# Techniques for Pixel Level Analog to Digital Conversion

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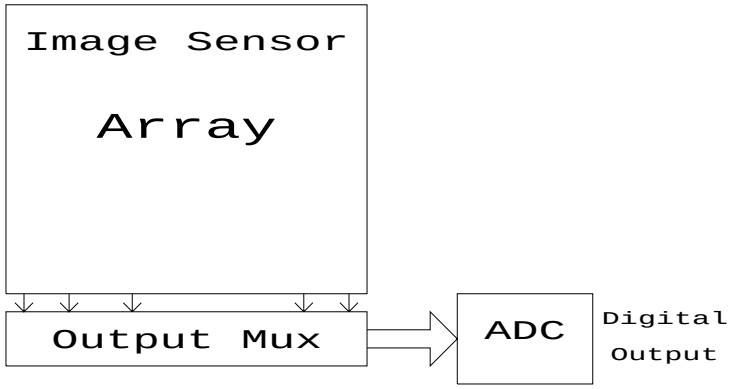
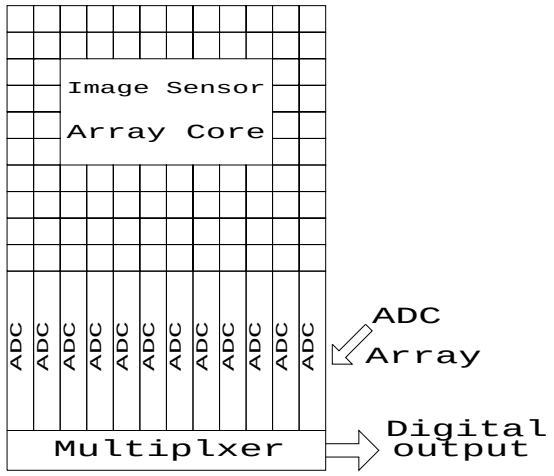
**Stanford University**

# Approaches to Integrating ADC with Image Sensor

- Chip Level




- Column Level




- Pixel Level

# Pixel Level ADC

- Advantages
  - Continuous observation of the pixel
  - Low noise
  - Low power
- Disadvantages
  - Limited area at the pixel level – this becomes less of a problem as technology scales

# Outline

⇒ • **Architecture**

  – **$\Sigma\Delta$ ADC**
  – **MCBS ADC**
  – **Readout circuitry**

• **Circuits**

  – **$\Sigma\Delta$ pixel**
  – **MCBS pixel**

• **Results**

• **Comparision**

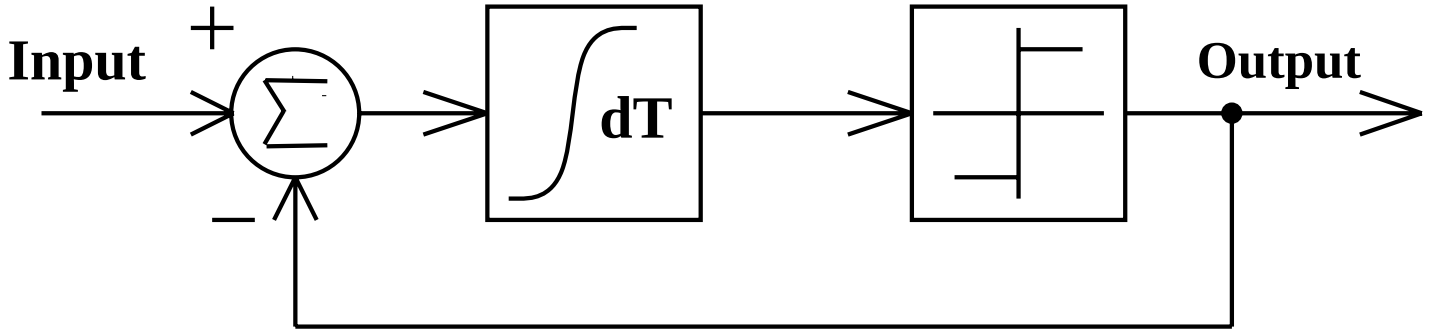
# Pixel Level ADC

- **Pixel size limits ADC architecture**
- **Cannot use conventional bit-parallel ADC techniques, because they require memory at the pixel**
- **Bit serial ADC is required but conventional techniques are too complicated**
- **To overcome this problem we developed two bit serial techniques**
  - **Oversampled**
  - **Nyquist rate**

# Oversampled ADC

- **Robust operation over process variation and noise**
- **Simple imprecise circuits can be used**
- **Use first order 1 bit $\Sigma\Delta$ modulation**
  - **Requires small silicon area**

# First Order 1 Bit $\Sigma\Delta$ Modulation




**Output decimated using LPF to obtain pixel values - performed off chip.**

# Oversampling Ratio L as a function of SNR

**Number of bit planes L per frame for a desired average SNR**

$$\log_{\mathbf{2}}(\mathbf{L}) = \frac{\mathbf{SNR + 5.2dB}}{\mathbf{9.0}}$$

**Examples:**

- $\mathbf{SNR = 48dB\ (8\ \ \ bits) \Rightarrow L = 60}$
- $\mathbf{SNR = 20dB\ (3.3\ bits) \Rightarrow L = 7}$

# $\Sigma\Delta$ ADC Limitations

- **Increased output bandwidth caused by oversampling**
- **Decimation/DSP is required to resample the data at the Nyquist frequency**
- **Poor low light response due to nonuniform quantization**

# Pixel Level Nyquist Rate ADC

**Recently developed a new multi-channel bit-serial (MCBS) ADC technique (Yang, Fowler, El Gamal CICC'98)**

- **Low output data rate**
- **Requires very few transistors at the pixel**
- **Uses very simple circuits**
- **Complex circuits shared by all pixels**
- **No external DSP is required to consturct image**

# MCBS ADC

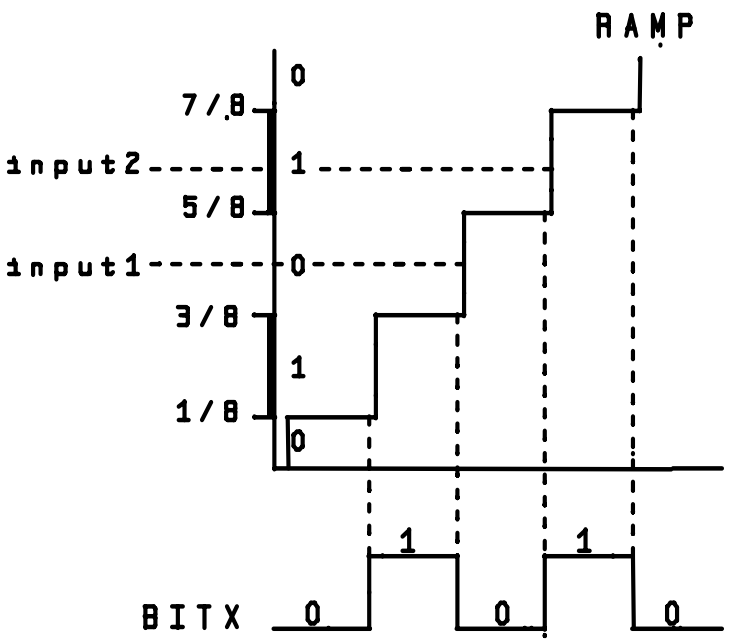
**ADC assigns binary codewords to quantization intervals 3-bit example: signal $S \in [0, 1)$)**

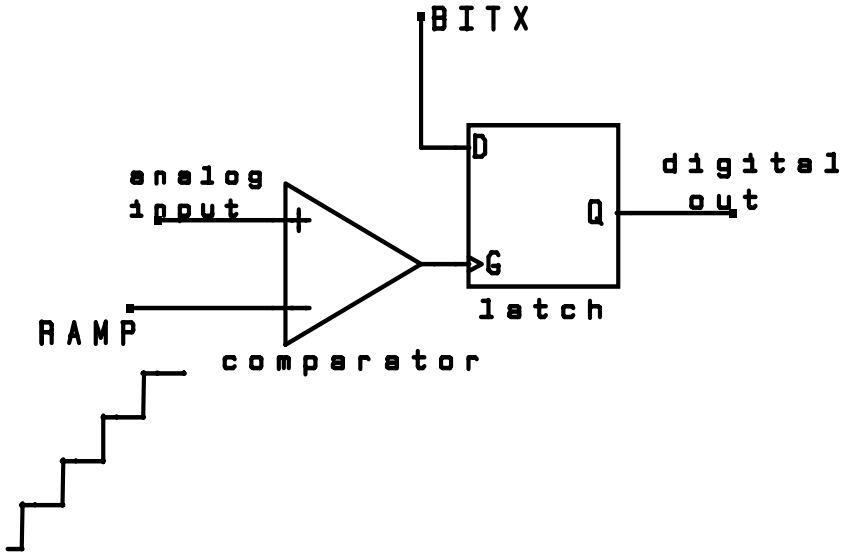
| Quantization table | |
|---|---|
| S | Gray Code |
| $0 - \frac{1}{8}$ | 0 0 0 |
| $\frac{1}{8} - \frac{2}{8}$ | 0 0 1 |
| $\frac{2}{8} - \frac{3}{8}$ | 0 1 1 |
| $\frac{3}{8} - \frac{4}{8}$ | 0 1 0 |
| $\frac{4}{8} - \frac{5}{8}$ | 1 1 0 |
| $\frac{5}{8} - \frac{6}{8}$ | 1 1 1 |
| $\frac{6}{8} - \frac{7}{8}$ | 1 0 1 |
| $\frac{7}{8} - 1$ | 1 0 0 |

**Key observation: Each output bit can be viewed as a binary-valued function over intervals (independent of other bits!)**

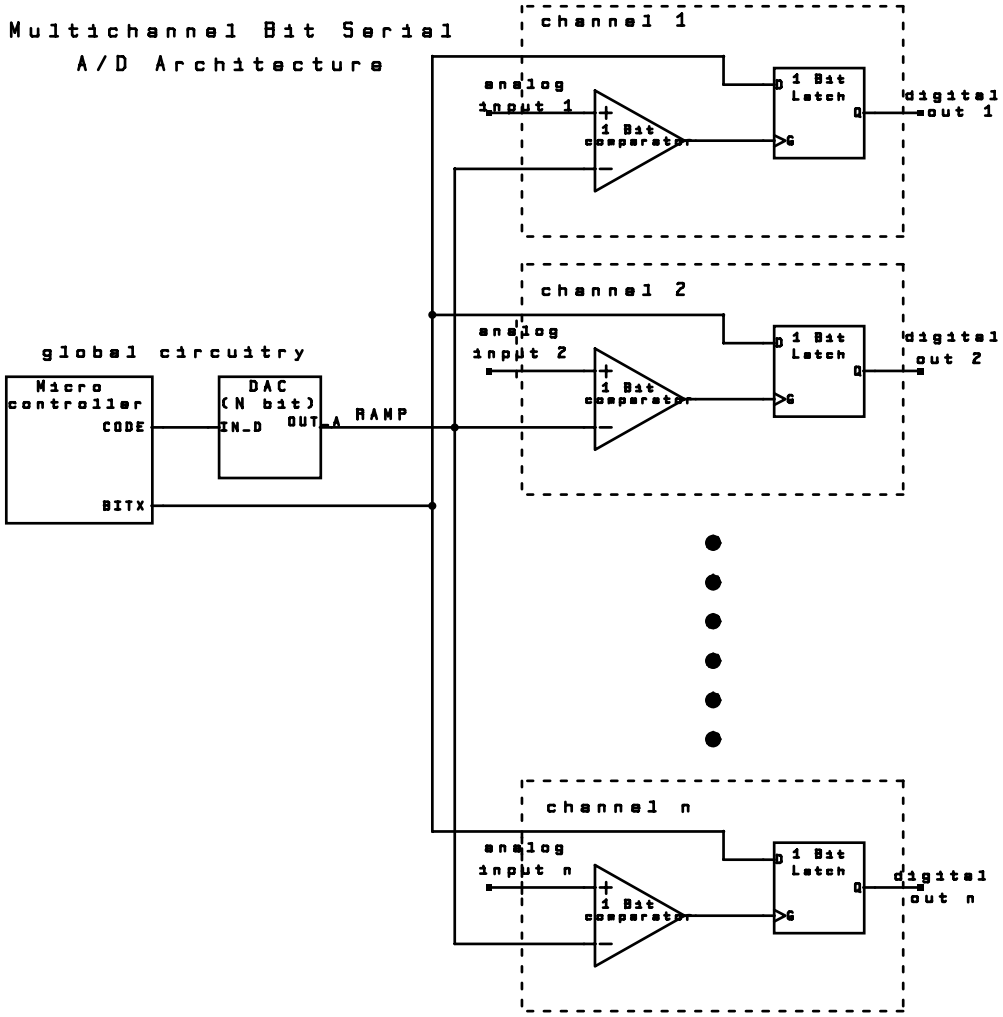
# Operation of the 1-bit Comparator/Latch

## 3 Bit LSB Example



# MCBS ADC – Block Diagram

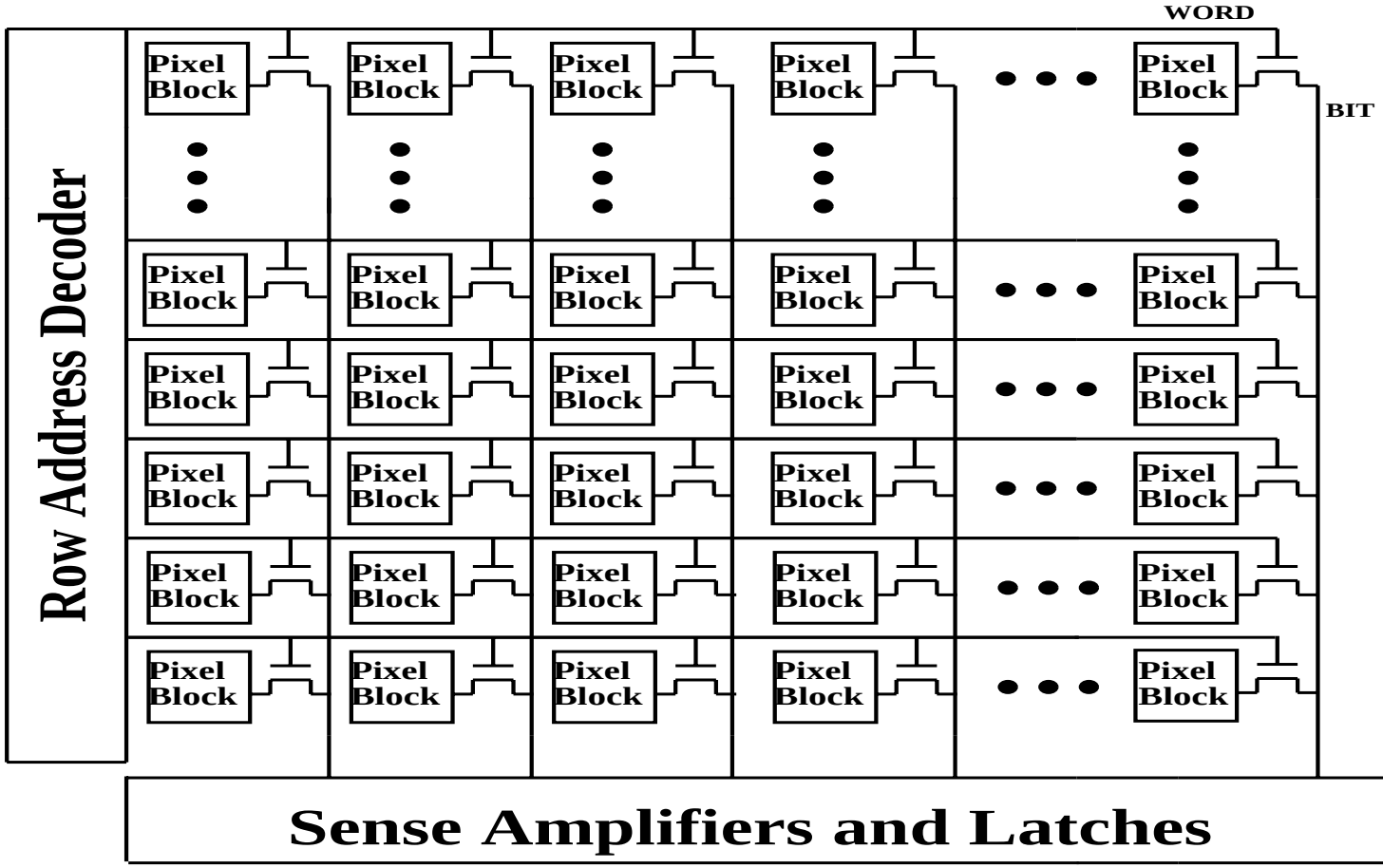


# MCBS ADC Limitation

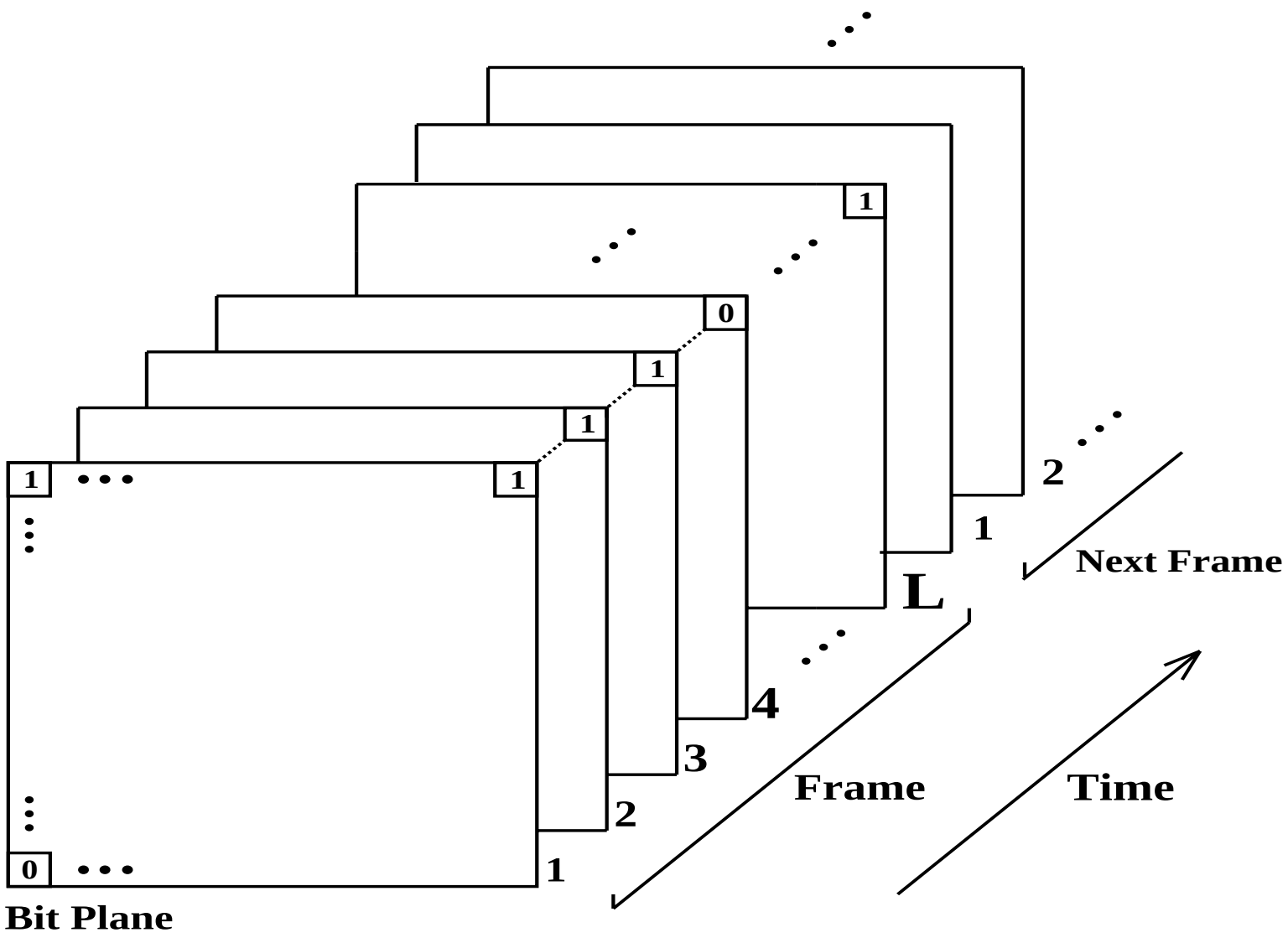
**The gain bandwidth product must exceed $2F_d \times 4^m$**

- **To perform $m$ bit quantization at least $2^m - 1$ comparison must be performed**
- **Assuming uniform quantization, the gain of the comparator must be proportional to $2^m$.**

# Block Diagram for Image Sensor with Pixel Level ADC



# Output of Image Sensor with Pixel Level ADC



# Outline

- **Architecture**

  - **$\Sigma\Delta$ ADC**
  - **MCBS ADC**
  - **Readout circuitry**

$\Rightarrow$ - **Circuits**

  - **$\Sigma\Delta$ pixel**
  - **MCBS pixel**

- **Results**

- **Comparision**

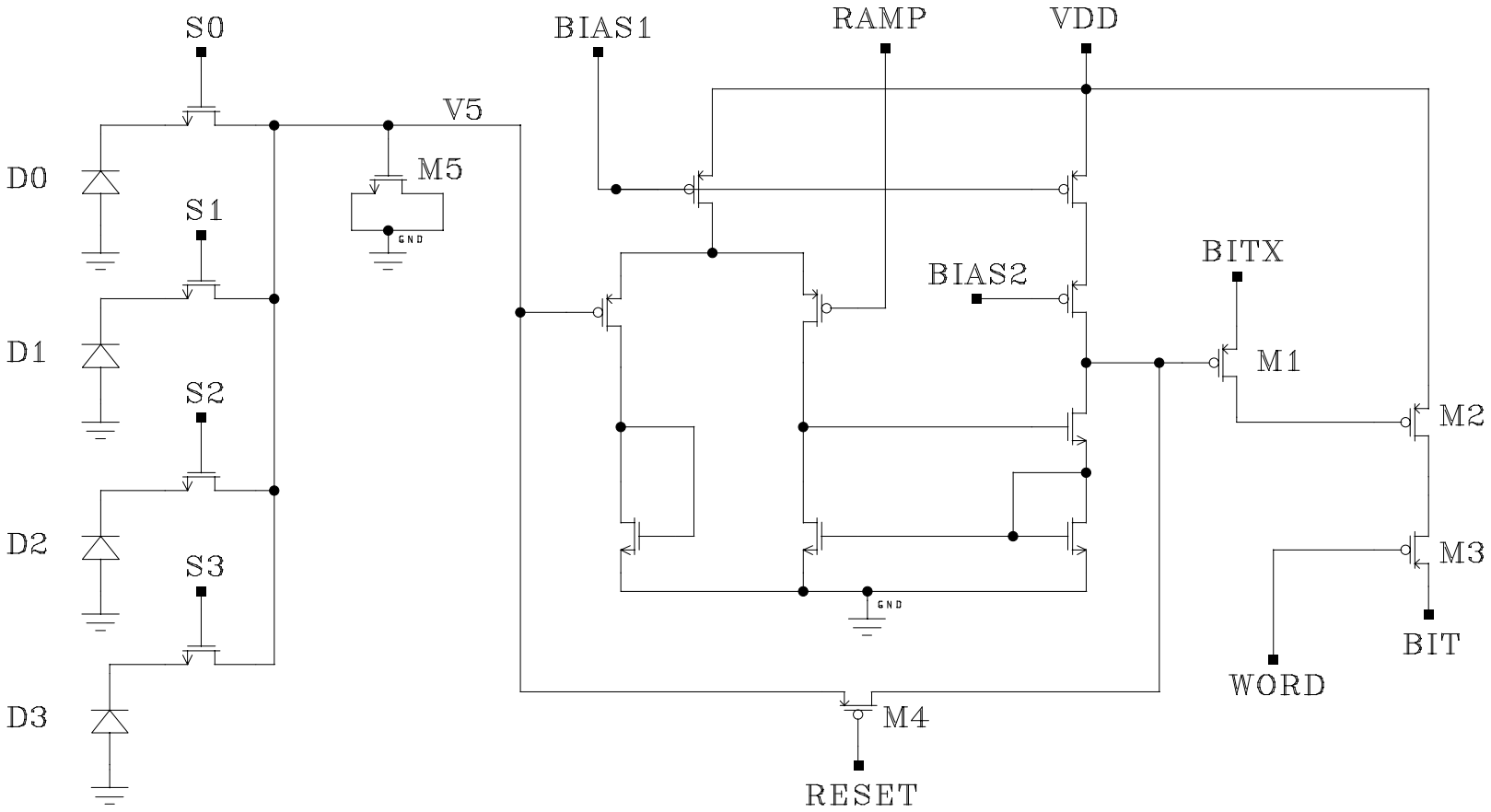
# Multiplexed $\Sigma\Delta$ Pixel Block Diagram - 17 Transistors

# Multiplexed $\Sigma\Delta$ Pixel Block Circuit Schematic - 17 Transistors

# $\Sigma\Delta$ ADC Circuit

- **Advantages**
  - **Small size**
  - **Low sensitivity to transistor noise, and no offset FPN**
  - **Large charge handling capacity**
- **Disadvantages**
  - **Moderate gain FPN**
  - **Poor low light response**
  - **High output data rate**

# MCBS ADC Pixel Block Circuit Schematic - 19 Transistors



# MCBS ADC

- **Advantages**
  - **Small size**
  - **Low gain and offset FPN**
  - **Complete testability**
- **Disadvantages**
  - **Moderate comparator gain-bandwidth**
  - **Reduced sensitivity caused by sample capacitor**

# Outline

- **Architecture**
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- **Circuits**
  - **$\Sigma\Delta$ pixel**
  - **MCBS pixel**

$\Rightarrow$ • **Results**

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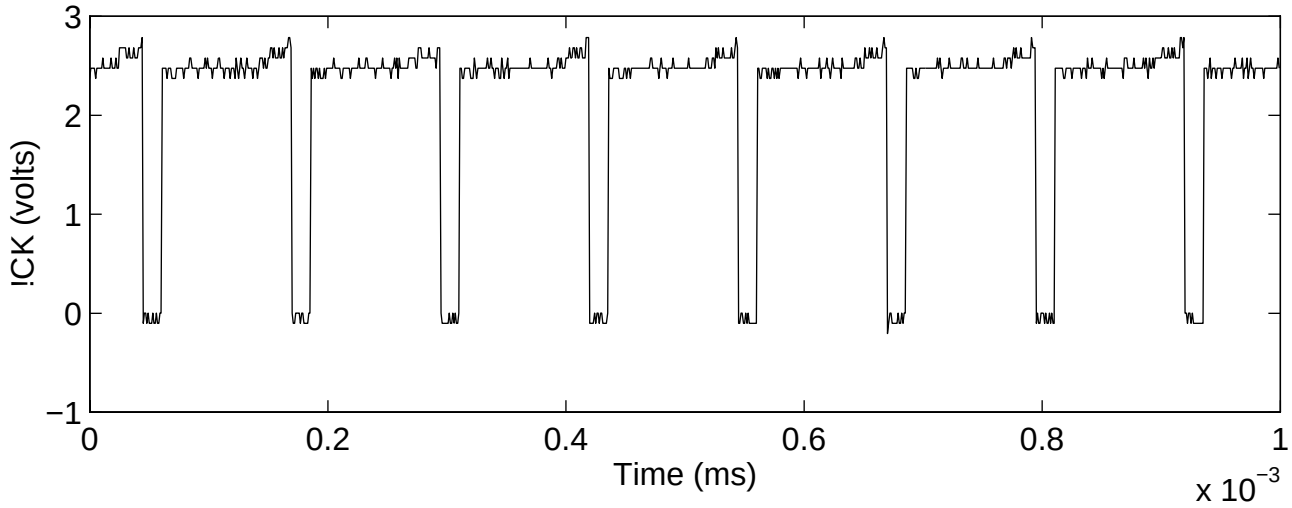
# Chip Characteristics

