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Multi-electroanalytical method capable, duty-cycled, 0.36 mm2 electrochemical frontend, achieving 170dB current sensing range with extended compliance voltage adopting feedforward cancellation

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Agenda

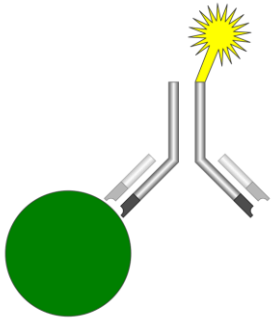
- Motivation
- Challenges
- Proposed AFE
  - Differential biasing
  - Feedforward cancellation technique
  - 20b DAC implementation
  - Potentiostat amplifier
  - Chopping strategy
  - Dynamic range scaling
- (In-vitro) Measurement results
- Comparison and summary

Motivation : Advantages of electrochemical sensing

- Electrochemical sensing offers several advantages compared to traditional methods
  - Highly integrated, compact and portable
  - Low power
  - Low cost
- Rapidly gaining traction in Point of Care and wearable applications

Chromatography

Immunoassays



Mass spectrometry

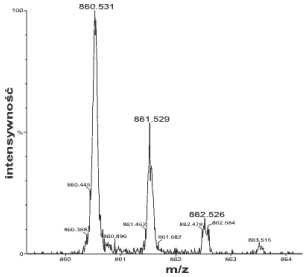
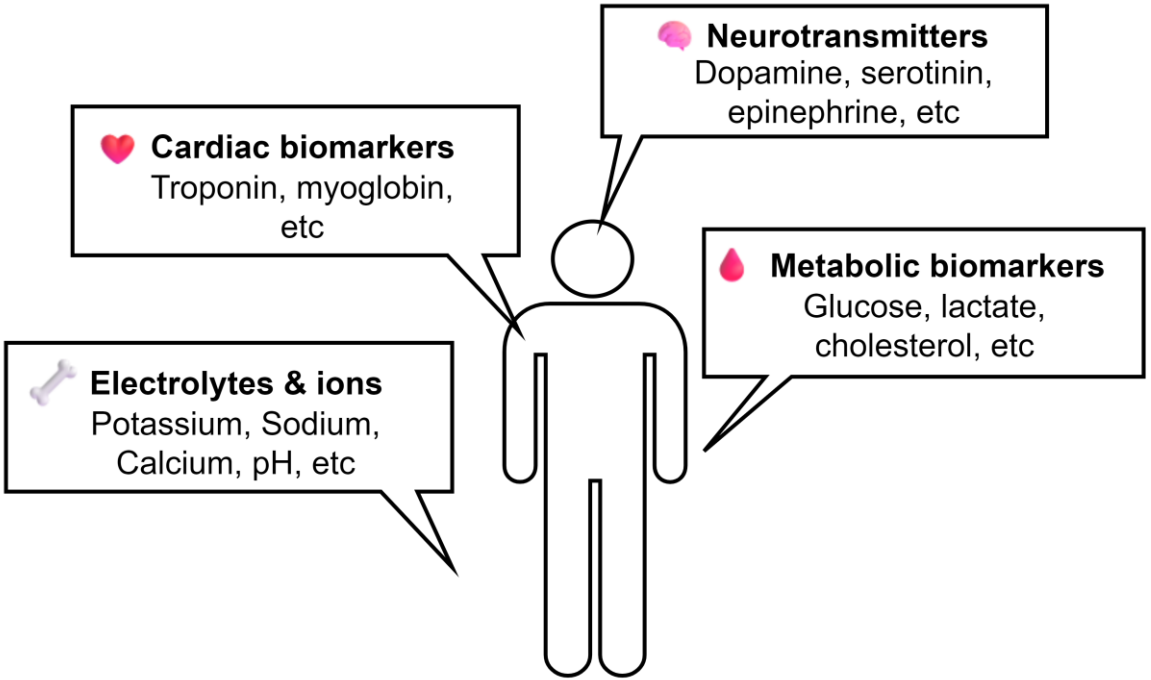


Image Ref: Wikipedia

Motivation : Applications in healthcare



- Vital biomarker analysis and monitoring
- Preventive healthcare
- Sports, fitness and performance improvement

Motivation : Challenges

- Modern applications require measuring diverse analytes. This necessitates the electronics (Analog Front End – AFE) to
  - ! Support diverse electroanalytical methods (Voltammetry, amperometry and potentiometry) ..
  - ! Sense and digitize a huge dynamic range of sensor currents (a few pA to 100's of µA) ..
  - ! Support a large sensor bias and compliance voltage (V_{WE}-V_{RE} & V_{WE}-V_{CE}) ..
  - ! Precisely voltage-bias the sensor to distinguish analytes having closely spaced redox potentials[1]
  - ! Offer a high input impedance

[1] C. Stucky and M. A. Johnson, "Improved Serotonin Measurement with Fast-Scan Cyclic Voltammetry: Mitigating Fouling by SSRIs," Journal of The Electrochemical Society, 2022,

Motivation : Proposal

- Modern applications require measuring diverse analytes. This necessitates the electronics (Analog Front End – AFE) to
  - ! Support diverse electroanalytical methods (Voltammetry, amperometry and potentiometry) **-> A highly programmable low noise analog front end**
  - ! Sense and digitize a huge dynamic range of sensor currents (a few pA to 100's of µA) **-> 20b ΔΣ- FIR feedback ADC, Feedforward cancellation technique, Multi-stage chopping**
  - ! Support a large sensor bias and compliance voltage (V_{WE}-V_{RE} & V_{WE}-V_{CE}) **-> Differential biasing**
  - ! Precisely voltage-bias the sensor to distinguish analytes having closely spaced redox potentials[1] **-> 20b on-chip ΔΣ DAC**
  - ! Offer a high input impedance **-> Cascaded multi-stage chopping strategy**

[1] C. Stucky and M. A. Johnson, "Improved Serotonin Measurement with Fast-Scan Cyclic Voltammetry: Mitigating Fouling by SSRIs," Journal of The Electrochemical Society, 2022,

Motivation : Challenges (Contd..)

The portability nature necessitates the AFE to

- ! Be self-sufficient with fully-integrated programmable waveform control
- ! Support low-power operation

[1] C. Stucky and M. A. Johnson, "Improved Serotonin Measurement with Fast-Scan Cyclic Voltammetry: Mitigating Fouling by SSRIs," Journal of The Electrochemical Society, 2022,

Motivation : Proposal (Contd..)

