Sub-ppm Sensitivity

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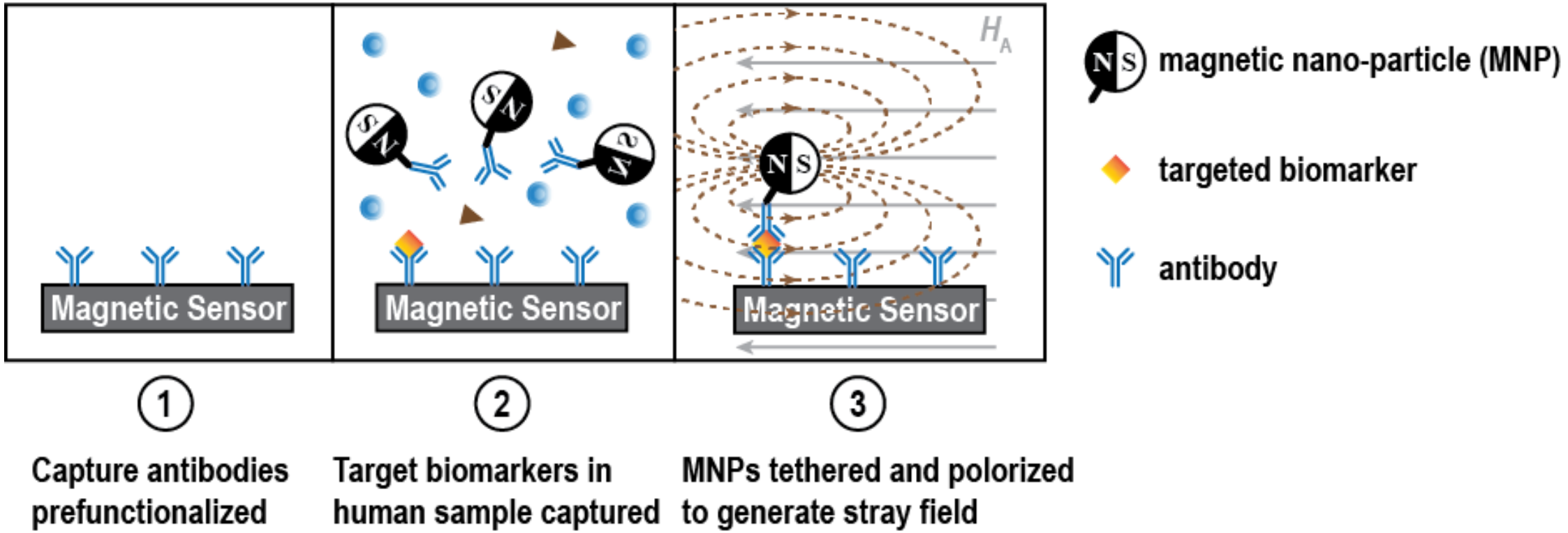
Motivation: Point-of-Care (PoC) Devices

Centralized Laboratory
- Bulky instruments
- Professional personnel required
- Long turnaround time

Point-of-Care Devices
- Small and portable
- Easy operation
- Near instant results

NEED: Accurate and fast diagnostic tests

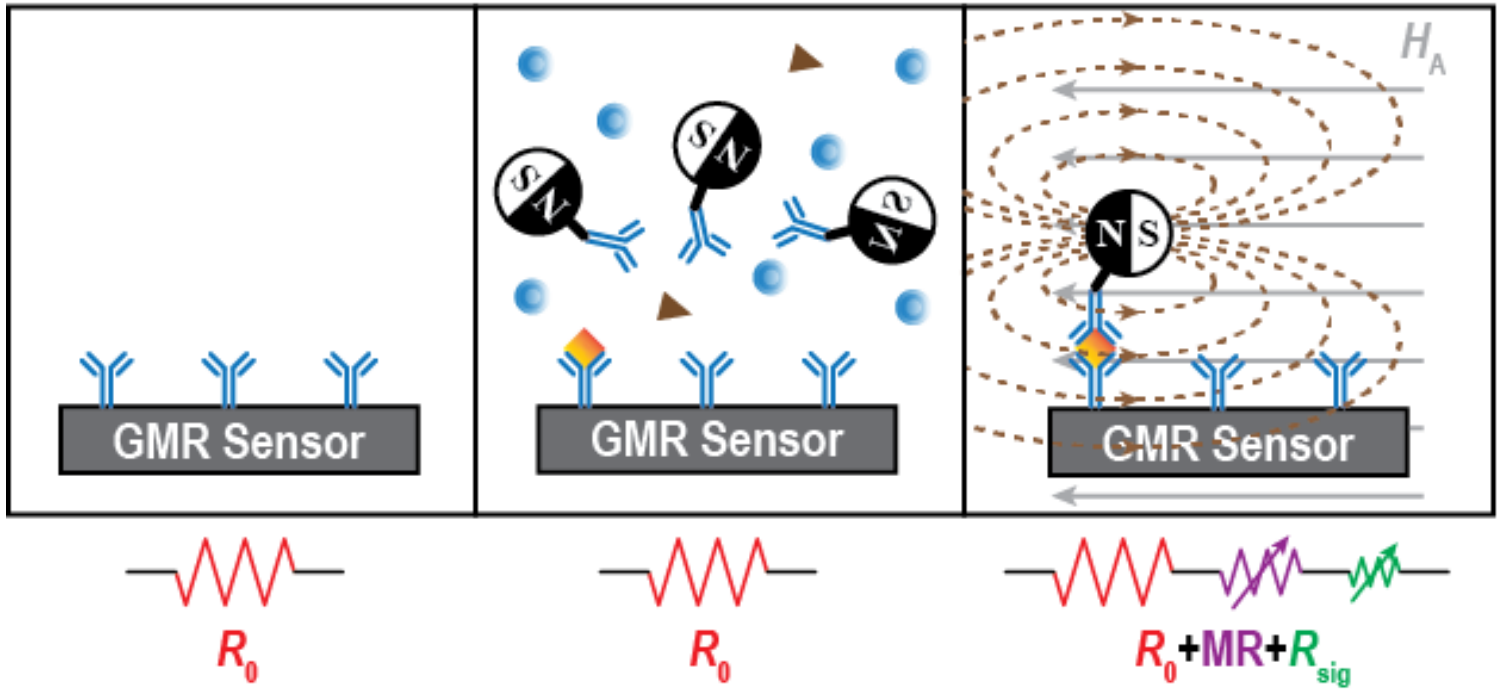
Magnetic Immunoassay

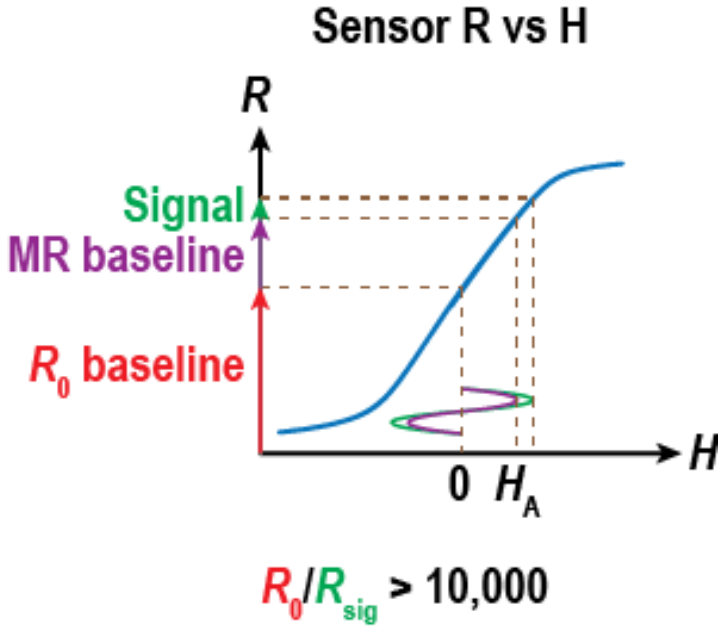


Magnetic sensor

Human biological samples intrinsically lack magnetic background → high sensitivity

