Pixel array for 3-D integration with an intra-cortical electrode array.

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Outline

1. Introduction, purpose
   ⇒ Direct extracellular neuron signal sensing
   ⇒ Our approach

2. Pixel design & performance
   ⇒ Sense amplifier design
   ⇒ Measured performance

3. Future outlook
   ⇒ In-pixel analog domain filtering
   ⇒ Prototype results
1. Introduction: purpose

Detecting neural events in the brain
by an array of microelectrodes connected to
an array of voltage amplifiers
like a large channel count oscilloscope with
10µV 20kHz resolution
Microwire Electrodes

One microwire electrode can record spiking activity from several neurons.
Recording from microwire electrodes

Connecting microwires directly to a CMOS array allows for readout, digitization, and multiplexing.
Press the bundles onto CMOS sensor

Bundle before Pressing

Exposed wire core

100 mm

Microwire bundle

Bundle after Pressing

CMOS Sensor w/ metal bond pads

Flexible diaphragm (for alignment)
### Henry/Argo sensor array

Each pixel contains a high-gain, AC-coupled, low-noise voltage amplifier.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td># of neural sensors</td>
<td>65,536 (256x256)</td>
</tr>
<tr>
<td>Full frame readout</td>
<td>up to 39,000 frames/s on 32 analog outputs</td>
</tr>
<tr>
<td>Input referred noise</td>
<td>&lt; 10 µVrms (100 Hz- 20 kHz)</td>
</tr>
<tr>
<td>Voltage gain</td>
<td>100 – 800 V/V</td>
</tr>
<tr>
<td>Input impedance</td>
<td>&gt; 1 TΩ</td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>50 mm</td>
</tr>
</tbody>
</table>
Pixel array

Top electrode to be hybridized to the microwire electrode

Y scanner

50µm

Pixel biasing

Column ampl, X-scanner

16 differential output buffers

14.3mm

15.8mm

Henry
2. Pixel design & performance

→ overall pixel topology
→ design for compactness & for low noise
→ sense amplifier
→ pixel layout
→ measured performance in the array
Class-A amplifier with resistive self-biasing

Optimized for 1/f noise: single PMOSFET

input

\[ >1 \text{M} \Omega \]

\[ 2 \ldots 4 \text{pF} \]

\[ \text{R}_{\text{tissue}} \]

\[ \text{C}_{\text{elu}} \sim 1 \text{pF} \]

\[ \text{C}_{\text{coup}} \]

\[ \text{output} \]

\[ >1 \text{T} \Omega \]

\[ 1 \text{V} \]

\[ 1 \text{MegOhm} \]
Compact high value resistor

\[ R = \frac{1}{g_m} = \frac{kT}{q \cdot I_{BIAS}} \]

**PRO**
- Compact: a diode-connected MOSFET + a MOSFET bias current source
- \( R = \frac{1}{g_m} \) AC value hardly dependent on variability of the 1st MOSFET. Dependent on the variability of the bias
- Can make extremely high \( R \)
e.g. 1TΩ for \( I_{BIAS} = 25fA \).
  Needed to make very low RC time:
  \( 1T\Omega \times 100fC = 0.1s \)

**CON**
- Needs an exclusive DC path for the \( I_{BIAS} \)
- Only AC / small signal: \( \ll 100mV \)
- Not very linear
- Offset must be solved by AC coupling
- \( 1/f \) noise
Actual Class-A amplifier self-biasing with MOSFETs

- Gain = 10
- $R_{load} = 1\, \text{Mohm}$
- LNA+LPF input referred noise reaches $10\mu V_{\text{RMS}}$
Actual Henry pixel topology

Self biased class-A amplifiers
3 X 1-st order Gm-C LPF

Electrode
LPF
to column load/buffer
Ib1
Ib2
VDD
VCC
Rload
Self biasing
Out
In
Gm
C
3 X
Self biased class-A amplifiers
Column wire
3 X
Row select
to column load/buffer

