A Low-Power Spiking Chemical Pixel Sensor

P. Georgiou, T. G. Constandinou and C. Toumazou

Abstract: This letter introduces an ISFET-based integrate and fire neuron forming the front-end of a chemical pixel sensor. With the sense data being encoded in the spike domain, i.e. asynchronous/continuous time and discrete value, it is directly compatible with asynchronous communication hardware, e.g. Address Event Representation. The circuit is shown to be tunable to yield a linear relation with both pH and actual hydrogen ion concentration with a peak power consumption of 35µW. Furthermore, its compact pixel footprint of under 6500µm^2, makes it ideal for use in arrayed architectures with application in biochemical imaging.

Introduction**:** ISFET (Ion Sensitive Field Effect Transistor) based chemical sensors pioneered by Bergveld [1], have gained considerable interest due to their ability to sense hydrogen ions, fast temporal response, compact size and prospect of monolithic integration [2]. By patterning a matrix of sensors on a single substrate, robustness and accuracy can be vastly improved through redundancy. Furthermore, by embedding local processing throughout the sensor array, added functionality can be realised in chemical sense applications, such as spatiotemporal chemical filtering, multi-chemical sensing and action potential detection from neural ensembles.

Presented here is a monolithic chemical sensing chip with integrated signal conditioning and pre-processing circuitry. Fabricated in standard CMOS technology, the sensor includes a modified ISFET device, bias, drive and signal conversion circuitry. The processing circuitry adopted within the chemical sensor pixel is a low power integrate and fire (I&F) neuron circuit, initially proposed by Indiveri [3], encoding the sensor information in the spike domain. In the case of a chemical image

sensor, multiple sensor fusion and off-chip transmission is facilitated using a standard AER (Address Event Representation) [4] protocol.

***Circuit Description*:** Fig. 1 shows the schematic of the chemical pixel sensor (excluding the in-pixel AER handshake switches). The circuit comprises of a custom ISFET device, the H-Cell module [5] and a leaky I&F neuron. The ISFET device sinks an output current which is dependant on the pH of the solution. This is due to the binding of hydrogen ions to the silicon nitride surface (CMOS passivation layer) above the gate forming a capacitive coupling with the Ag/AgCl reference electrode [1]. The ISFET is biased in the weak inversion region of operation to minimise power consumption and exploit the exponential device characteristic. The output current relation to hydrogen ion concentration is given by Eqn. 1 and to pH by Eqn. 2, where K_{chem} is a pH independent constant, n the sub-threshold slope factor, U_t is the thermal voltage and a is a dimensionless sensitivity parameter relating the ISFET's sensitivity to the Nernstian relationship [5]. The function of the H-cell is to linearise the drain current to hydrogen ion concentration relationship, as analysed in [5].

$$I_D = I_o \exp\left(\frac{V_{G'S}}{nU_T}\right) K_{chem}[H^+]^{\frac{a}{n}} \quad \text{where: } K_{chem} = \exp\left(\frac{-\gamma}{nU_T}\right) \tag{1}$$

$$I_D = I_o \exp\left(\frac{V_{G'S}}{nU_T}\right) K_{chem} \exp\left(\frac{2.3apH}{n}\right) \tag{2}$$

This sensor current is fed directly into the leaky I&R circuit, where the current magnitude representation is translated into the frequency domain (spike rate), i.e. pulse position modulation (PPM). Encoding the sensor data in the spike domain has the advantages of improved versatility in dynamic range (i.e. tradability between dynamic range and response time), robustness in signal integrity, in addition to inherent compatibility to address-event encoding. AER is an established, asynchronous method of relaying single-bit data from multiple pixels by transmitted

address-events (i.e. the pixel co-ordinates of the active pixel). This reduces both bandwidth and therefore power as it is an event-driven (data-dependant) architecture, in addition to being easily scalable for sparse data sets [4].