Giant Magnetoresistive (GMR) Sensor



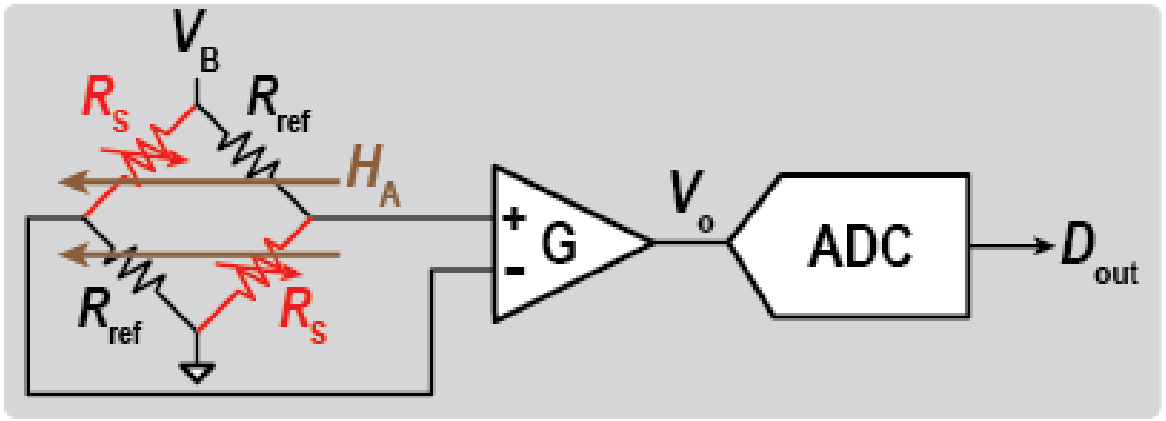


Problem: Wide dynamic range AFE is required to accommodate large R_0/R_{sig}

Large baseline-to-signal ratio precludes high sensitivity detection

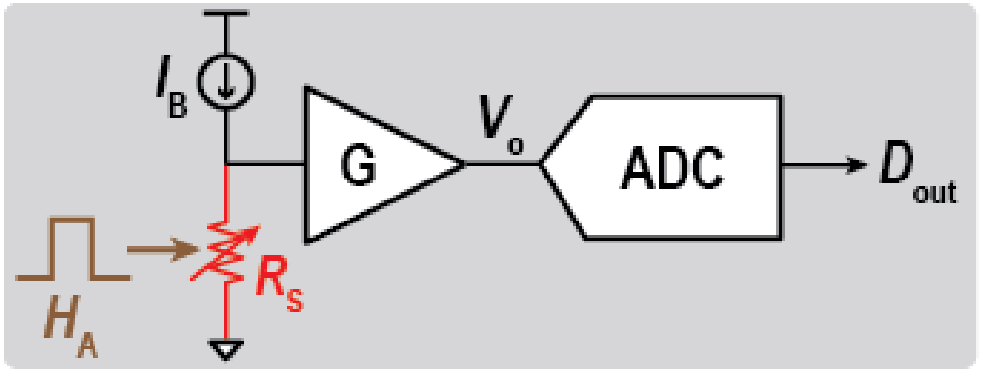
Conventional MR AFE Architectures

Wheatstone bridge



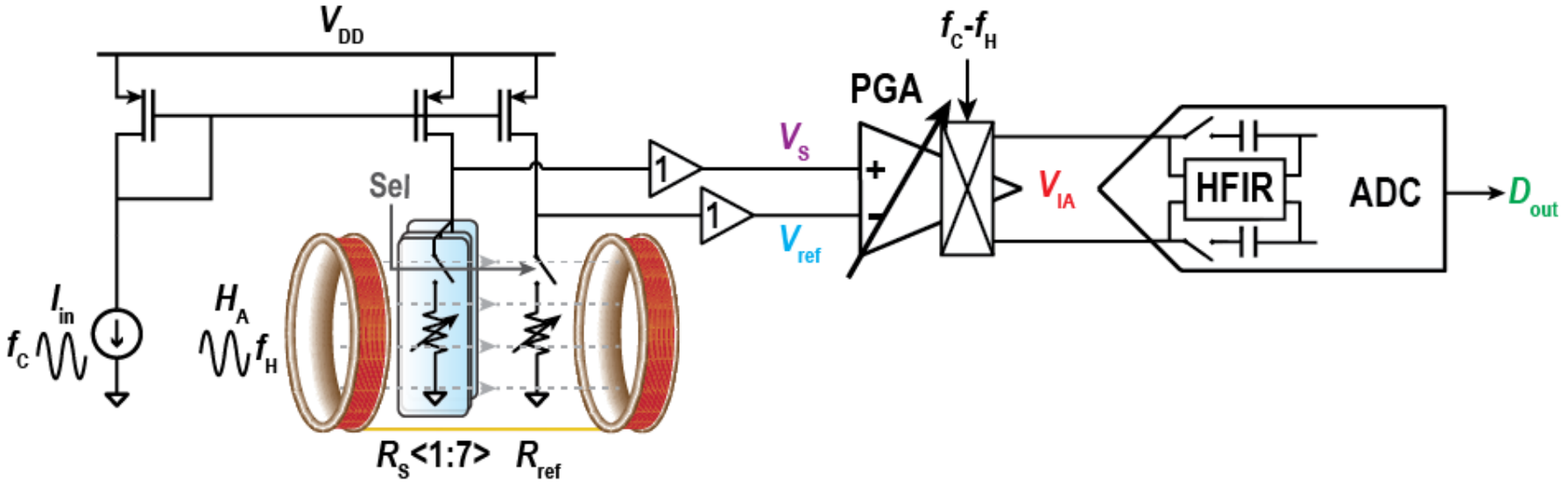
Problem:
Sensor mismatch ΔR limits sensitivity

Magnetorelaxometry



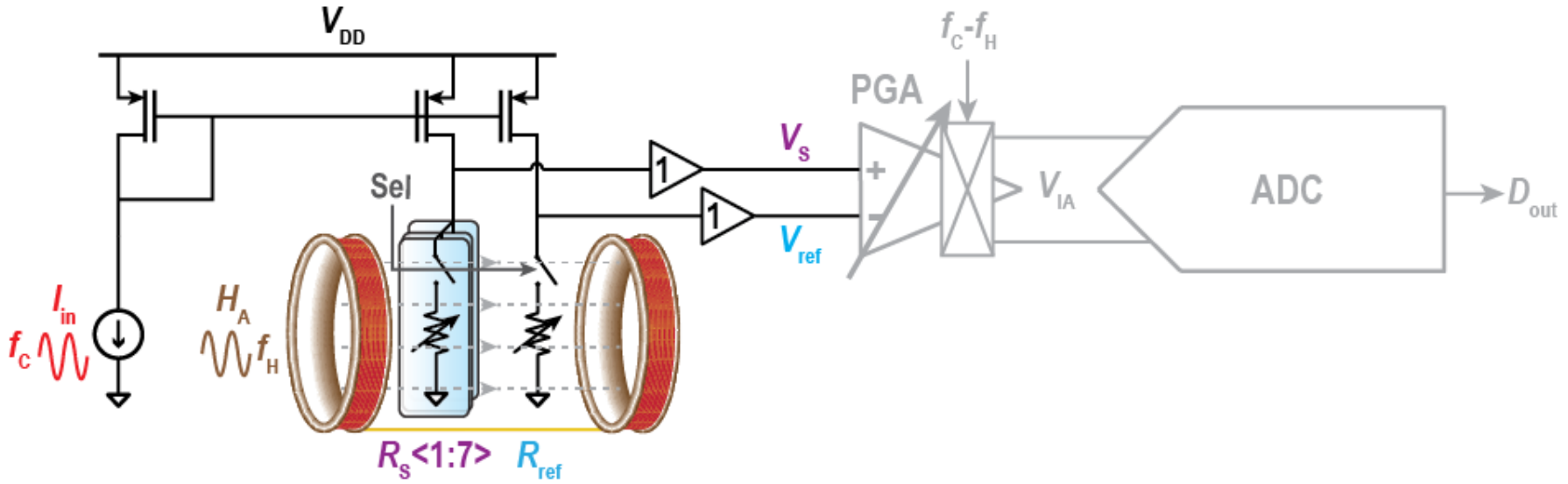
Problem:
Fast transient signal → requires fast-switching magnetic field and high speed ADC

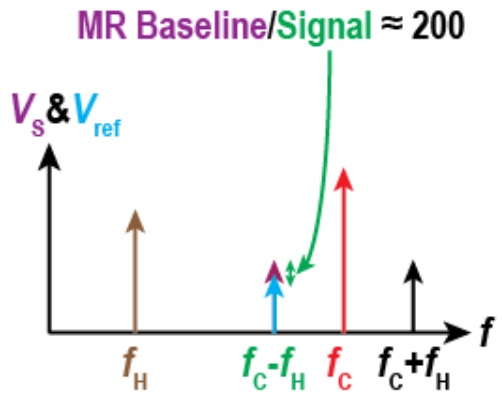
System Architecture

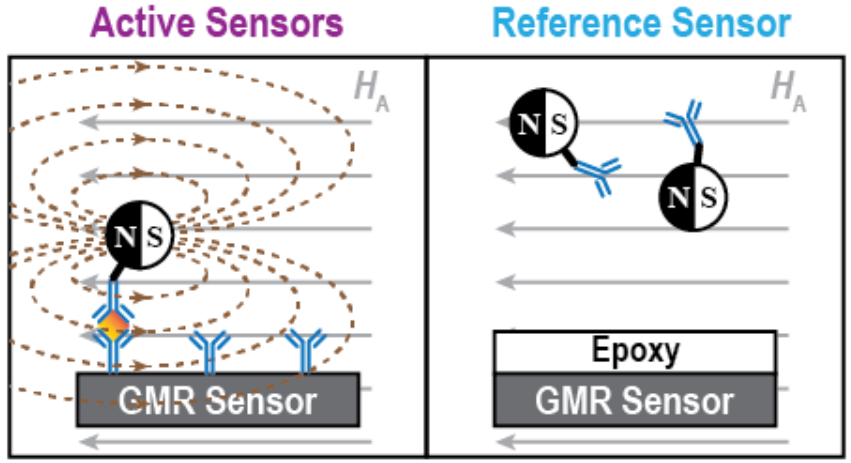


Problems	Proposed Solutions
Large baseline/signal	Reference sensor
High speed ADC required	Down-modulator in PGA
Sensor mismatch	HFIR in ADC

