A 28.4 pJ per Conversion ISFET-based pH Sensing Design for Low-Energy Applications

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Outline

- Introduction
- Proposed ISFET-based pH sensor Design
- Simulation Results
- Conclusion
ISFET

- Ion Sensitive Field Effect Transistor
- Sense the presence and concentration of ions in a solution
- Replaces the metal gate of a MOSFET with a complex gate consisting of an electrode, the solution and a passivation layer

(Bergveld, 1970)
ISFET Operation

\[ V_{TH(IS)} = E_{ref} - \Psi_o + \chi^{sol} - \phi_{Si} - \frac{Q_{ox} + Q_{SS} + Q_B}{C_{ox}} + 2\phi_f \]

\[ I_D = \frac{1}{2} C_{ox} \mu \frac{W}{L} (V_{GS} - V_{TH})^2 \]

(Dutta, 2012)
ISFET Applications

- General pH sensing, applied in water quality monitoring (Chen, Chan, & Tse, 2005)

- Detection of the ratio of methylated DNA which can be used in the detection of cancers (Kalofonou, Georgiou, Ou, & Toumazou, 2012)

- Measurement of Urea, Creatinine concentration and their ratio in the prediction of renal failure (Pookaiyaudom, Seelan, Lidgey, Hayatleh, & Toumazou, 2011)
ISFET Read-out Circuits

- Bridge-type floating drain source follower (BFDSF) design
- Output proportional to $V_{th}$ of MISFET, which is proportional to pH of solution
- Higher system complexity
- Required more power consumption

(Wen-Yaw et al., 2010)
ISFET Read-out Circuits

- Differential current mode design (Nobpakoon, Pijitrojana, & Poyai, 2013)
- pH of solution proportional to the difference in current flowing through M1 & M2
- Temperature compensated
- Critical matching of transistors
- Hard to generate $V_{\text{float}} = V_{\text{ds}}$ of M2
Motivations

- Most ISFET read-out circuits utilizes analog intensive circuits ➔ Proposed digital intensive design

- Reduce analog circuitry to minimize common issues faced such as mismatches

- Do not require ADC to convert analog output into digital bits
ISFET-Based pH Sensing System

- pH range of 4-12
- Converts pH directly to binary output (10-bits)
- Minimal analogue front end circuitry
pH-to-time Conversion

- Based on storing and discharging charges of a capacitor
- pH of solution proportional to time taken to discharge the capacitor

\[ Q = C \Delta V = I \Delta t \]
pH-to-time Conversion

- Characteristics of time taken for capacitor to discharge across pH inputs
- High non-linearity across the full pH range
- High resolution with good linearity can still be achieved by using only a portion of the graph
Proposed Design Circuit Operation

- Divide full pH range into sub-ranges
- Each fine sensing ISFET is responsible for a pH sub-range
Proposed Design Circuit Operation

Coarse sensing

Fine sensing

Precharge to \( V_{DD} \)

\( V_{cap} \)

Coarse sensing

Fine sensing

ISFET

\( S_2 \) \( S_3 \) \( S_4 \) \( S_5 \) \( S_6 \)

Node A

\( V_{DD} \)

\( C_0 \)

\( D_9-D_8 \)

\( D_7-D_0 \)
Proposed Design Circuit Operation

Coarse ISFET discharges the capacitor

Coarse ISFET discharges the capacitor

Process the time taken & determine the sub pH range

Coarse sensing

Fine sensing

Coarse ISFET discharges the capacitor

Coarse sensing

Fine sensing
Coarse Sensing Structure

- Flash-type structure
- Senses pH boundary of pH 6, 8 and 10

![Diagram of Coarse Sensing Structure]

- V_{cap} (V)
- Time (ns)
- pH 10: 1.09V
- pH 8: 884mV
- pH 6: 545mV

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Proposed Design Circuit Operation

Coarse sensing  Fine sensing

Precharge to V_DD

Coarse sensing

Fine sensing

V_{DD}  S_1  V_{cap}  C_0  ISFET

D_9-D_8  D_7-D_0
Proposed Design Circuit Operation

Fine ISFET discharges the capacitor

Coarse sensing

Fine sensing

Process the time taken to resolve the pH value
- Basic binary counter
- Counts the time taken for the capacitor to discharge from $V_{DD}$ to $V_{ref}$
Latch-based comparator

- Output precharged to $V_{DD}$
- Cross coupled inverter pair latches output depending on the input differential pair

JK Flip Flop-based binary counter

- Standard asynchronous binary counter
- When counting is enabled, it counts the number of rising clock edges
Design Considerations

- The capacitor is a main component in the design

- Affects the sizing of the ISFETs, and hence the pH resolution

- Determines the area consumed by the circuit

- Trade off between area, resolution, speed and power
### Design Considerations

- ISFET were sized such that the highest pH of each sub range will allow the capacitor to discharge for the full sensing operation
- Biased in the subthreshold region

<table>
<thead>
<tr>
<th>pH range</th>
<th>Type of ISFET</th>
<th>Region of operation</th>
<th>W/L ratio</th>
<th>Resolution (pH/LSB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse (4-12)</td>
<td>Low VT</td>
<td>Subthreshold - Saturation</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Fine (4-6)</td>
<td>High VT</td>
<td>Subthreshold</td>
<td>7.7</td>
<td>0.0348</td>
</tr>
<tr>
<td>Fine (6-8)</td>
<td>Standard VT</td>
<td>Subthreshold</td>
<td>2</td>
<td>0.0335</td>
</tr>
<tr>
<td>Fine (8-10)</td>
<td>Standard VT</td>
<td>Subthreshold</td>
<td>23.4</td>
<td>0.0437</td>
</tr>
<tr>
<td>Fine (10-12)</td>
<td>Low VT</td>
<td>Subthreshold</td>
<td>4.3</td>
<td>0.0382</td>
</tr>
</tbody>
</table>
Simulation Environment