The spike-rate dependence on the sense current is expressed in Eqn.3, where: I_{sensor} is the linearised sense-current output from the H-Cell and is assumed to be considerably larger than the leakage current I_{leak}. The maximum frequency, $f_{rfr}=1/t_{rfr}$,,is determined by the time taken for the charge on node V_{02} to discharge through device M12, allowing for the capacitor to start charging up again and spike, this time being tunable by adjusting V_{rfr}. C is the integrating capacitor and V is the voltage at which the neuron spikes, i.e. the threshold level. What can be observed from this equation is that when $I_{sensor} << C.V.f_{rfr}$ then f_{spike} increases linearly (with sense current), but as the sense current continues to increases then f_{spike} converges to the maximum spiking rate (i.e. f_{rfr}). Thus, operating the circuit in the linear region of operation (where the hydrogen ion concentration is proportional to the sense current), gives a linear relation with spike rate when the current range is smaller than $C{\cdot}V{\cdot}f_{rfr}$. When operating at current ranges which make the frequency plateau at f_{rfr} the current to spike-frequency relation is compressive. Considering that the sense current to pH relation given by Eqn. 2, is exponential, operating with similar input currents in this region also yield a linear relationship with pH.

$$f_{spike} = \frac{I_{sensor} \cdot f_{rfr}}{I_{sensor} + C \cdot V \cdot f_{rfr}} \tag{3}$$

The feedback current I_{fb} serves to limit the short-circuit currents in the inverters during switching and therefore reducing the power consumption. Furthermore, the voltage bias V_{sf} defines the neurons threshold voltage [3].

***Simulated Results*:** This circuit was simulated using the Spectre simulator (v5.1.41usr2) under the Cadence IC design environment with foundry supplied

models for a standard 0.35µm CMOS process. The ISFET was implemented using a spice behavioral macro model derived from fabricated devices. The spike frequency dependence on hydrogen ion concentration is shown in Figure 2, with frequency increasing linearly with the ISFET sense current. Figure 3 shows the spike frequency dependence on the pH of the test solution, during operation in the “compressive region”, yielding a linear relationship. The peak power consumption at the maximum spike frequency of operation was 35µW at 3.3 V supply voltage.

***Conclusion*:** Presented is the front-end implementation of a spiking chemical sensing neuron based on a leaky integrate and fire neuron with an ISFET chemical sensor for application in real time chemical imaging. An array of chemical pixel sensors has been designed and sent for fabrication with a pixel footprint of 65µm×100µm. Although by (optical) imaging standards this would represent a large pixel footprint, in this case this is due mainly to the large sensor surface required for the chemical sensing. This is confirmed by a good pixel fill-factor (active sensor area to total pixel area ratio) of 97%, due to the sensing area of the ISFET overlaying the processing circuitry. The spike rate has been shown to be tunable to be linear both with both hydrogen ion concentration and pH. Although this paper presents the application of pH sensing, the ISFET can be modified to sense a wide range of chemicals and bio-related substances (including sodium, potassium, creatinine, urea, glucose, lactate), thus largely expanding its potential field of application.

References:

[1] P. Bergveld, "Thirty years of ISFETOLOGY - What happened in the past 30 years and what may happen in the next 30 years," Sensors and Actuators B-Chemical, vol. 88, no. 1, pp. 1-20, 2003.

[2] P. A. Hammond, D. Ali, and D. R. S. Cumming, "Design of a single-chip pH sensor using a conventional 0.6-mu m CMOS process," Ieee Sensors Journal, vol. 4, no. 6, pp. 706-712, 2004.

[3] G. Indiveri, "A low-power adaptive integrate-and-fire neuron circuit," Circuits and Systems, 2003. ISCAS '03. Proceedings of the 2003 International Symposium on, 4 ed 2003, p. IV-820.

[4] P. Häfliger, A Spike-based Learning Rule and its Implementation in Analog Hardware". PhD thesis, ETH Z¨urich, Switzerland, 2000.

[5] L. Shepherd and C. Toumazou, "Weak Inversion ISFETs for ultra-low power biochemical sensing and real-time analysis," Sensors and Actuators B-Chemical, vol. 107, no. 1, pp. 468-473, 2005.

Authors' affiliations:

P. Georgiou, T.G. Constandinou and C. Toumazou (Institute of Biomedical Engineering, Imperial College London, South Kensington, London SW7 2AZ, United Kingdom) E-mail: pg200@imperial.ac.uk

Figure captions:

Fig. 1. Circuit schematic of chemical pixel sensor. The circuit comprises of the H-cell with the ISFET sensor and a leaky integrate and fire neuron circuit.