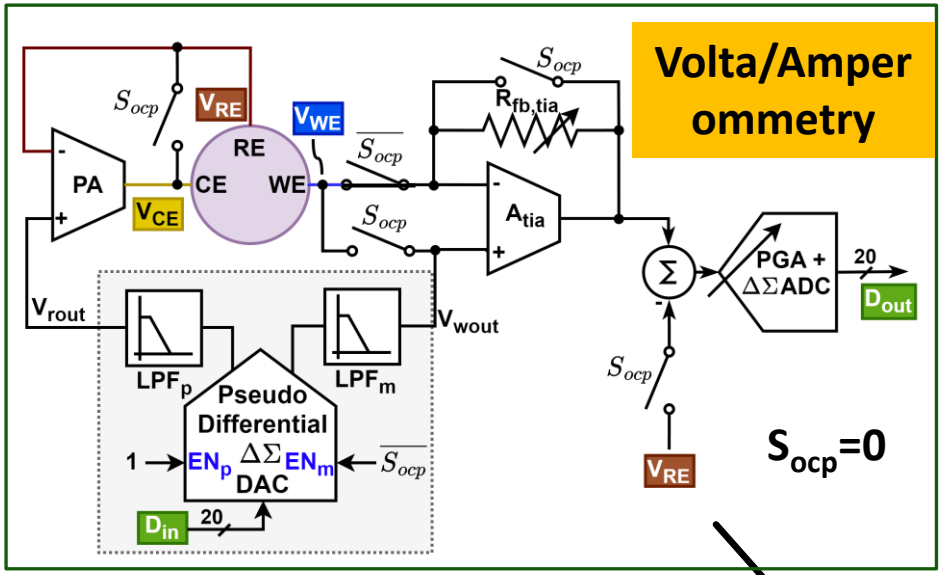
The portability nature necessitates the AFE to

- ! Be self-sufficient with fully-integrated programmable waveform control -> **On-chip ΔΣ DACs**
- ! Support low-power operation -> **Duty-cycling and other low-power circuit techniques**

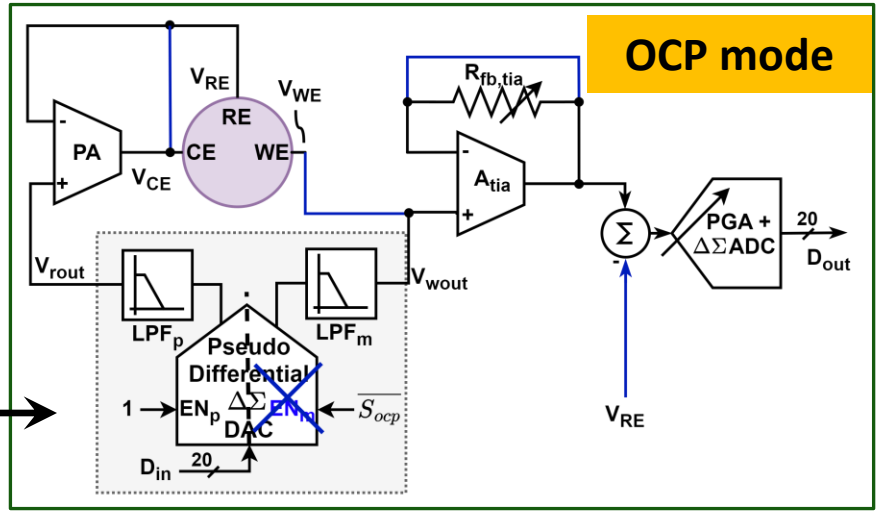
[1] C. Stucky and M. A. Johnson, "Improved Serotonin Measurement with Fast-Scan Cyclic Voltammetry: Mitigating Fouling by SSRIs," Journal of The Electrochemical Society, 2022,

Analog front end

Programmable AFE - Simplified illustration

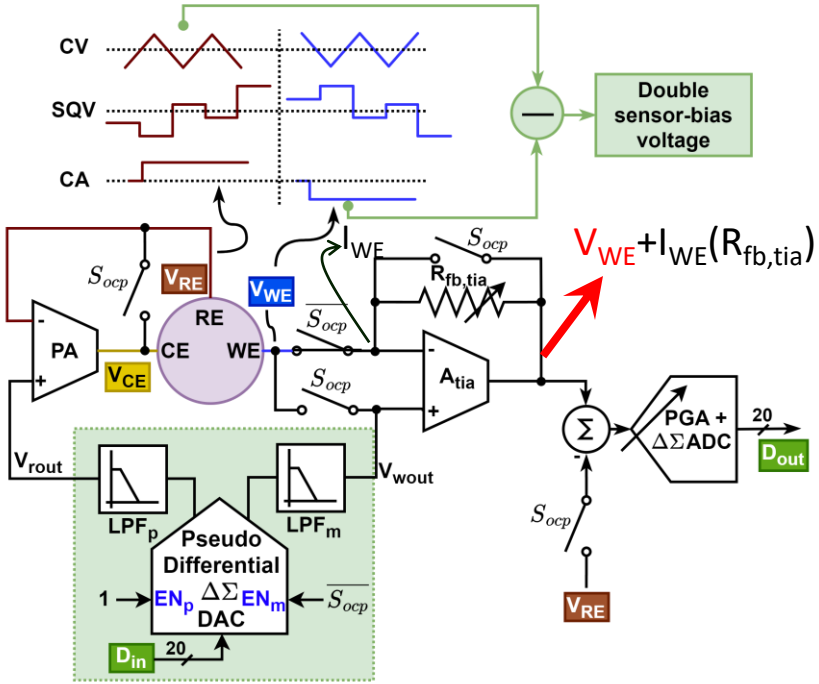


- Programmable front-end
- Addresses 3-electrode amperometric and 2-electrode potentiometric sensors



Analog front end

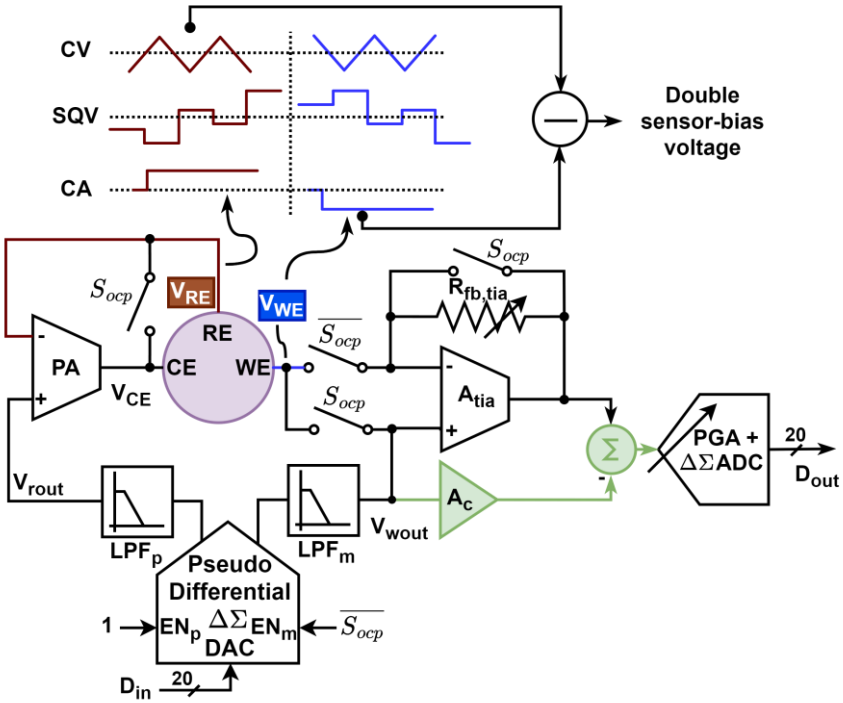
Dynamic range enhancement of sensor biasing path - Differential biasing strategy