Double Modulation Scheme

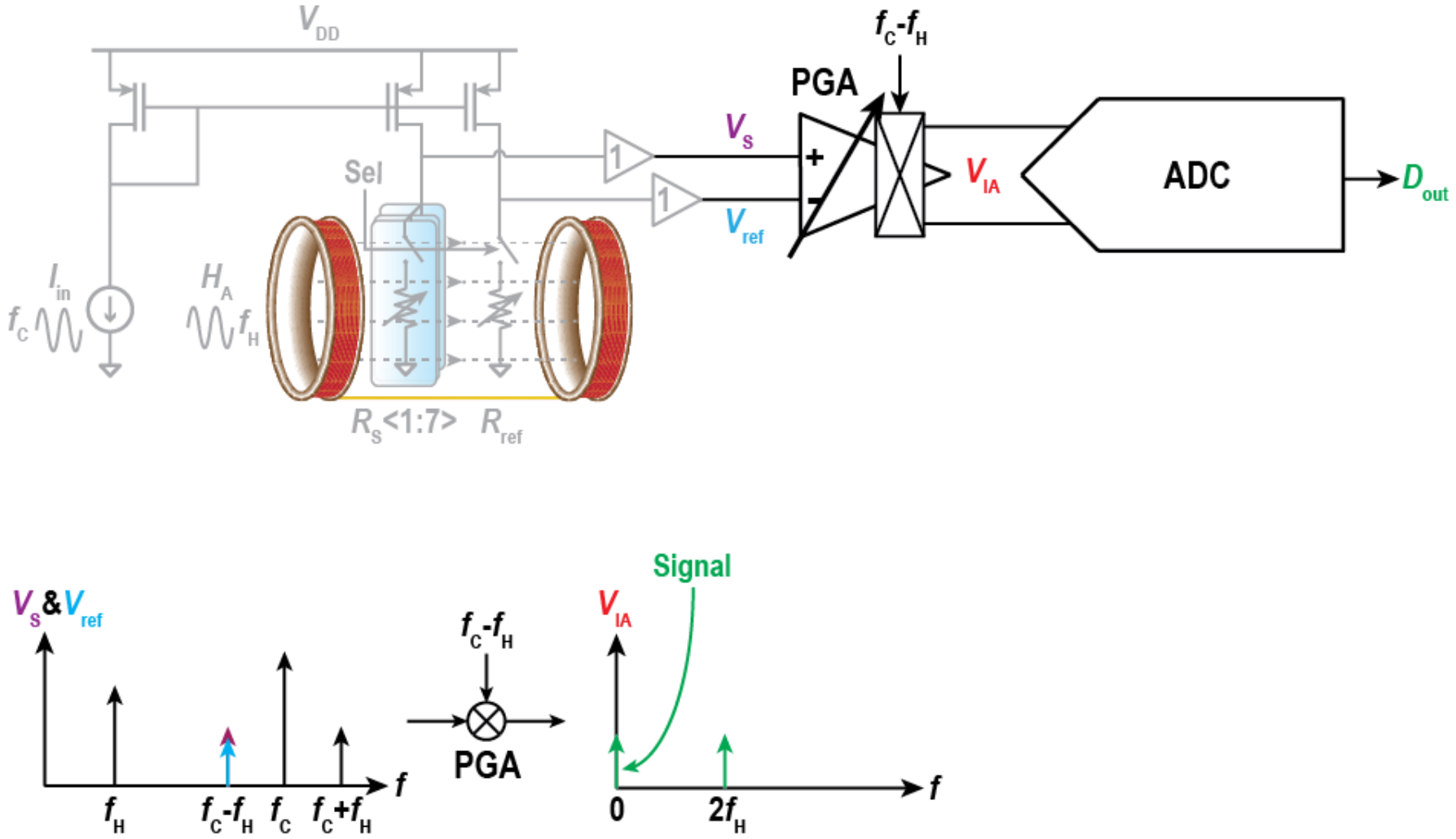






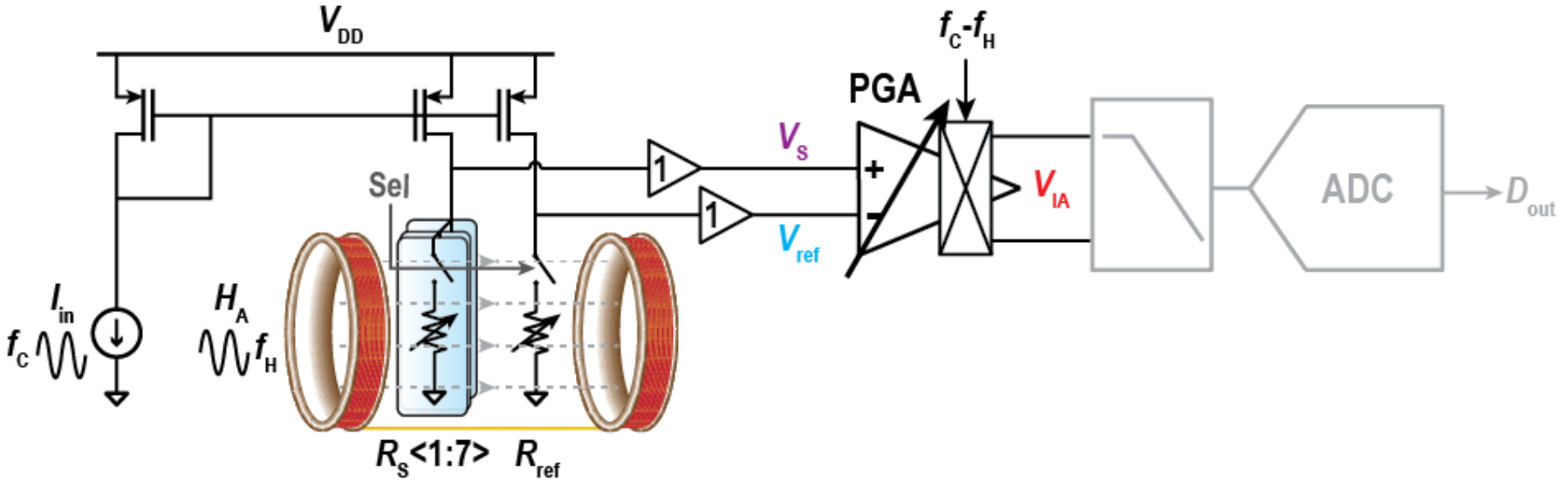
Reference sensor rejects MR baseline

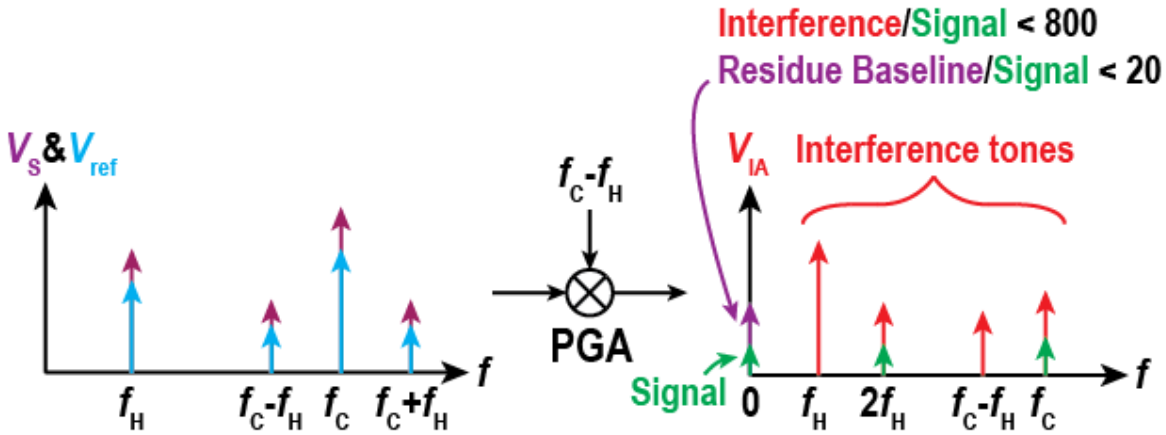
Analog Front-End



Built-in down modulator relaxes speed requirement on ADC

Sensor Mismatch

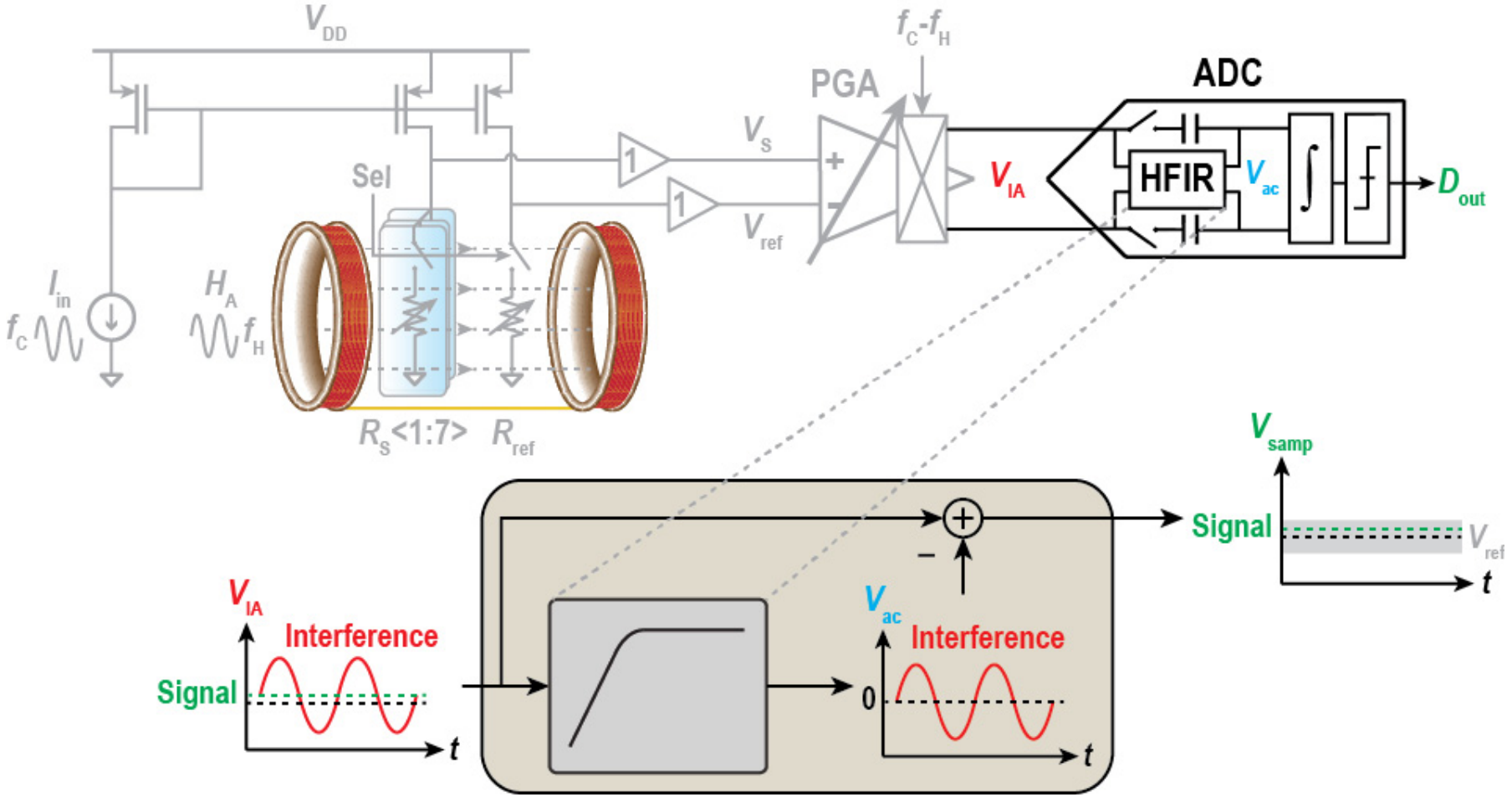




Sensor *MR* mismatch →
Residual baseline at DC
Sensor R_0 mismatch →
Interference at f_H