Fig. 2. Spike frequency response (linear) with the hydrogen ion concentration of test solution

Fig. 3. Spike frequency response (linear) with the pH of the test solution

Figure 1:

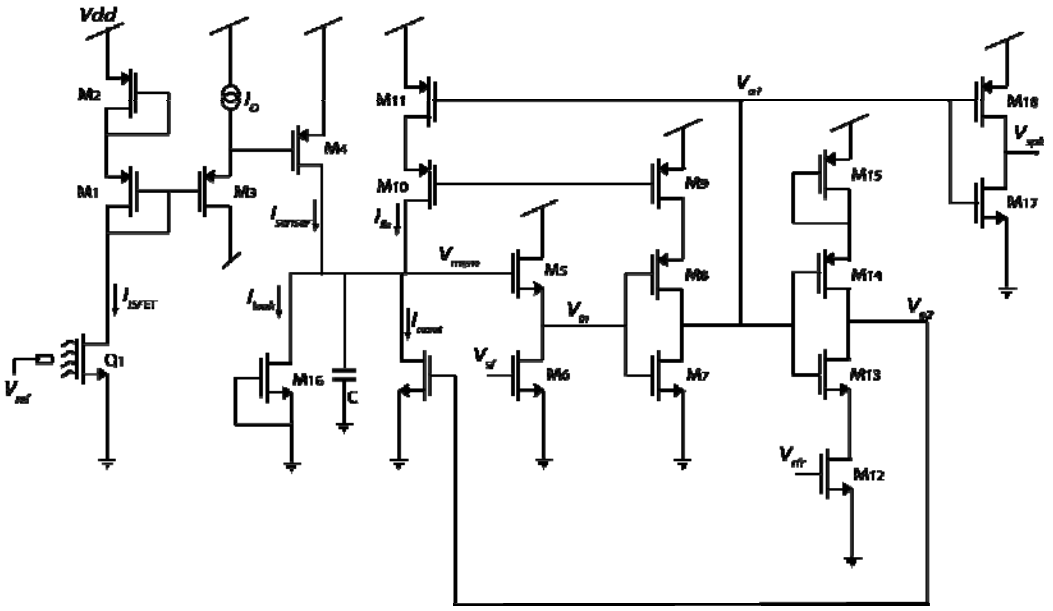
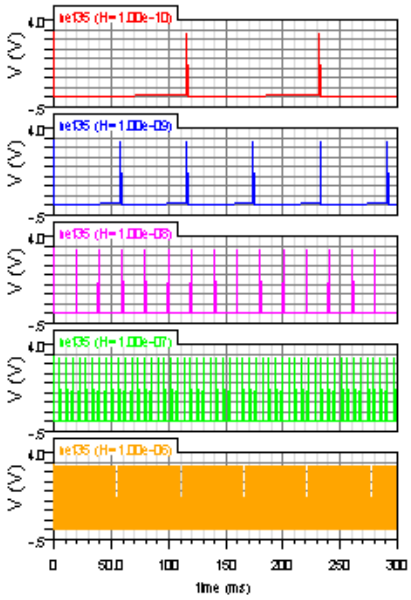

Vdd
M2
M1
M3
M4
M11
M10
M9
M15
M18
M17
M5
M8
M14
M6
M7
M13
M12
M16
C
Q1

Figure 2:



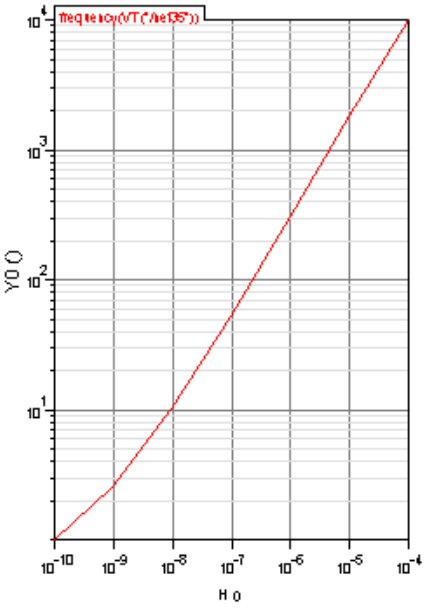


Figure 3:

