Brain Inspired ISFET Arrays

Prateek Tripathi

Supervisors: Prof. Pantelis Georgiou & Dr. Nicolas Moser

Dept. of Electrical and Electronic Engineering, Imperial College London, SW7 2BT, United Kingdom and Centre for Bio-Inspired Technology, Institute of Biomedical Engineering, Imperial College London, SW7 2AZ, United Kingdom
Outline

• Background

• Opportunity (The future of Diagnostics and ML is tiny and bright)

• Research Questions

• Current Progress

• Future Work
The ISFET is fabricated as a MOSFET with a floating gate. A change in the ion concentration at the gate causes a variation in the threshold voltage of the device.
Non-ideal Effects

ISFETs suffer from:

- **Trapped Charge:**
  Charge gets trapped on the floating gate of the ISFET, most likely due to charge transfer during chip production, introducing an offset in its threshold voltage.

- **Drift**
  Slow monotonic change in the threshold voltage of the ISFET and originates from a transport phenomenon at the interface between the insulator and the solution.

Non idealities are spatially correlated

• My experiments with a previous chip Titanicks has brought me to the conclusion of spatial correlation

• I will test this hypothesis with further chips over the course of my PhD

Application: DNA Detection

2 wells:

• Top well - sample
• Bottom well - control

Neurons

- Spike domain
- High dynamic range
- Low power
- Cooperation
- Plasticity

Neuromorphic Intelligence

- Analogous to the morphology of nervous systems due to spiking
- Combines analog, asynchronous digital and logic circuits.
- Yields application specific devices optimal for edge computing.
- MOSFETs in Weak inversion use diffusion for charge transfer similar to the ionic current in neurons.

Source: TinyML EMEA Webinar July 2021 by G. Indiveri & The future of computing beyond Moore’s Law, John Shalf, 2020
Opportunity

- Since both neurons and ISFETs respond to variation in ion concentrations, there is a great opportunity to combine neuromorphic circuits with potentiometric ISFET sensing.
- Asynchronous (Event based)
- Low latency
- Ultra low power

The Future of ML is Tiny and Bright

- 5 Quintillion bytes of data produced by IOT devices everyday.

- <1% of unstructured data is used.

- In TinyML, we are typically interested in sensor data in the form of an image or time series, enabling us to perform **spatial** or **time series** analysis using machine learning models at the edge.
Brain Inspired ISFET Sensing
Research Questions

• What is the role of non-ideal effects on a cluster of neighboring ISFET pixels? Do non-ideal effects present any form of spatial correlation? What methods can be used to multiplex compensation approaches among clusters of ISFET sensors?

• How can slow chemical reactions on the surface of electrochemical sensors benefit from the event-based neuromorphic approaches?

• How can the neuromorphic approach be implemented for ISFET architectures?

• Are the properties of an ISFET sensor closer to an image sensor or to an audio sensor?
Research Questions

- What are the best transformation techniques to better visualize and make decisions from the ISFET sensors?
- What role can AI play in the speedup of diagnostics for new diseases? Does the use of AI-based solutions bring any concerns on privacy and security and how can edgeAI alleviate these concerns?
- What are the tradeoffs between compensation using neuromorphic approaches vs tinyML?
Current Progress

- 1 chip fabricated
- ISFET neurons work
- Spatial correlation proven
- tinyML model for classification
Original Contributions


Neuron based ISFET Arrays

- We presented neuromorphic-based ISFET arrays with encoding of pH in the spike domain and spatial compensation of device non-idealities in a cluster-based structure.
- The use of AER for array data acquisition enabled low power operation.
- Overall, this work paves the way to both neuron-based architectures for ISFET front-end and relaxed requirements for compensation circuit by leveraging on spatial correlation.

Pixel Architecture

- Readout Voltage to Spike frequency

\[ f_{spk} = \frac{I_{cap} \times f_{rfr}}{I_{cap} + C_{mem} \times V \times f_{rfr}} \]
Cluster-based System

- Left configuration sacrifices pixel area to implement the additional blocks.
- Right configuration implements the extra circuitry between the pixels, allowing a larger sensing area and more uniform imaging.

Cluster-based System

- Spike domain makes compatible to the use of Address-Event Representation (AER).
- Logic contains:
  - Array control circuits,
  - Address encoding, and
  - Arbiter.
Multiple Ion Channel ISFET neuron

• A novel multiple ion-channel ISFET neuron is proposed in this study that performs spatial averaging using temporal integration at ultra low power consumption per pixel.

• This paper presents a novel approach towards implementing an on-chip sensor learning solution. This is achieved by a novel hardware implementation of backpropagation using predictive SAR logic.

• Geoff Hinton is deeply suspicious of backpropagation and believes that there could be a better alternative approach*

Silicon Testing (Goku)

- Taped out first IC for testing.
- The preliminary results are listed here.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>0.18 μm</td>
</tr>
<tr>
<td>Power Supply</td>
<td>1.8 V</td>
</tr>
<tr>
<td>Gate Bias Voltage</td>
<td>100 mV</td>
</tr>
<tr>
<td>Voltage Sensitivity</td>
<td>0.026 KHz/mV</td>
</tr>
<tr>
<td>Chemical Sensitivity</td>
<td>0.33 KHz/pH</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>12.82 mV/pH</td>
</tr>
<tr>
<td>W/L electrical</td>
<td>200 μm/0.18 μm</td>
</tr>
<tr>
<td>W×L chemical</td>
<td>48.975 μm x 38.705 μm</td>
</tr>
</tbody>
</table>
Current Progress

Photoreceptor vs ISFETs

This paper presents a winner-take-all (WTA) approach for implementing background inhibition in neuromorphic Ion-Sensitive Field-Effect Transistor (ISFET) arrays.

Aim: Investigate the benefits of neuromorphic electronics by taking advantage of
- fault-tolerant nature,
- spatial connectivity,
- spike-domain processing capabilities,
- neuron inhibitions and
- AER compatibility

WTA Pixel Architecture

ISFET pixel that converts the pH on the surface of the gate to the spike domain.

Winner take all implementation

The WTA thus acts as a spatial filter which is adaptive due to the current averaging and acts as a bias current generator for the WTA. In the end, the address of spike generation is the location of the largest variation in ionic concentration.
Background Inhibition using Winner take all

The WTA can be operated in parallel and distributed across circuits to achieve spatial filtering, allowing tracking pixels for salient features like targeting areas of early nucleic acid amplification in molecular assays.

TinyML in Diagnostics

The contributions of this work include:

- a benchmark for combining the field of deep learning with point-of-care lab-on-chip (LoC) diagnostics for infectious diseases and cancer

TinyML in Diagnostics

- A novel spectrogram-based approach that facilitates the application of image-processing ML techniques, including 2D-CNNs, for the classification of ISFET data.
- An approach that can help train neural networks with a limited dataset of infectious diseases for high precision and accuracy.

TinyML in Diagnostics

- A framework towards accelerating the response to future pandemics by leveraging the combined advances in the fields of spectrogram, deep learning and electrochemical-based detection to


Current Progress
Next Steps

- Taping out the WTA architecture and testing ISFETs on 65nm
- Implement deep learning classification algorithms on a microcontroller (Nano 33 BLE Sense)
- Run Multi-Ion imaging experiments for nucleic acid amplification detection.
Copyright Notice

This presentation in this publication was presented as a tinyML® EMEA Innovation Forum. The content reflects the opinion of the author(s) and their respective companies. The inclusion of presentations in this publication does not constitute an endorsement by tinyML Foundation or the sponsors.

There is no copyright protection claimed by this publication. However, each presentation is the work of the authors and their respective companies and may contain copyrighted material. As such, it is strongly encouraged that any use reflect proper acknowledgement to the appropriate source. Any questions regarding the use of any materials presented should be directed to the author(s) or their companies.

tinyML is a registered trademark of the tinyML Foundation.

www.tinyml.org