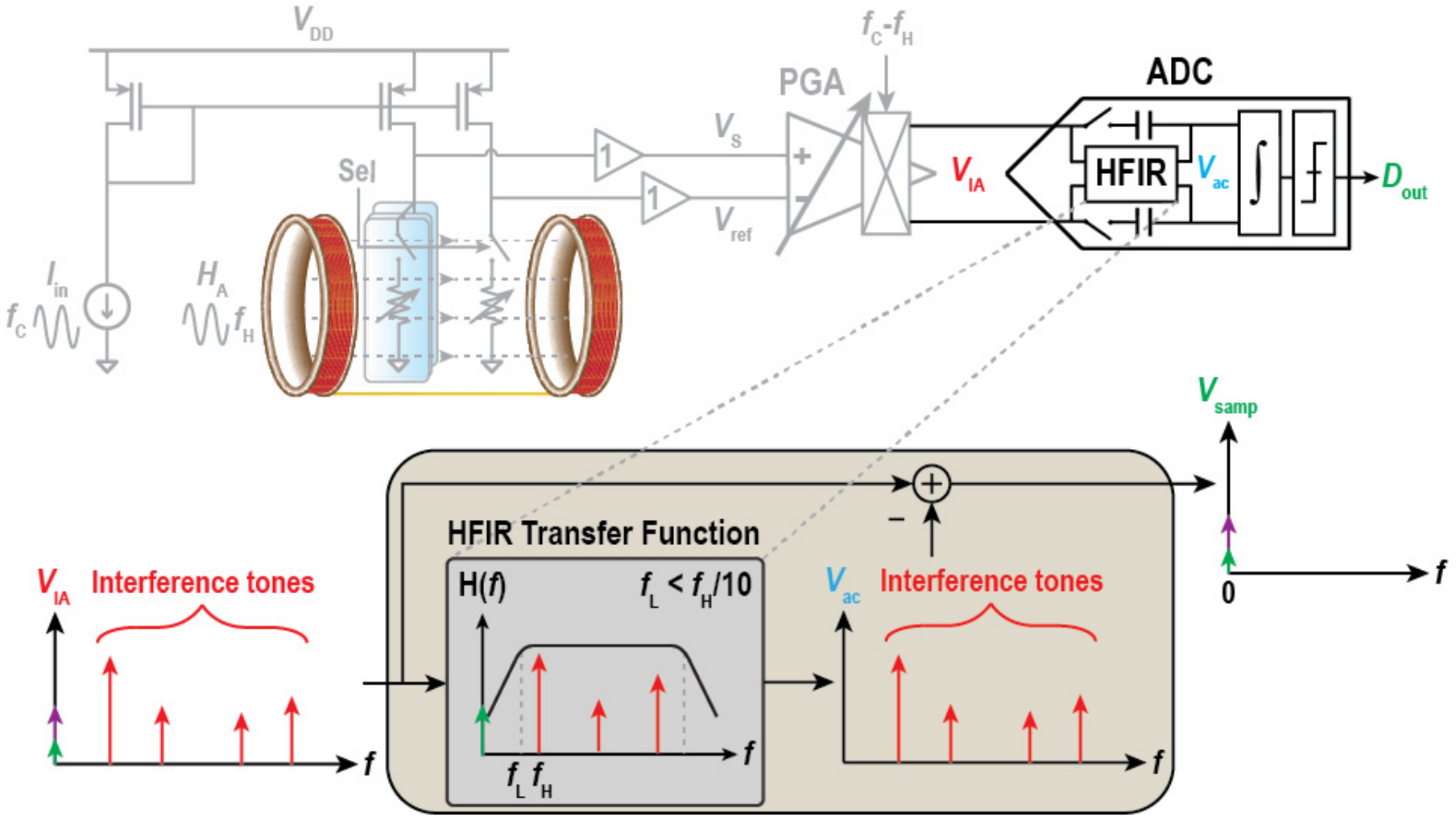
Sensor mismatch increases ADC dynamic range requirement

High Frequency Interference Rejection



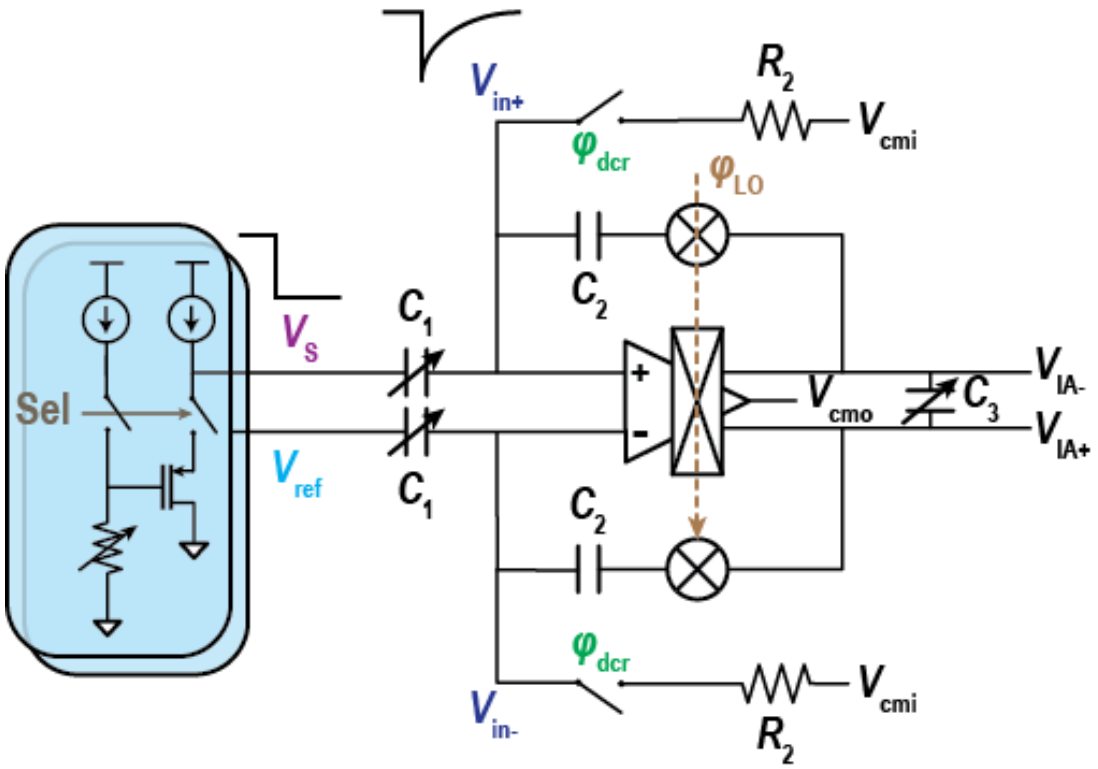
ADC applies HP feedforward method to realize a fast-settling LPF function