- The pseudo-differential DAC receives a 20b digital input and outputs a differential signal on Working (WE) and counter (CE) electrodes
- Effectively doubles the sensor bias voltage paving the way to analysing analytes with higher standard cell potentials

Analog front end

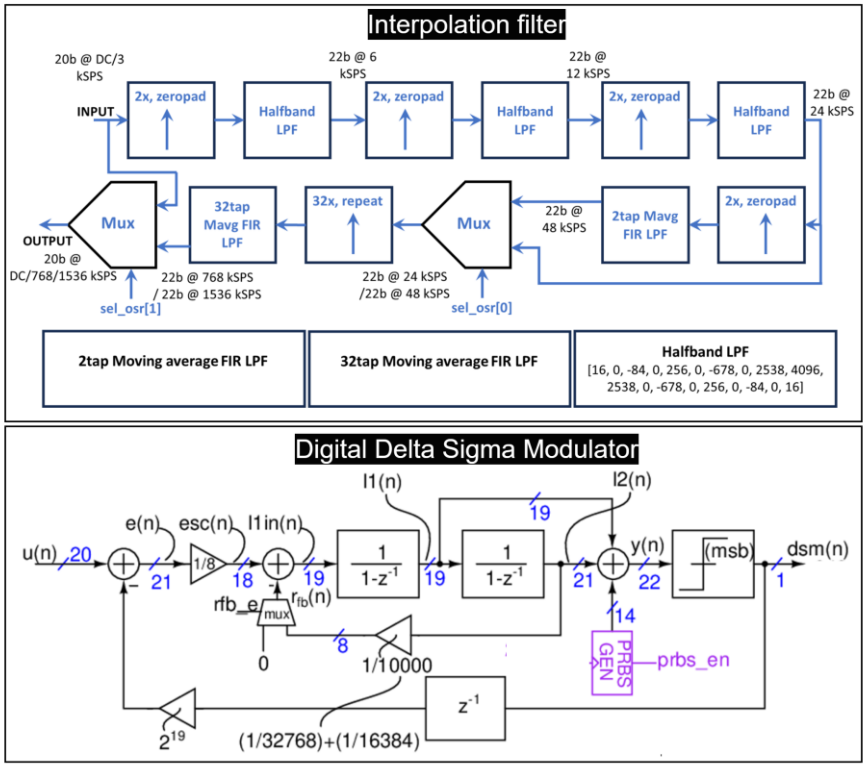
Dynamic range enhancement of readout path through feedforward cancellation



- The WE sensor-bias voltage occupies a large voltage range at the input to the PGA/ADC
- This signal is inverted and feedforwarded effectively cancelling the sensor bias voltage while presenting the ADC with only the sensor bias current thereby enhancing the dynamic range of the readout path

20b Digital-to-Analog converter

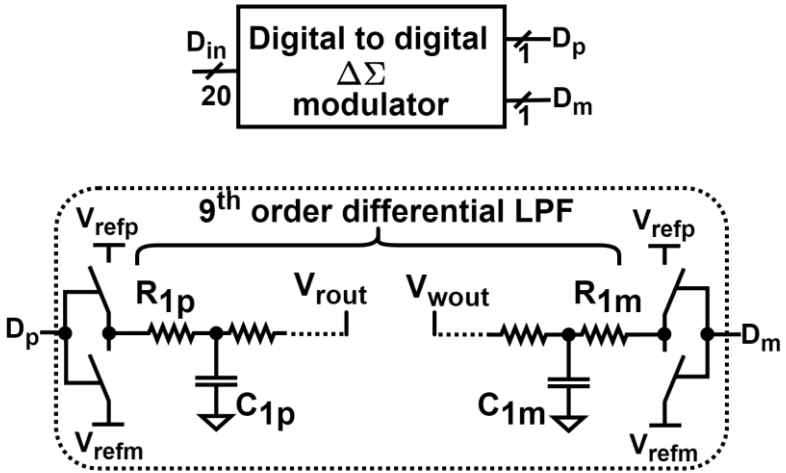
Digital to digital converter



- Accepts arbitrary digital inputs at 3 kSPS –> Supports various voltametric techniques
- Interpolation filter followed by Digital-to-digital converter followed by Digital to analog converter
- Digital ΔΣ modulator converts the 20b oversampled input into a 1b digital bit stream ensuring high linearity in the subsequent DAC

Pseudo-differential DAC

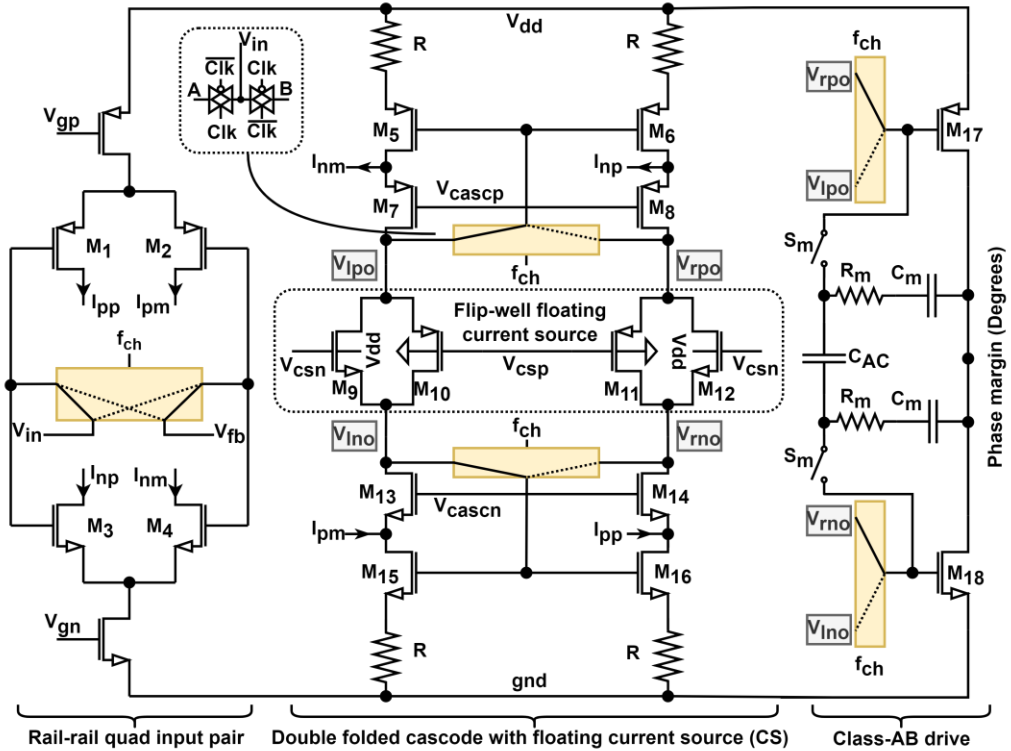
Architecture



- The 1b ΔΣ modulated bitstream is applied to a 9th order RC low pass filter having an effective cut-off of ~1 kHz
- The references are generated by a chopped reference buffer to reduce the impact of flicker noise

Potentiostat / TIA amplifier

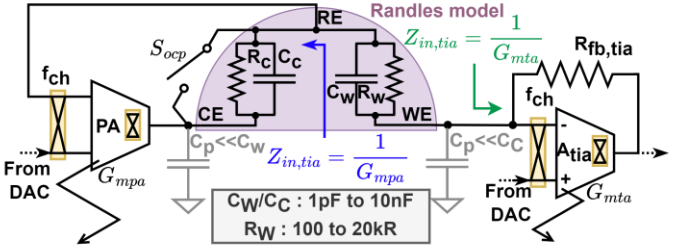
Architecture



- Double folded-cascode structure with floating current source input stage
- Class-AB biased output stage
- Fully chopped (both stages) amplifier

Potentiostat / TIA loop interaction

Stability considerations

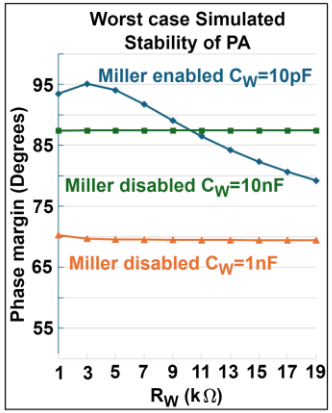


$$LG_{pa}(s) \approx \frac{G_{mpa}R_W(1+s/\omega_{z1})}{1+s/\omega_{p1}}$$

$$\omega_{z1} = \frac{G_{mta}}{C_W} \quad \omega_{p1} = \frac{1}{R_W C_W}$$

$$LG_{ta}(s) \approx \frac{G_{mta}R_W(1+s/\omega_{z2})}{1+s/\omega_{p2}}$$

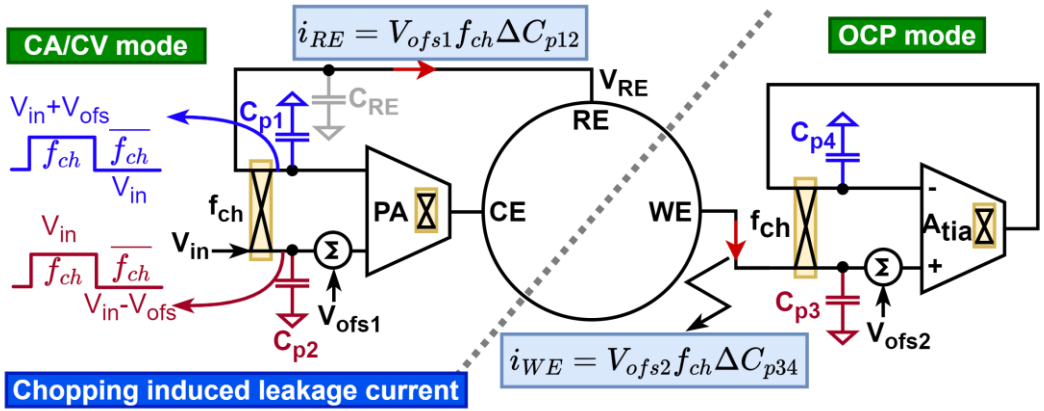
$$\omega_{z2} = \frac{G_{mpa}}{C_W} \quad \omega_{p2} = \frac{1}{R_W C_W}$$



- The TIA loads the potentiostat through the sensor and vice-versa
- Careful placement of pole/zeros and option to switch between Miller compensation and load compensation to ensure stability across a wide range of sensor geometries

Chopping strategy

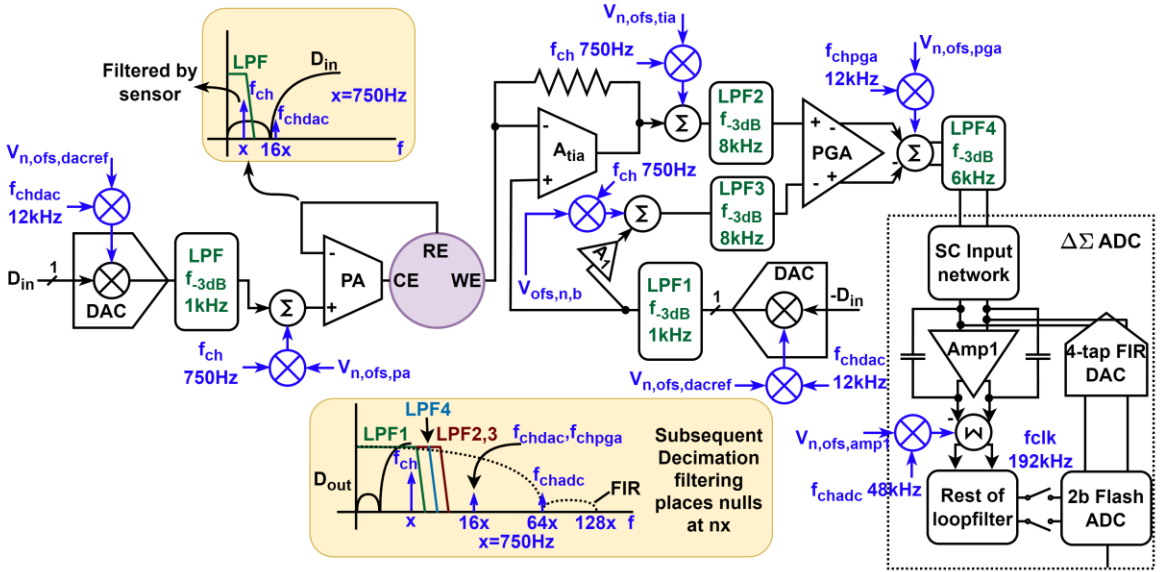
Input impedance – chopping frequency tradeoff



- The DC input impedance is inversely proportional to chopping frequency
- Any chopping-induced current drawn from sensor electrodes would disturb the sensor operating points

Chopping strategy

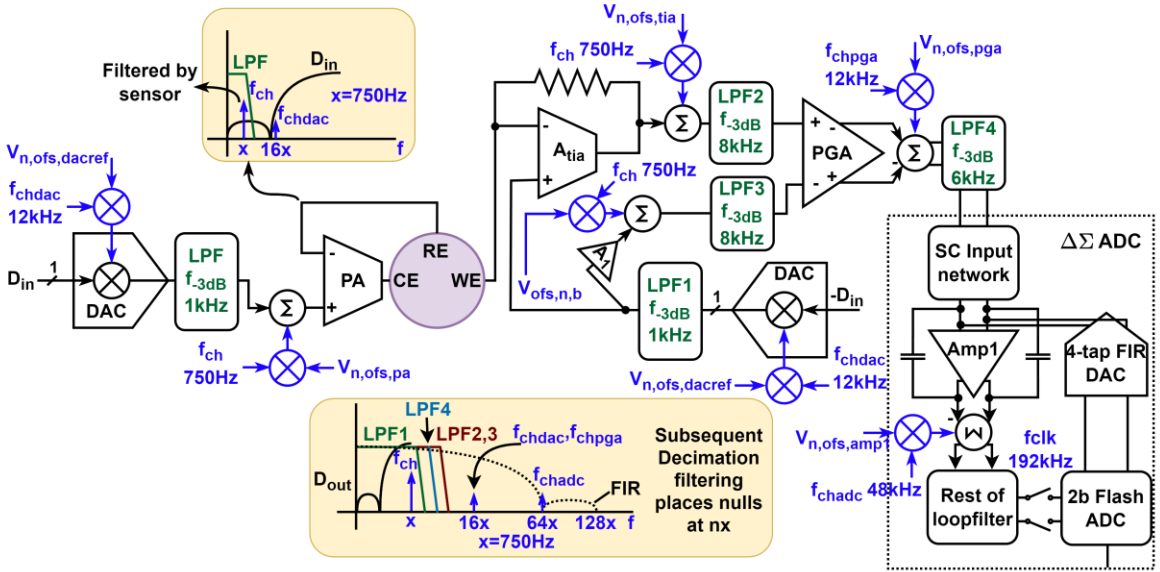
Progressively increasing frequency full-chain chopping



- Entire signal path is chopped
- PA and TIA amplifiers chopped only at 750 Hz to present high input impedance to the electrodes.
- Over a 1 Hz bandwidth, this yields ~750-fold reduction in flicker noise power

Chopping strategy

Progressively increasing frequency full-chain chopping

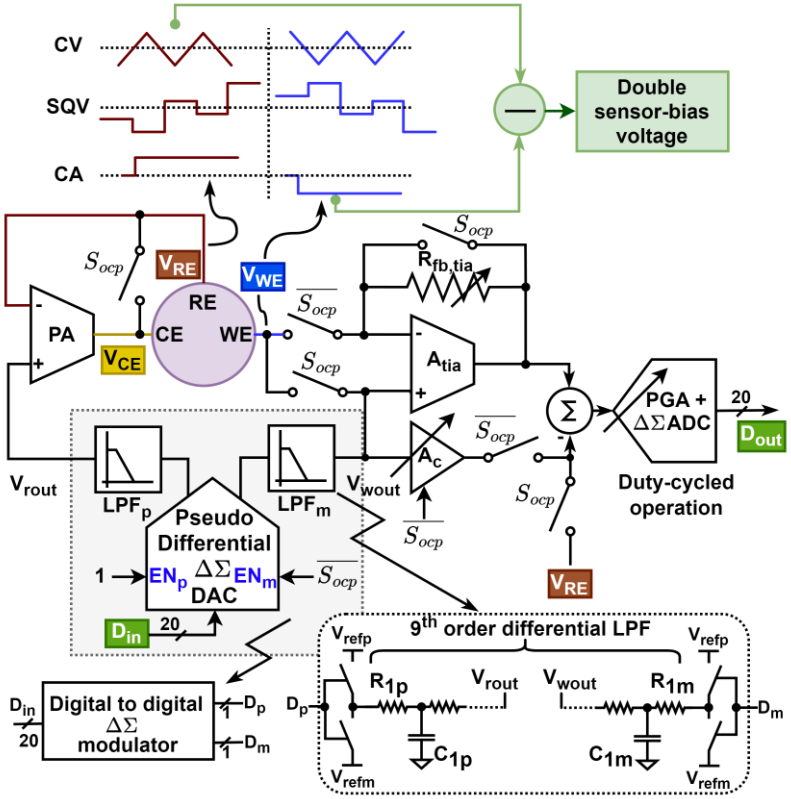


- PGA chopped at 12 kHz and the 20b ΔΣ-ADC at 48 kHz
- Nominally the flicker noise is upconverted to odd multiples of the chopping frequency. Therefore, the subsequent blocks were chopped at even multiples of the chopping frequency
- All blocks interspersed with LPF to mitigate residual chopping ripple around their even harmonics

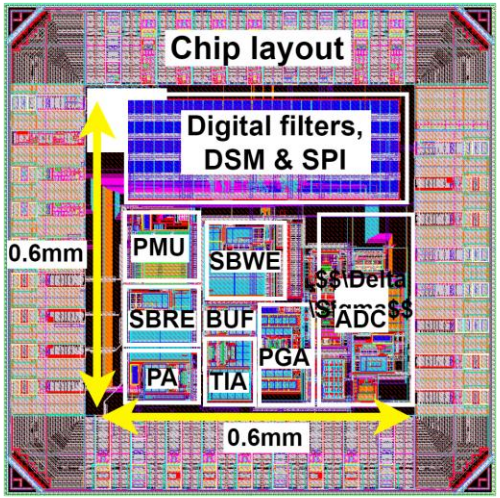
Dynamic range and node scaling

- The gain of the readout path is partitioned between TIA and the PGA
- The transimpedance of the TIA is programmable from 6.7 kΩ to 1 MΩ while the gain of PGA is programmable from 0 Db to 20 dB
- This split-up ensures optimal node swings and noise attenuation from the subsequent blocks like the ADC resulting in additional dynamic range enhancement

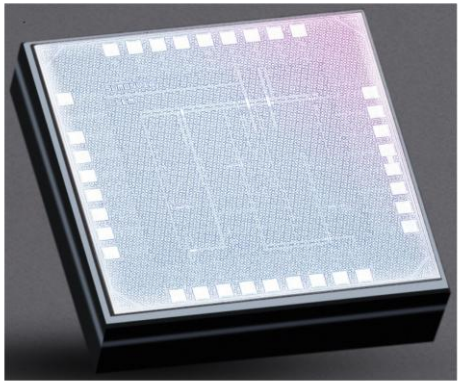
All pieces together…



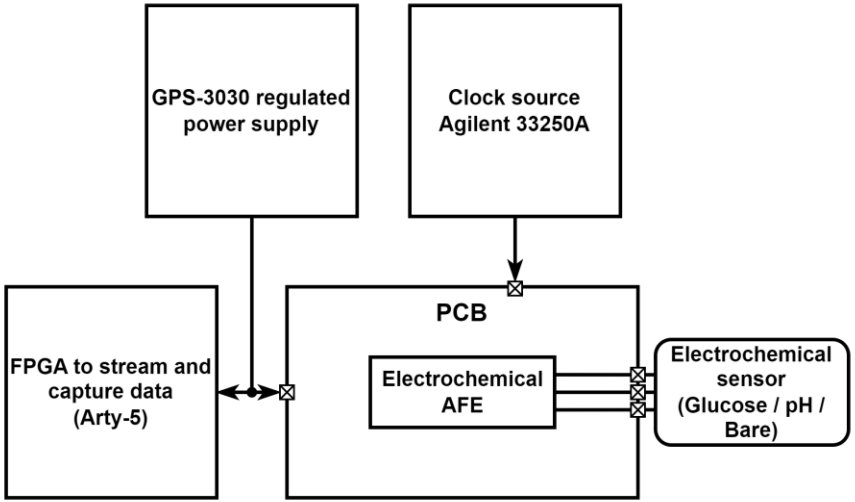
Implementation details

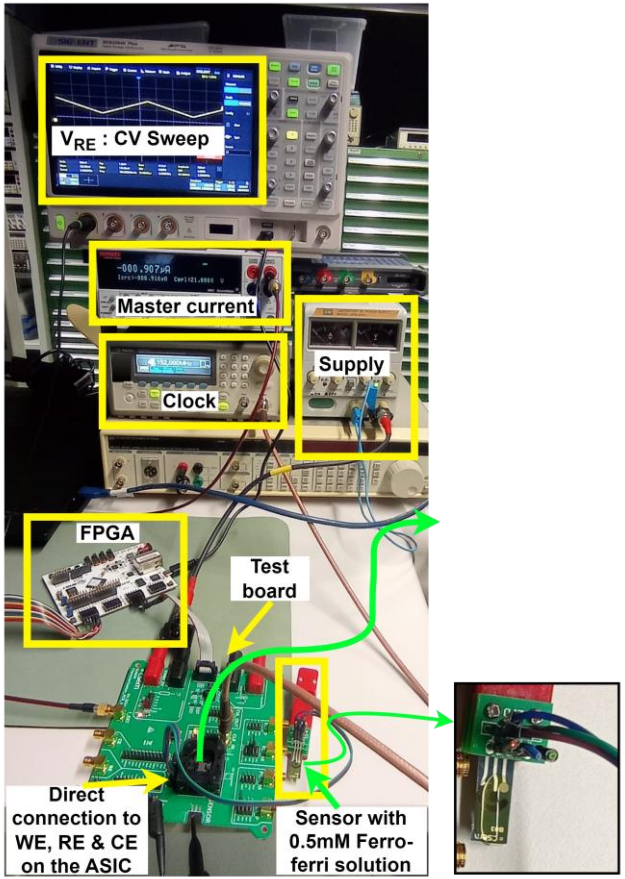


- The AFE was designed and fabricated in a 22nm CMOS process
- High performance analog sub-blocks operate from a supply of 1.8V while digital and low performance analog from 0.8V
- The 20b ΔΣ DAC is clocked at 3 kHz while the 20b ΔΣ ADC at 192 kHz
- Occupies a core area of only 0.36mm^2



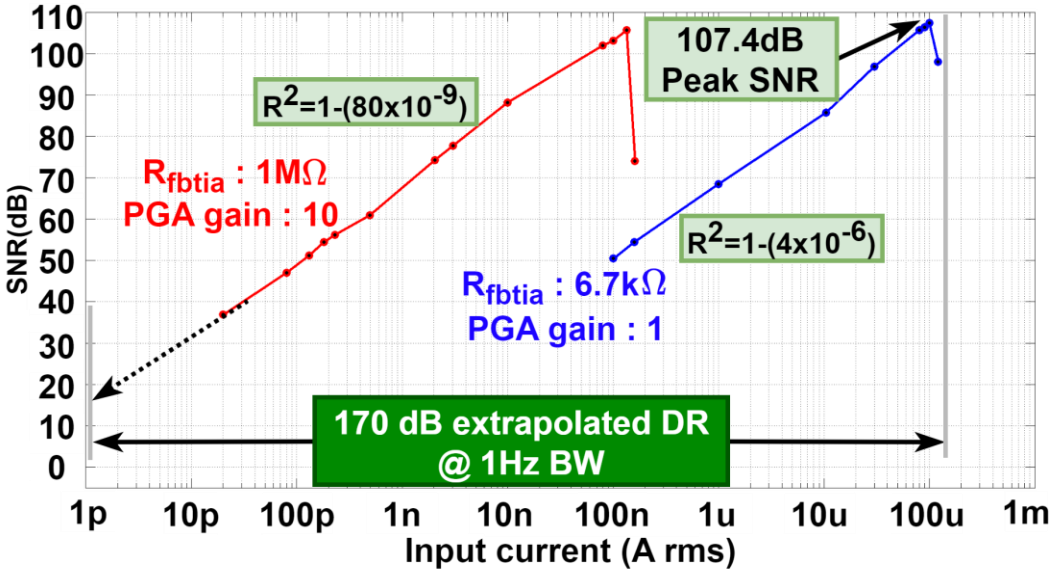
Measurement setup





Measurement results

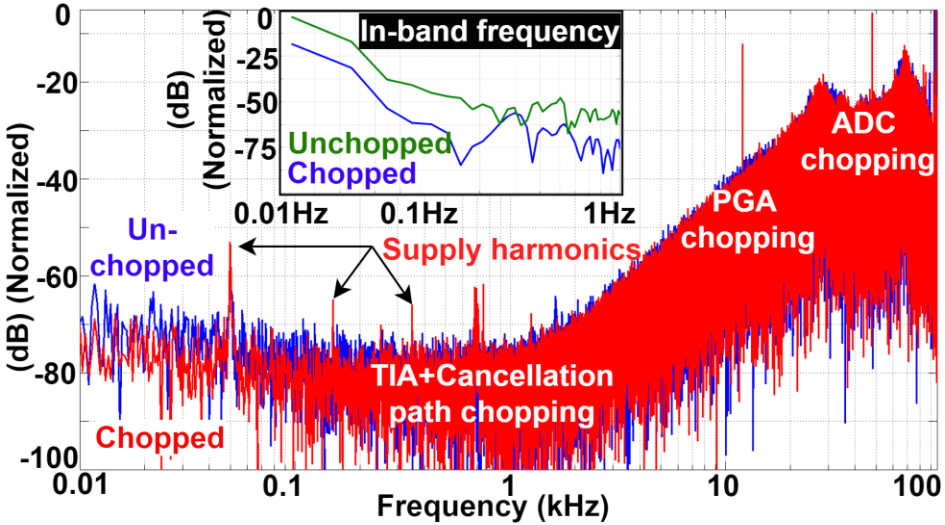
Dynamic range plot



- Readout path achieves a peak SNR > 105 dB for any gain setting
- 170 dB overall measured dynamic range (extrapolated) allowing to measure pA to 100 µA sensor currents

Measurement results

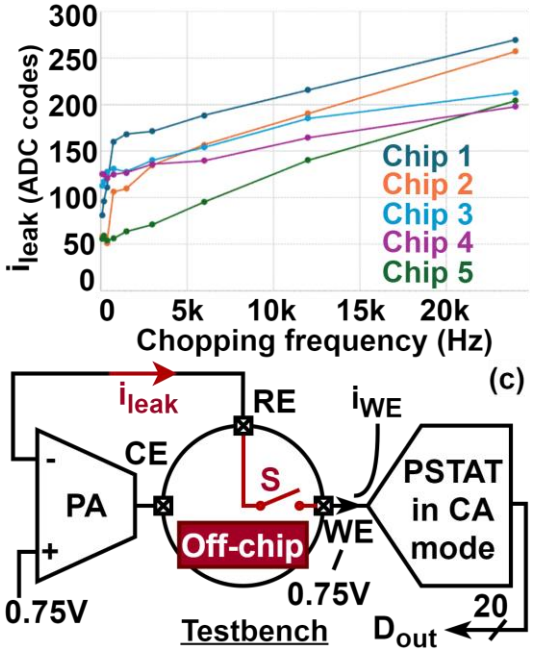
Effectiveness of chopping strategy



- The measured spectrum shows ~20 dB improvement in the low frequency noise within the bandwidth of interest
- Other upconverted chopping ripple clearly observed

Measurement results

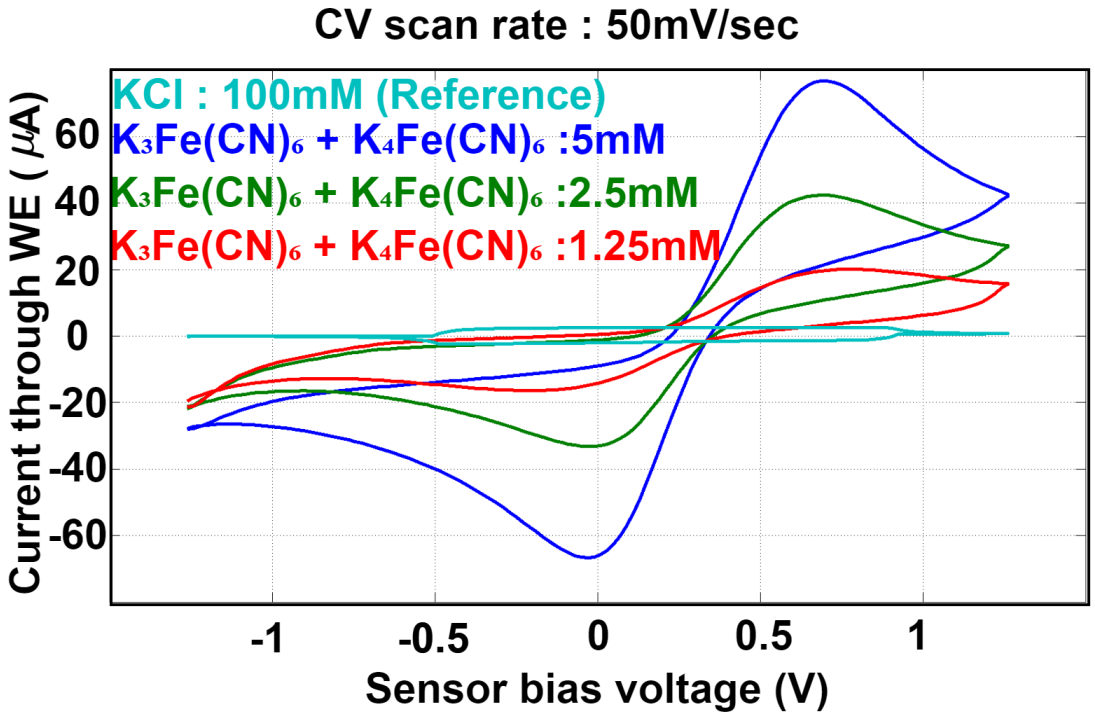
Leakage current measurements



- The leakage current through the WE and RE measured across 5 chips
- A differential measurement strategy was adopted as the currents are very low
- As the chopping frequency is increased, the leakage current shows a clear increase
- At low frequencies, the input referred leakage current can be evaluated to be ~35pA

In-vitro measurement results

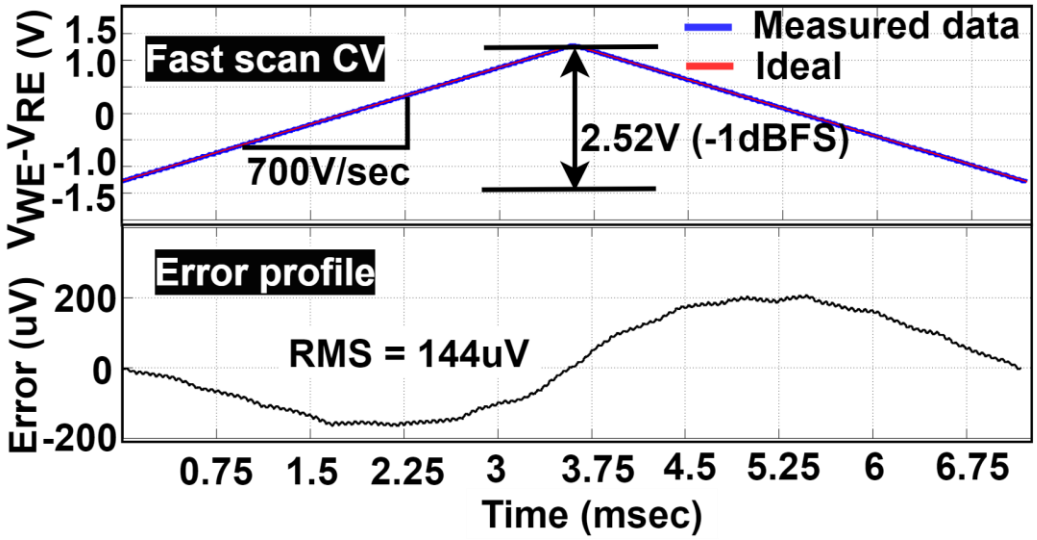
Cyclic voltammetry



- Expected oxidation and reduction peaks observed from measurements
- Appropriate increase in the redox currents with increasing concentration of the Ferro-Ferri cyanide solution

In-vitro measurement results

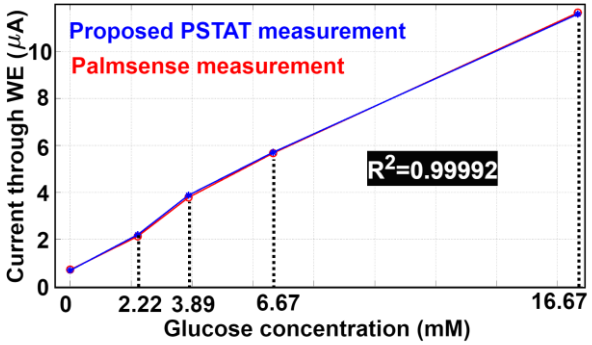
Fast scan cyclic voltammetry

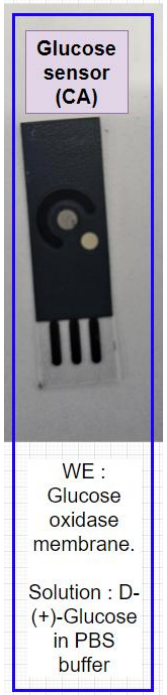


- Showcases the ability of the 20b DAC to generate waveforms for fast scan cyclic voltammetric measurements (FSCV)
- Thanks to the digital control, various sensor bias voltage profiles can be generated

In-vitro measurement results

Chronoamperometry

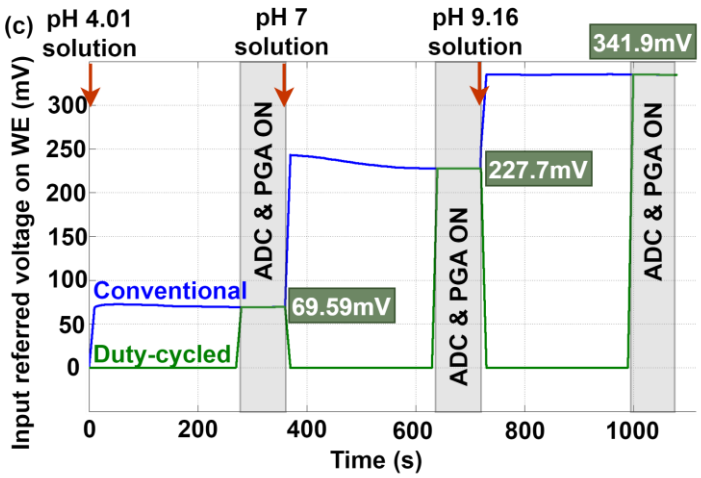


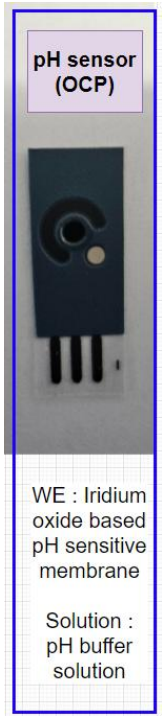


- Varying concentrations of Glucose measured using the proposed AFE
- Shows good agreement with a laboratory device

In-vitro measurement results

Open circuit potentiometry

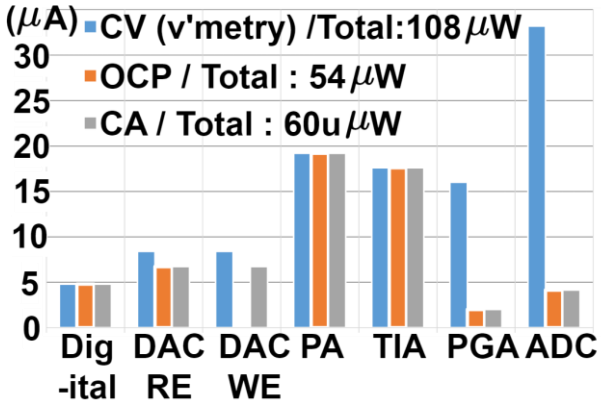




- Varying concentrations of pH measured using the proposed AFE
- Shows good agreement with expectations
- The enabling of PGA and ADC were duty-cycled to the final 25% of the measurement thereby significantly reducing power consumption

Measurement results

Power consumption



Comparison with the state of the art

	This work	[1]	[6]	[7]	[11]	[10]	[15]
Process (nm)	22	180	180	180	180	350	350
Supported methods	CA, CV, OCP, etc	CA	CA	CA,OCP	CA/CV/ FSCV	CA/FSCV	CA/CV/EIS
On-chip bias generator	Yes - Arbitrary	NA	NA	NA	Triangle generator	Triangle generator	No
Nominal supply voltage (V)	1.6 / 0.6 Ana / Dig	1.2	1.8	1.8	1.2	2.5	3.3
Power consumption (µW)	CA : 60 / OCP : 54 / CV : 108 [f]	0.00372[a]	295[a]	15	19	37.3	188 [a]
Current sense range (A)	300f - 105u	80p-240u	100f-10u	20p-10u	12.6n-10u	78p-950n	24p-350n
Linearity (R^2)	0.999996	0.998	NAV	NAV	0.999	NAV	NAV
DR of current sensing (dB)	170 [b]	129.5 [c]	160	114 [b]	58	80.8	95
Peak SNR (dB)	107.4	45	NAV	76.5	NAV	76.3	70.2
Sensor bias noise (uVrms)	140	NA	NA	NA	NAV	NAV	NA
Max V_{WE}-V_{RE} (V)	2.8	NA	NA	NA	1	1.7	NA
Max scan rate (V/sec)	750	NA	NA	NA	400	400	NA
RE/WE leakage	35pA	NA	NA	2.5pA	NA	NA	NA
Bandwidth (Hz)	1	NAV	1.8	16	<1	5	50
Area (mm^2)	0.36	0.266	3 [e]	10.24 [e]	3.17 [e]	10 [e]	0.04[a]

NA / NAV - Not applicable / Not available. a - Power for sensor bias reference generation unaccounted. b - Extrapolated DR. c - SNDR > 23 dB across this DR. e - Area includes padring. f - At worst scenario where fast scan rate is greater than 232V/sec

Summary

- Presented a highly programmable low noise analog front end that supports **diverse electroanalytical methods**
- Sense and digitize a huge dynamic range of sensor currents (**a few pA to 100's of μA**) thanks to **20b ΔΣ- FIR feedback ADC, Feedforward cancellation technique, Multi-stage chopping techniques**
- Support a large sensor bias and compliance voltage (V_{WE}-V_{RE} & V_{WE}-V_{CE}) through **differential biasing**
- Precisely voltage-bias the sensor to distinguish analytes having closely spaced redox potentials[1] thanks to the **20b on-chip ΔΣ DAC**
- Offer a **high input impedance** thanks to the cascaded multi-stage chopping strategy
- A self-sufficient solution with fully-integrated **programmable waveform control** thanks to the On-chip ΔΣ DACs
- Support **low-power operation by duty-cycling** and other low-power circuit techniques


THANK YOU
hvala
danke
謝謝
どうも
ありがとう
gracias
merci
köszi
obrigado
danke schön
DANK U
takk
MERSI
PALDIES
muchas gracias
TEŞEKKÜR EDERIM
MOLTE GRAZIE
GO RAIBH MAITH AGAT
ARIGATO
OBRIGADO
grazas
GRAZZI
THANKS
quan
TAK
asante
muchas gracias
vielen dank
благодаря
grazie
DZIEKI
TACK
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