C1
M1
M2
M3
In
Out
Vcc
Vdd
C

Gm

Electrode
LPF
to column load/buffer
Henry pixel
Total pixel gain and BW
PSD + input noise histogram

Input-referred noise (V/√Hz)

Frequency [Hz]
Henry pixel noise
input referred noise of one row of pixels
3. Future outlook

→ recognize pulse shapes by matched filters
→ design of programmable filters
→ measured performance of prototypes
Data reduction == recognize these shapes

Matched filter

Approximated by a linear sum of 2nd order filters

“matched filters”
Pixel topology

Electrode in tissue

Sense amplifier 100x

Lowpass Bandpass Resonant

Principal component 1

+ \[ \Sigma \]

weights

Principal component 2

+ \[ \Sigma \]

weights

Principal component 3

+ \[ \Sigma \]

weights

Σ weights

reference comparator

time stamp

S&H

S&H

S&H

Pixel outputs
Programmable filters

Filters

• (resonant) bandpass filter
• (resonant) lowpass filter
• summator

Based on “ideal” R+C active filters
Actually $I_{BIAS}/g_m + C$ implementations

Continuous programmability of center/lowpass frequency, Q and gain, by programming $I_{BIAS}$

Patent WO 2018/191725 pending
The OTA

• All transistors are minimum sized, or larger for mismatch
• Tail current can be adjusted between <1fA and >1µA
• Gain = between 100x and 200x
Resonant bandpass filter (ideal)

Bandwidth = $\beta$
Quality factor = $\omega_0/\beta$

$$H_o = -\frac{R_3}{2R_1}$$

<table>
<thead>
<tr>
<th>Radian frequency</th>
<th>Hertz</th>
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</thead>
<tbody>
<tr>
<td>$\omega_o = \frac{1}{C\sqrt{(R_1</td>
<td></td>
</tr>
<tr>
<td>$\beta = \frac{2}{CR_3}$</td>
<td>$B = \frac{\beta}{2\pi}$</td>
</tr>
</tbody>
</table>
Actual implementation

Pro: compact layout
Pro: easy to implement, pure MOS
Pro: input offset free
Pro: programmable by current
Con: one less degree of freedom (R2 absent):

If Q must be large, the difference between the two currents becomes huge.

If Q is too small, the center gain \( H_0 \) becomes small as well.
Sweeping both branch currents (simulation)

- The two branch currents are adjusted to obtain the desired Q and resonant frequency
- C=100fF
2nd order low-pass filter

\[ \text{Vin} \rightarrow C1 \rightarrow \text{OpAmp} \rightarrow \text{Vout} \]

C2

5µm
LPF measurement vs simulation

- **Gain [dB]**
  - Simulation
  - Chip 1
  - Chip 2
  - Chip 3
  - Chip 4

- **Frequency [Hz]**
  - Monte Carlo
  - Measurement

- **Peak gain**
  - Monte Carlo
  - Measurement

- **Peak frequency [Hz]**
  - Monte Carlo
  - Measurement
Multi-input differential summator

- Pure MOSFET design
  - All transistors have minimum size (except when needed for matching)
  - Capacitors are 100fF MOS
  - Input stages are PMOSFET source followers

- By adjusting the currents one can set the SF’s output impedance, hence the gain of each branch
Summator layout
4 + inputs
4 - inputs
Summator: simulation vs. measurement

Three different branches with different gains 0dB, -4.5dB, -9dB

Measurement compared with simulation
4 Conclusions
Conclusions

• Unprecedented massive parallel 256x256, 50µm pitch neural probe ROIC
• 10µV_{RMS} @ 20kHz bandwidth

• Compact, in-pixel analog domain filters demonstrated
• Fully programmable
• Key design issue: mismatch of MOSFETs causes variability of frequency, gain and Q
Thank you!

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