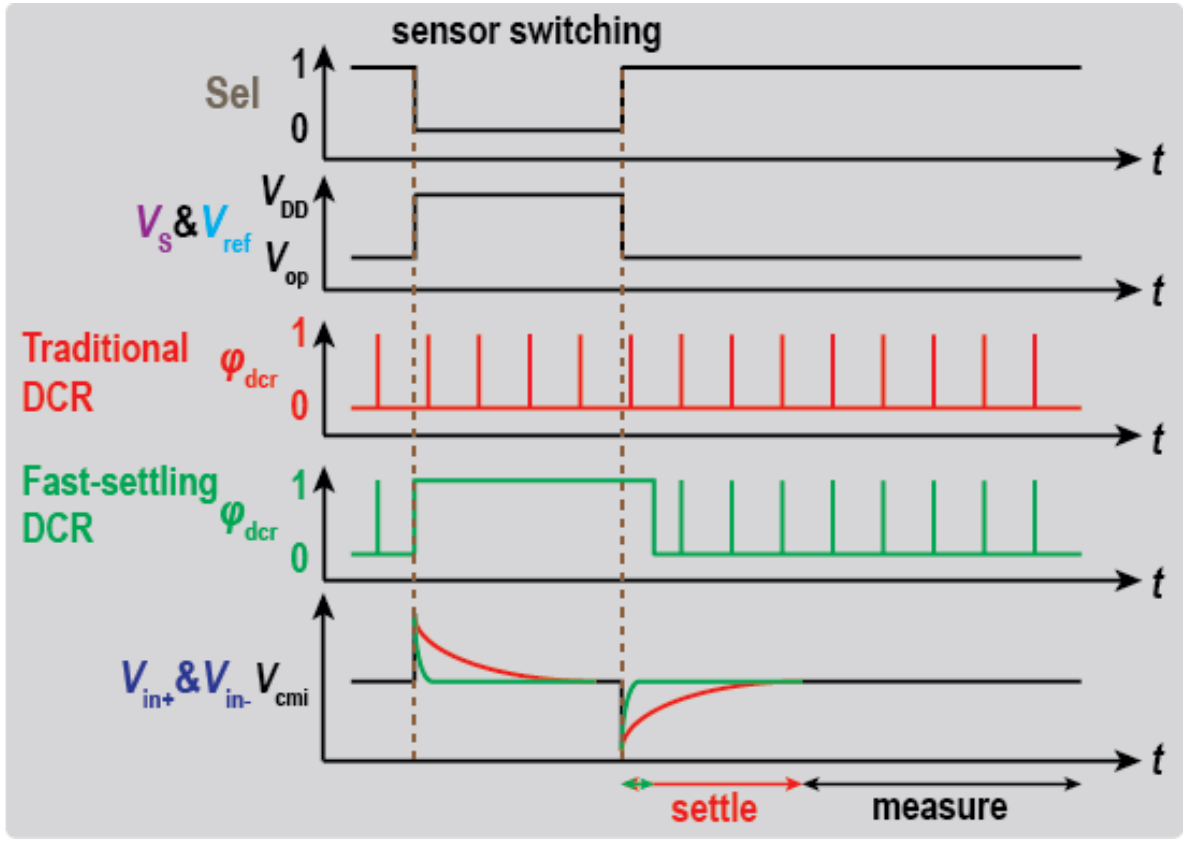
High Frequency Interference Rejection



HFIR sampling technique rejects high frequency interference

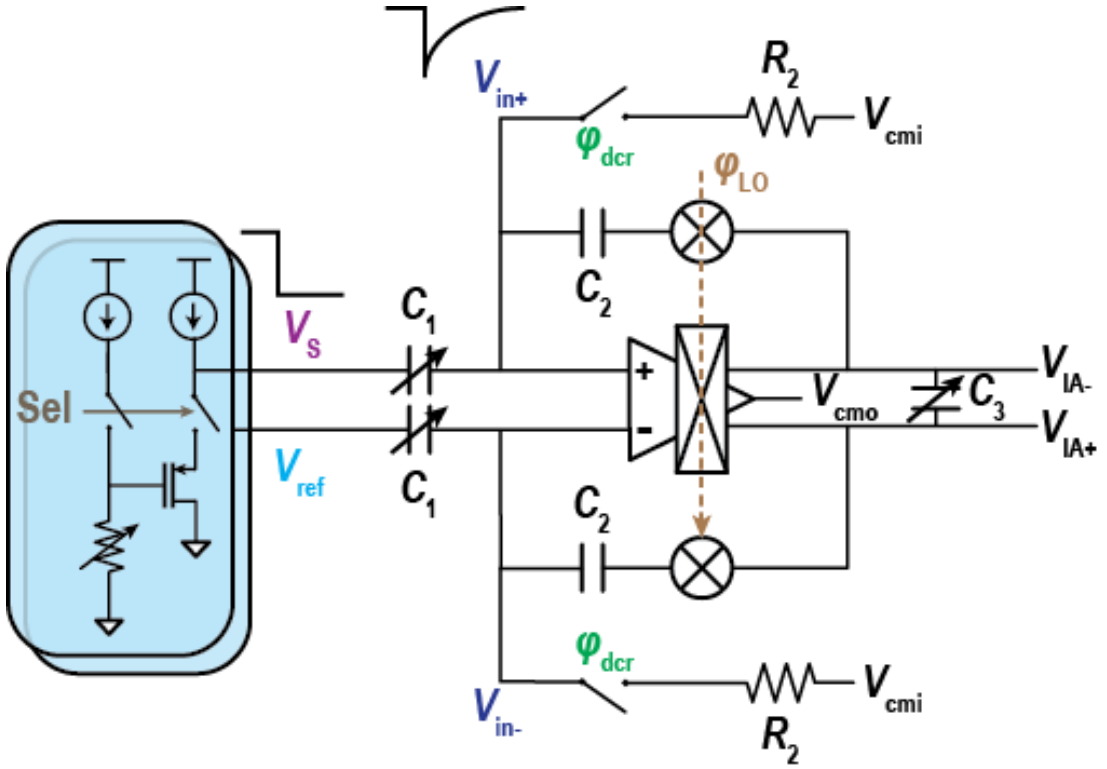
PGA Implementation



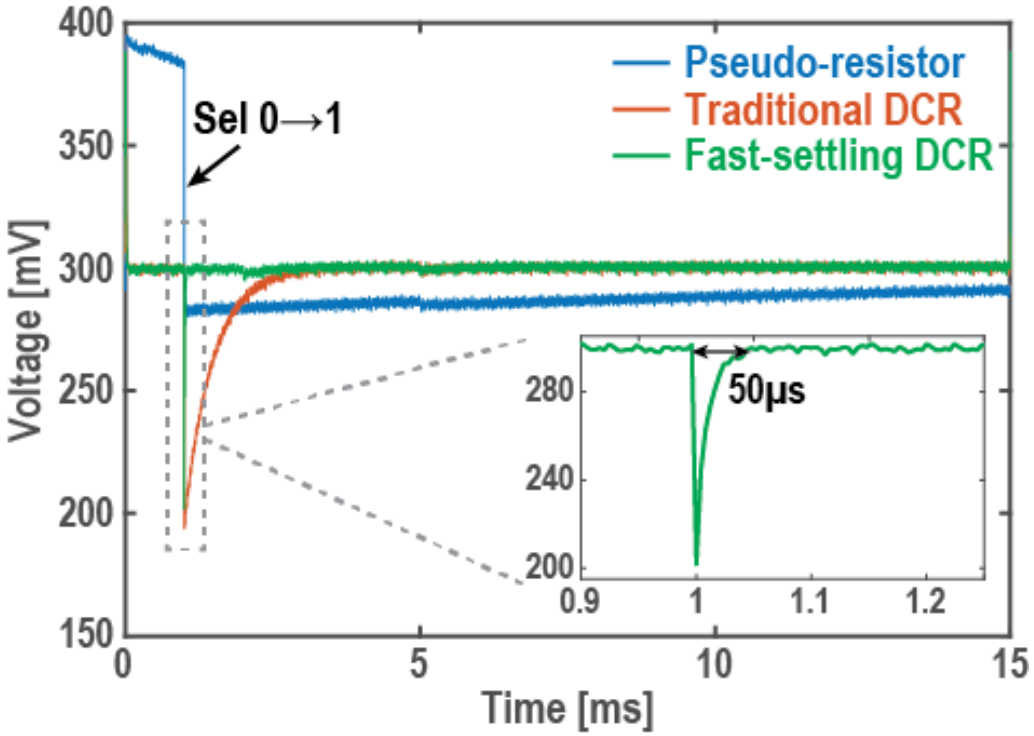


- Switches remain closed after sensor selection for 100μs → provide a low impedance path for fast settling
- Switches revert to duty-cycled mode afterwards → provide large bias resistance for low noise

Fast Settling Duty-Cycle Resistor (DCR)

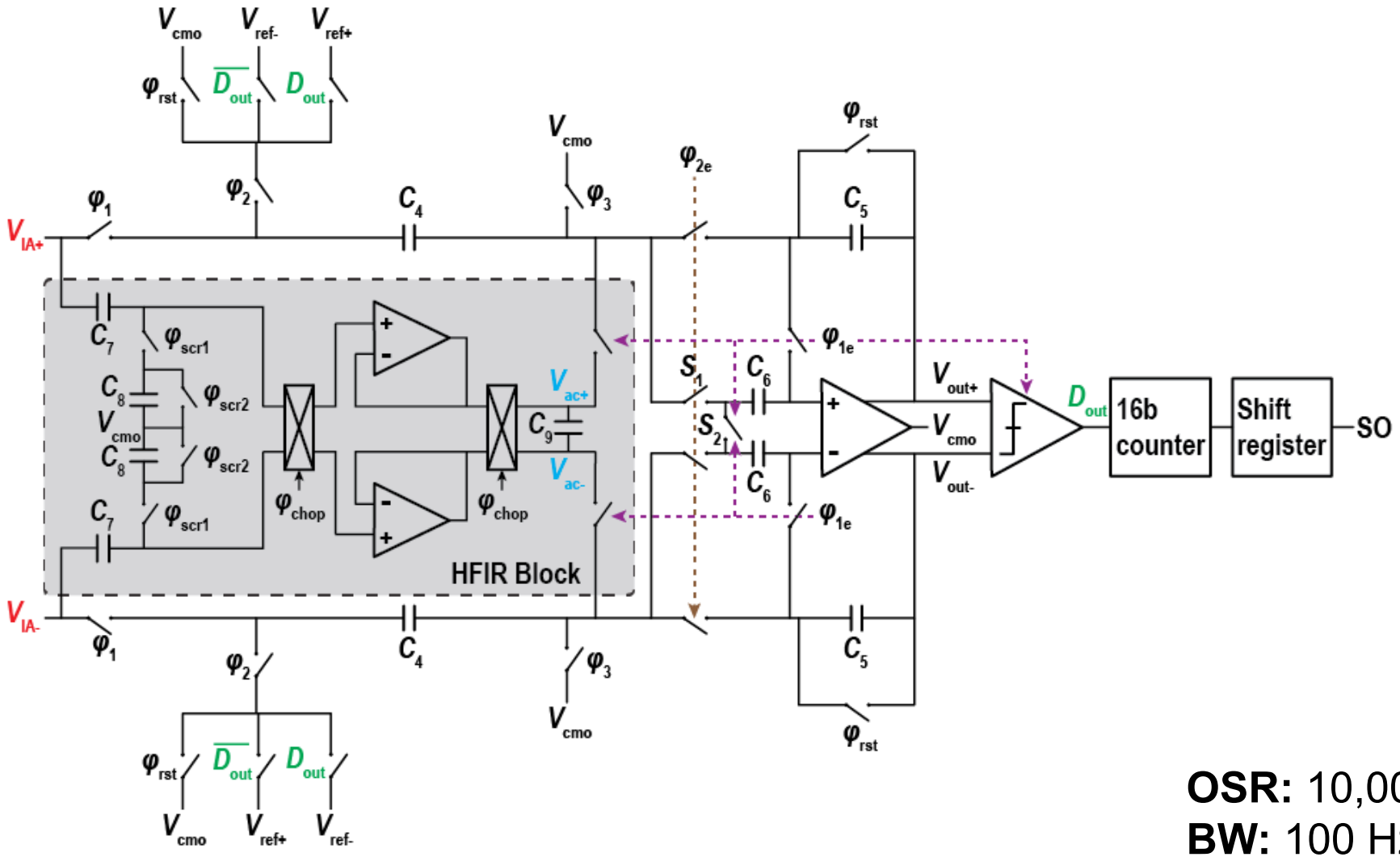


Measured transient waveforms



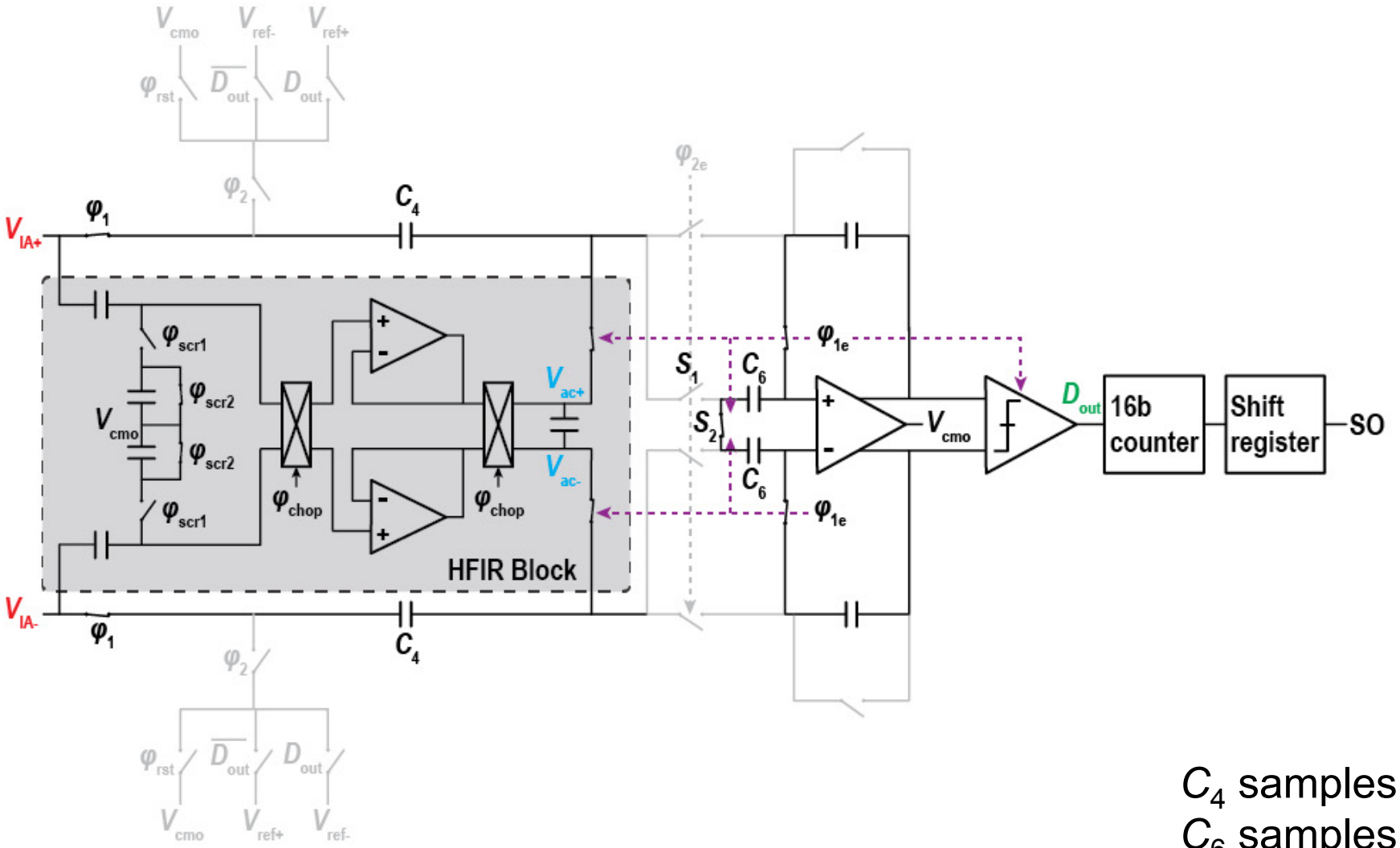
Fast settling DCR reduces the settling time by 40×

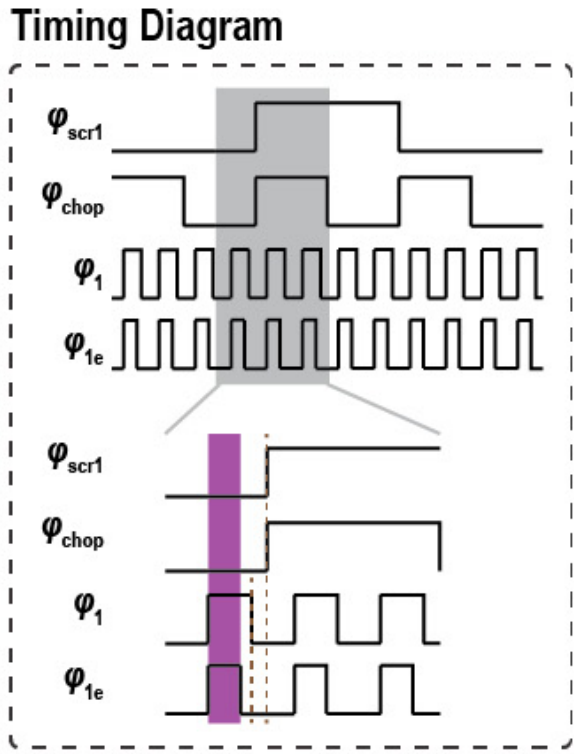
Incremental ΔΣ ADC



OSR: 10,000
BW: 100 Hz

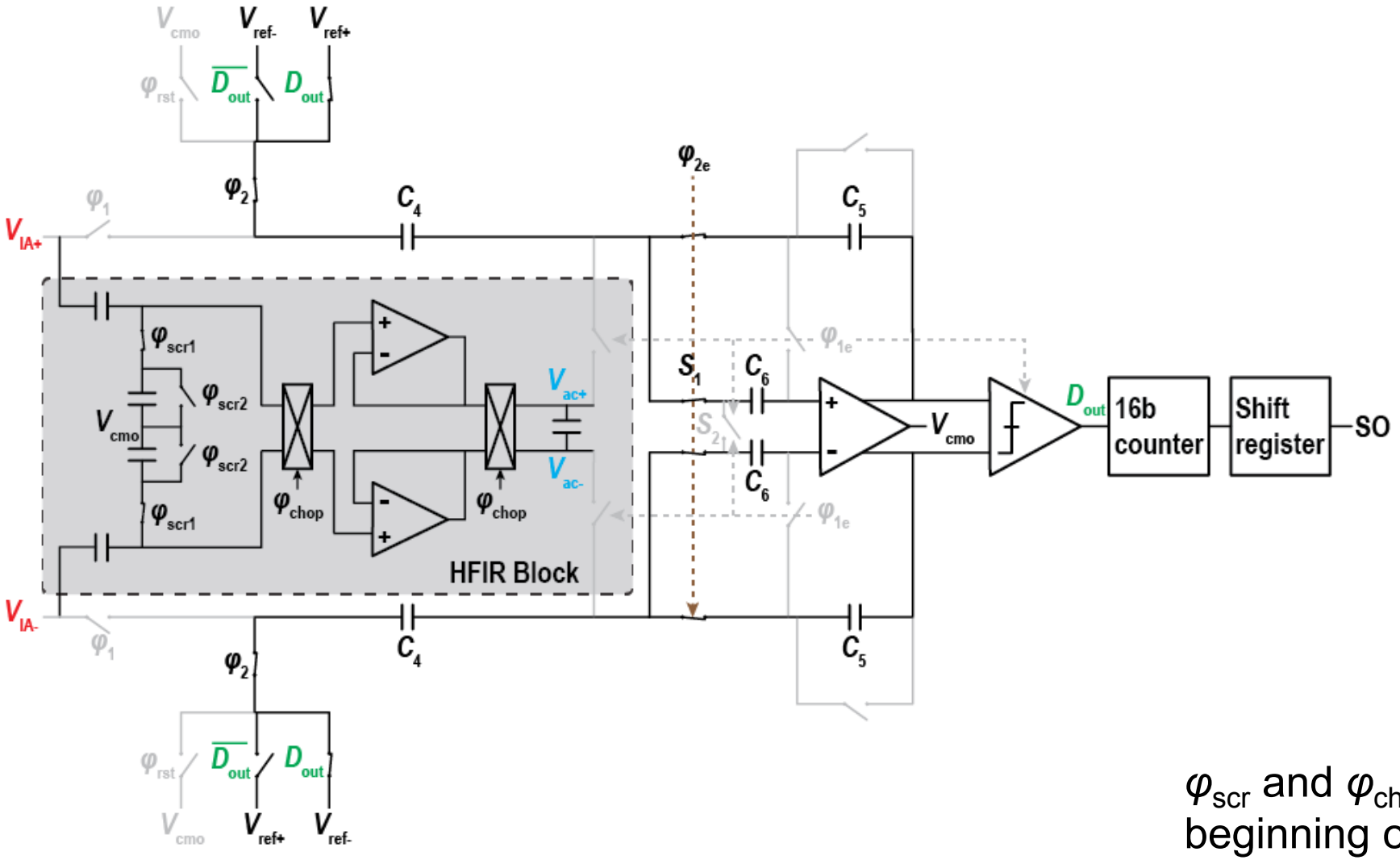
ADC Phase I

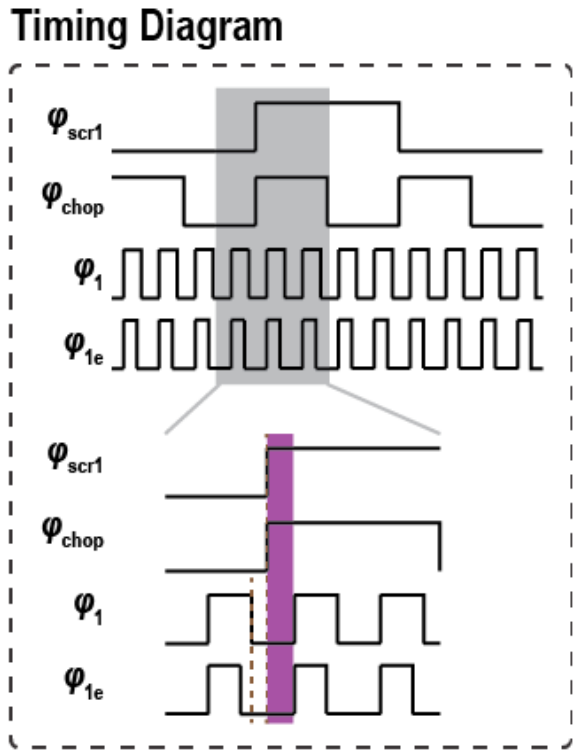




C_4 samples signal at DC
C_6 samples OTA offset

ADC Phase II

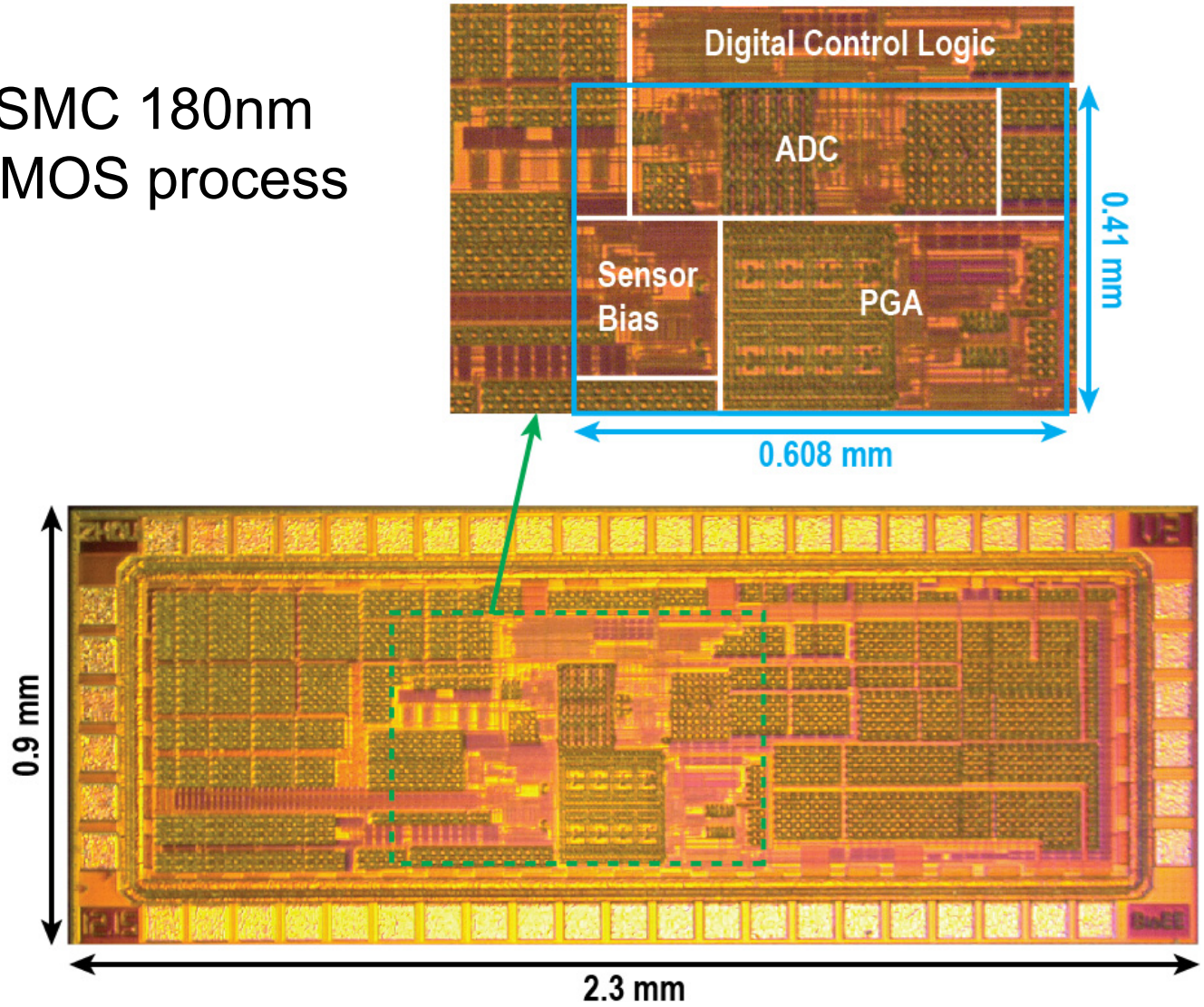




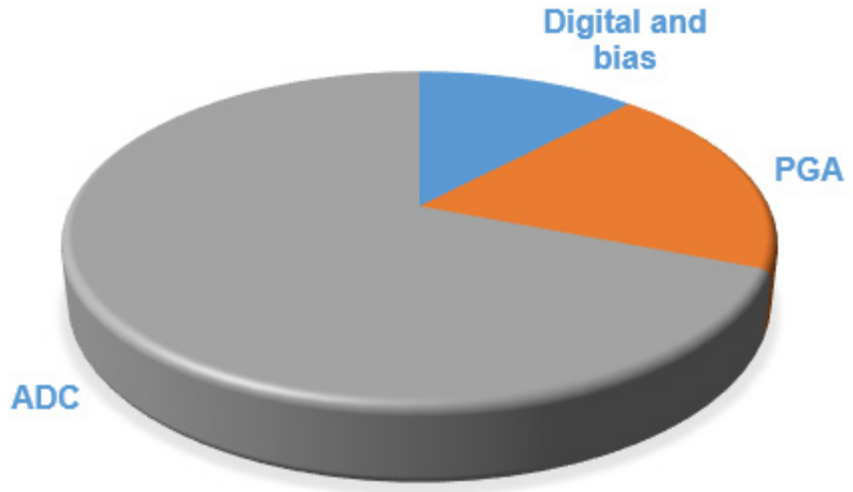
φ_{scr} and φ_{chop} change at the beginning of Phase II → Allow maximum time for settling

Die Photo and Power Breakdown

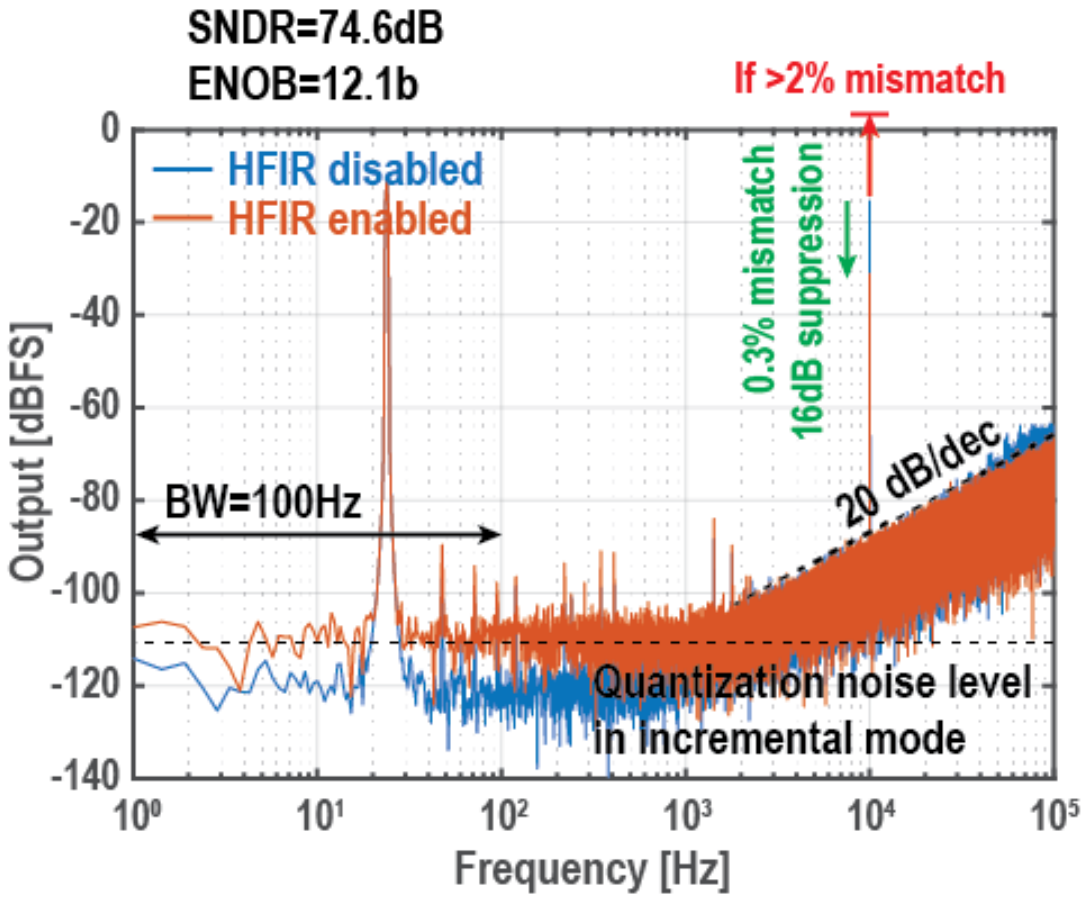
TSMC 180nm
CMOS process

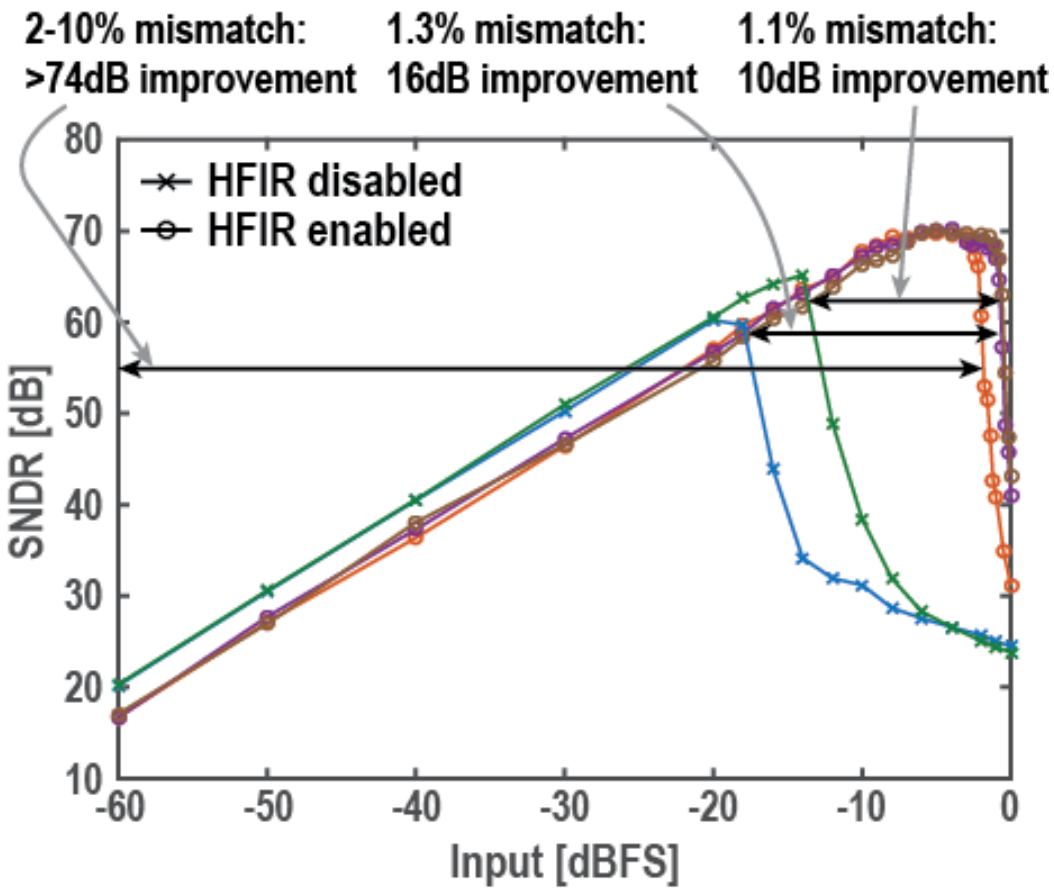


Total power: 1.39 mW



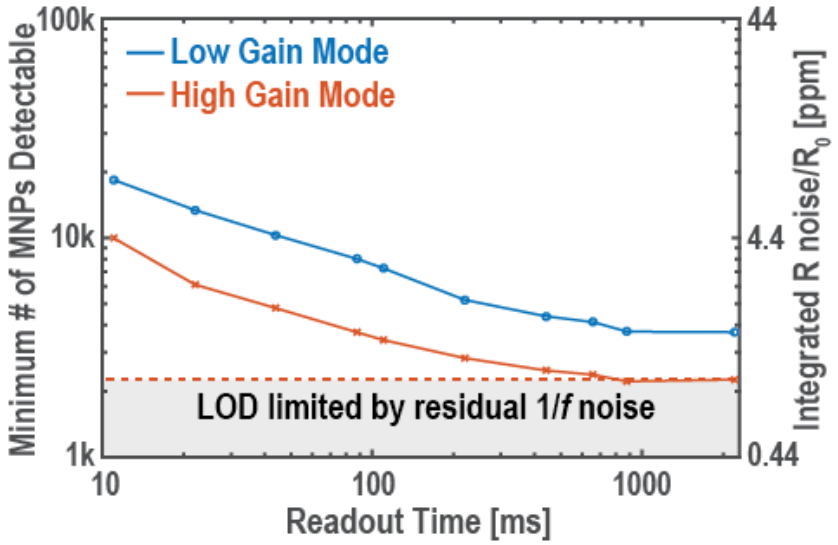
Measurement Results: ADC

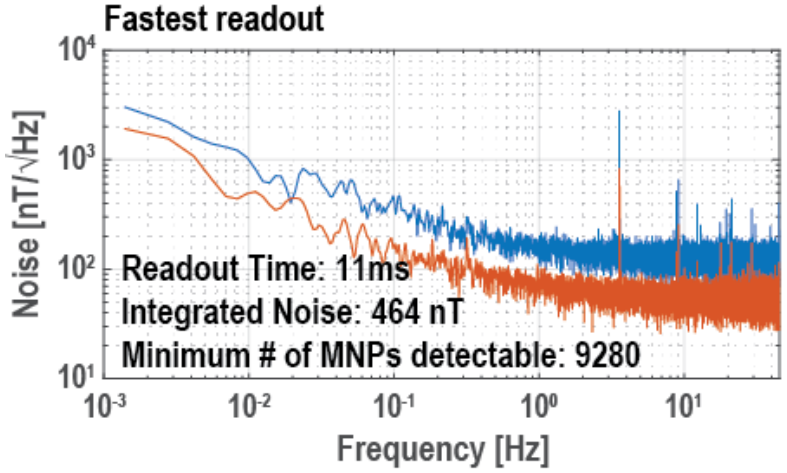


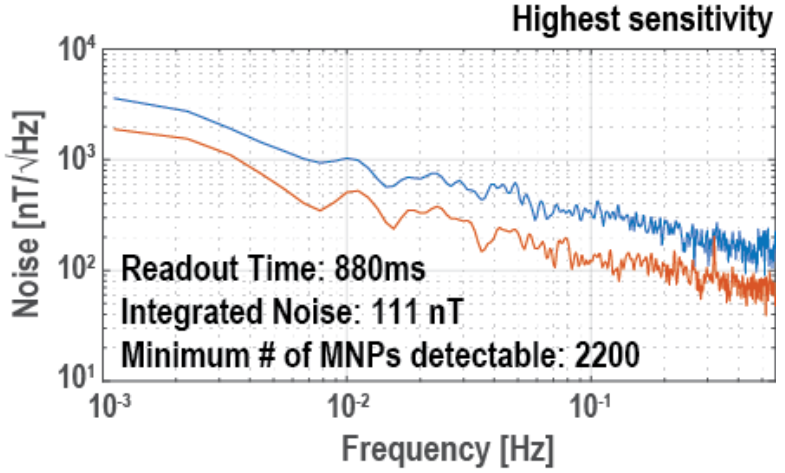


HFIR improves ADC DR significantly when sensor mismatch > 2%

Measurement Results: System

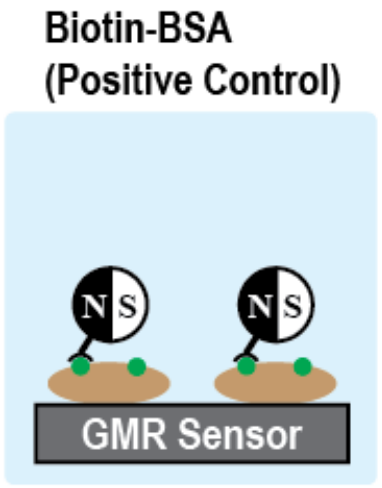


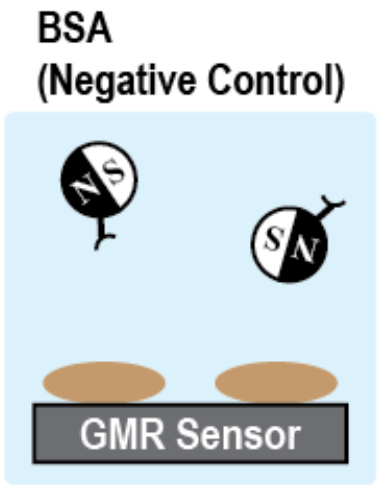


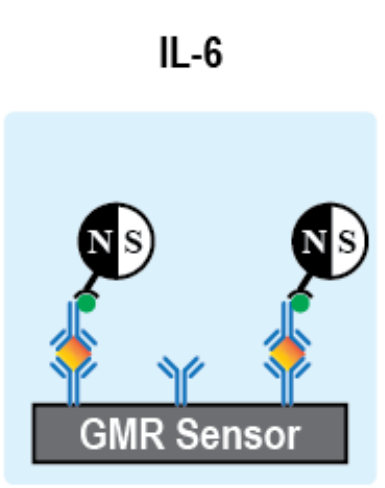


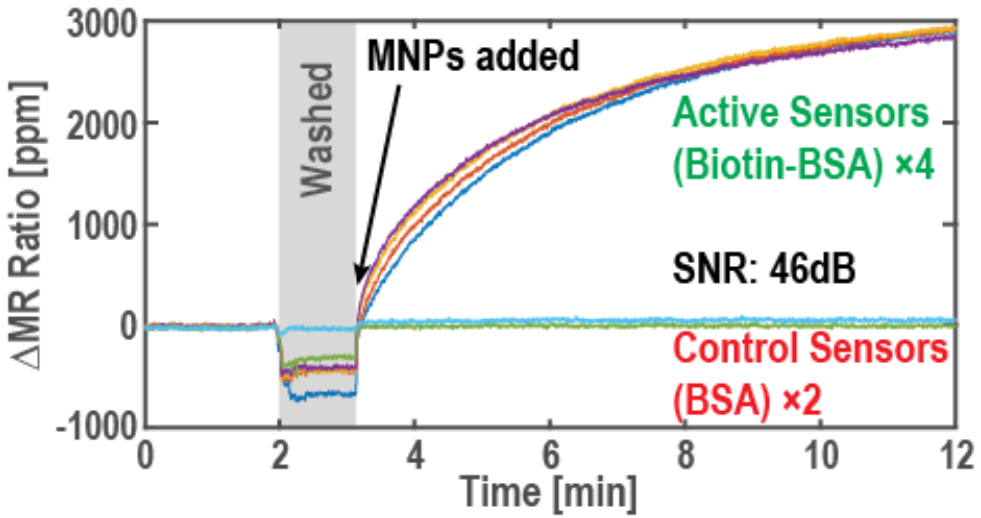
The system achieves 0.98ppm (147μΩ) sensitivity with a readout time of 880ms

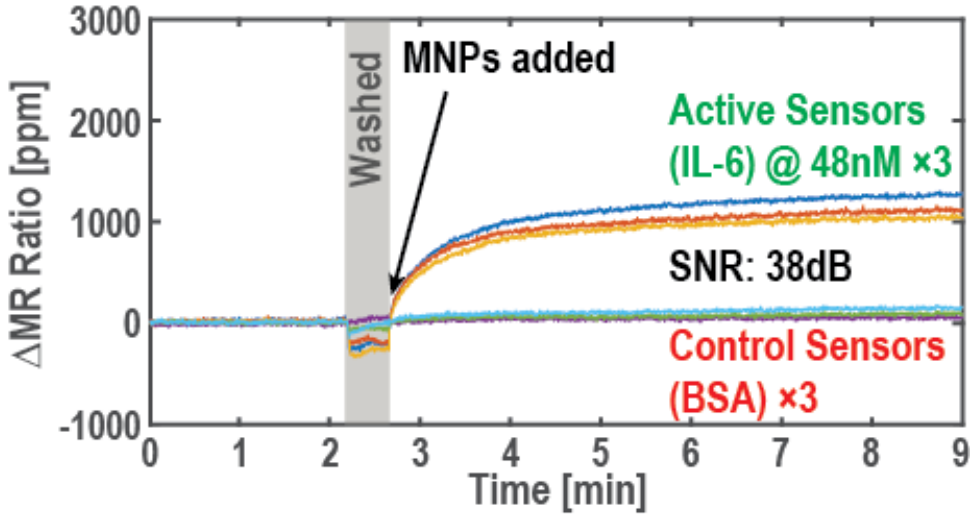
Measurement Results: BioAssay











Summary and Comparison

	H. Wang ISSCC 2009 [1]	S. Gambini JSSC 2013 [2]	T. Costa TBioCAS 2017 [3]	S.J. Han ISSCC 2007 [4]	D.A. Hall JSSC 2013 [5]	This Work
Sensor Type	LC	Hall	GMR	GMR	GMR	**GMR**
Sensor Resistance (kΩ)	N/A	N/A	0.85	N/A	1.92	**0.15**
MR Ratio (%)	N/A	N/A	5.37	N/A	9.2	**9.04**
MNP Size (nm)	1,000	1,000	250	50	50	**50**
Technology (μm)	0.13	0.18	0.35	0.25	0.18	**0.18**
AFE Architecture	LC oscillator	V/I converter	Amplifier	Mixer + PGA	TIA	**PGA with Mixer**
ADC Architecture	VCO-based	Inc. ΔΣ	No ADC	No ADC	ΔΣ	**Inc. ΔΣ + HFIR**