- Standard 65nm/1.2V CMOS technology
- Assumed sensitivity of 50mV/pH (Tomaszewski et al., 2007)
- Sensing cycle of 1.29µs or Sampling rate of 775kS/s
- Clock frequency = 200MHz
- $V_{bias} = 500mV$
- $V_{ref} = 400mV$
- Capacitor = 615fF
**Linearity of Proposed Design**

- 40 pH levels with resolution of 0.05pH
- Lines distributed evenly, showing good linearity
- Counter with clock period of 5ns able to distinguish the different pH levels
Simulation Example

- **D7 – D0 =** 1100 1101
- **D9 – D8 =** 00
- **S3 closed, S4/5/6 open**
- **Vcap**
  - Time (µs): 0.0 0.25 0.5 0.75 1.0 1.25
  - **1072.53ns**
  - **400mV**
  - **18.75ns each**
- **Precharge (S1)**
  - **11.25ns**
- **Coarse Sensing (S2)**
  - **D9 – D8 = 00**
- **Fine Sensing (S3/4/5/6)**
  - **S3 closed, S4/5/6 open**
  - **1241.25ns**
- **Result = 00 1100 1101**
- **Energy = 24.78pJ**
- **pH = 5.83**
- **Sensing period = 1290ns**

Time (µs):
- 0.0
- 0.25
- 0.5
- 0.75
- 1.0
- 1.25
As clock frequency increases, digital energy consumption per conversion remains approximately constant.

However, smaller energy consumption from capacitor.

Trend saturates, 200MHz clock was chosen.


\[
E_{Total} = E_{Cap} + E_{Digital}
\]

\[
E_{Cap} = \frac{1}{2} CV_{DD}^2
\]

\[
E_{Digital} = C_{eff}V_{dd}^2f_{clk}T_{total}
\]
Conclusion

- Digital Based ISFET pH sensor which converts pH into a 10-bits output

- High resolution (0.0437pH/LSB)

- Low energy consumption (28.43pJ/Conv)

- Sampling rate of 775kS/s with a digital clock frequency of 200MHz

- Highly flexible & reconfigurable
The End
References


Q & A
ISFET Applications

Conventional pH sensor

http://www.titralo.hu/WEBSET_DOWNLOADS/613/GLP%2022_Bench-pH-Ion_e.pdf

ISFET-based pH sensor

## Comparisons with other ISFET designs

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Output mode</td>
<td>Analog</td>
<td>Analog</td>
<td>Analog</td>
<td>Digital</td>
</tr>
<tr>
<td>Process</td>
<td>CMOS 0.35µm</td>
<td>CMOS 0.35µm</td>
<td>CMOS 0.35µm</td>
<td>CMOS 65nm</td>
</tr>
<tr>
<td>Number of bits</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>10</td>
</tr>
<tr>
<td>pH resolution</td>
<td>-50.68mV/pH</td>
<td>25.6µA/pH</td>
<td>3.79V/pH</td>
<td>0.0437pH/LSB*</td>
</tr>
<tr>
<td>Clock frequency (MHz)</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>200</td>
</tr>
<tr>
<td>Sampling rate (kS/s)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>775</td>
</tr>
<tr>
<td>Power (µW)</td>
<td>-**</td>
<td>937.6</td>
<td>-**</td>
<td>22.03</td>
</tr>
<tr>
<td>Energy/Conv (pJ)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>28.43</td>
</tr>
</tbody>
</table>

*Assumed pH sensitivity of 50mV/pH
**Power consumption not reported
ISFET Read-out Circuits

- Inverter-based ISFET design (Al-Ahdal & Toumazou, 2012)
- pH of solution proportional to trip point of the inverter
- Additional $V_{in2}$ & $C_2$ allows a high gain to be achieved
- pH measurement is not straightforward, as $V_{in2}$ has to be swept to find the trip point
Maximum Energy Consumption Breakdown

<table>
<thead>
<tr>
<th>Component</th>
<th>Energy per conversion (pJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charging of capacitor</td>
<td>0.88</td>
</tr>
<tr>
<td>Coarse sensing digital block</td>
<td>0.20</td>
</tr>
<tr>
<td>Fine sensing digital block</td>
<td>27.17</td>
</tr>
<tr>
<td>Digital Control block</td>
<td>0.18</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>28.43</strong></td>
</tr>
</tbody>
</table>

- Occurs when input pH level is highest
- Capacitor requires the full sensing operation to discharge, causing the counter to operate for the full sensing operation
Future Work

- Improve linearity
- Improve coarse sensing architecture
- Study other non-ideal effects (e.g. PVT variation, mismatch effects)
- Use of TDCs to improve resolution or reduce area
Transmission Gate Switch

\[ I_D = \frac{1}{2} C_{ox} \mu \frac{W}{L} (V_{GS} - V_{TH})^2 \]

\[ I_D = C_{ox} \mu \frac{W}{L} [(V_{GS} - V_{TH})V_{DS} - \frac{1}{2} V_{DS}^2] \]
Transmission Gate Switch

\[ R_{SAT} = \frac{2V_{DS}}{C_{ox} \mu \frac{W}{L} (V_{GS} - V_{TH})^2} \]

\[ R_{TRI} = \frac{2}{C_{ox} \mu \frac{W}{L} [2(V_{GS} - V_{TH}) - V_{DS}]} \]

\[ R_{Cut-off} = \infty \]
Transmission Gate Switch

Res (Ω)

nmos

pmos

Overall

time (ns)