Input-referred Noise (nT/√Hz)	N/A	270	11.5Ψ	N/A	49	**107.1 (low gain) 46.4 (high gain)**
Sensor Mismatch Tolerance	N/A	N/A	N/A	N/A	N/A	**10% (low gain) 2.5% (high gain)**
Power/Ch (mW)*	N/A	0.825	4.9Ψ	N/A	3.15	**1.39**
Area/Ch (mm^2)	N/A	0.012	3.17	N/A	0.219	**0.249**
Input-referred Baseline (mT)	N/A	0.007	1.84	N/A	7.09	**< 0.235**
Readout Time/Ch (ms)	400†	50	1,000	250	250	**11**

* Does not include sensor bias and magnetic field generator. Ψ Does not include power and noise from ADC. † Read from figures.

The chip achieves 22.7× faster readout time, >7.8× lower baseline, and 2.3× lower power than other GMR sensor-based designs

Conclusion

- Magnetic sensors are a promising candidate for PoC biosensing; however they suffer form large baseline/signal and sensor mismatch
- To address this we:
  - Used reference sensors to reduce baseline
  - Designed an integrated down-modulator to relax the ADC bandwidth requirement
  - Proposed a HFIR sampling technique to tolerate sensor mismatch
  - Designed a fast settling duty-cycle resistor to improve readout time
- Result: A design that achieves **sub-ppm sensitivity** and tolerates **10% sensor mismatch**

Acknowledgement

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- The authors would like to thank MagArray, Inc. for providing the GMR sensors

Thank you for your attention