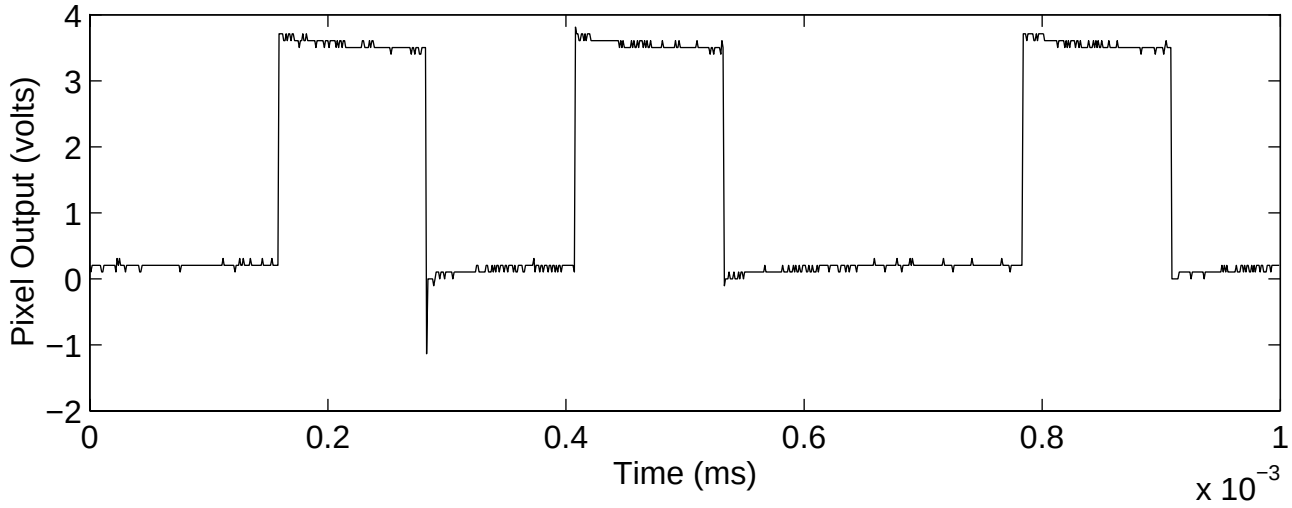
| | $\Sigma\Delta$ ADC | MCBS ADC |
|---|---|---|
| Technology | 0.8 $\mu$m 3M1P | 0.35$\mu$m 4M1P |
| Pixel Area | 20.8 $\mu$m $\times$ 19.8 $\mu$m | 8.9 $\mu$m $\times$ 8.9 $\mu$m |
| Transistors per pixel | 4.25 (17 per four pixels) | 4.5 (18 per four pixels) |
| Fill Factor | 30% | 25% |
| Array Size | 128$\times$128 | 320$\times$240 |
| Supply Voltage | 3.3 v | 3.3 v |

# $\Sigma\Delta$ ADC Output Waveforms

CLKB

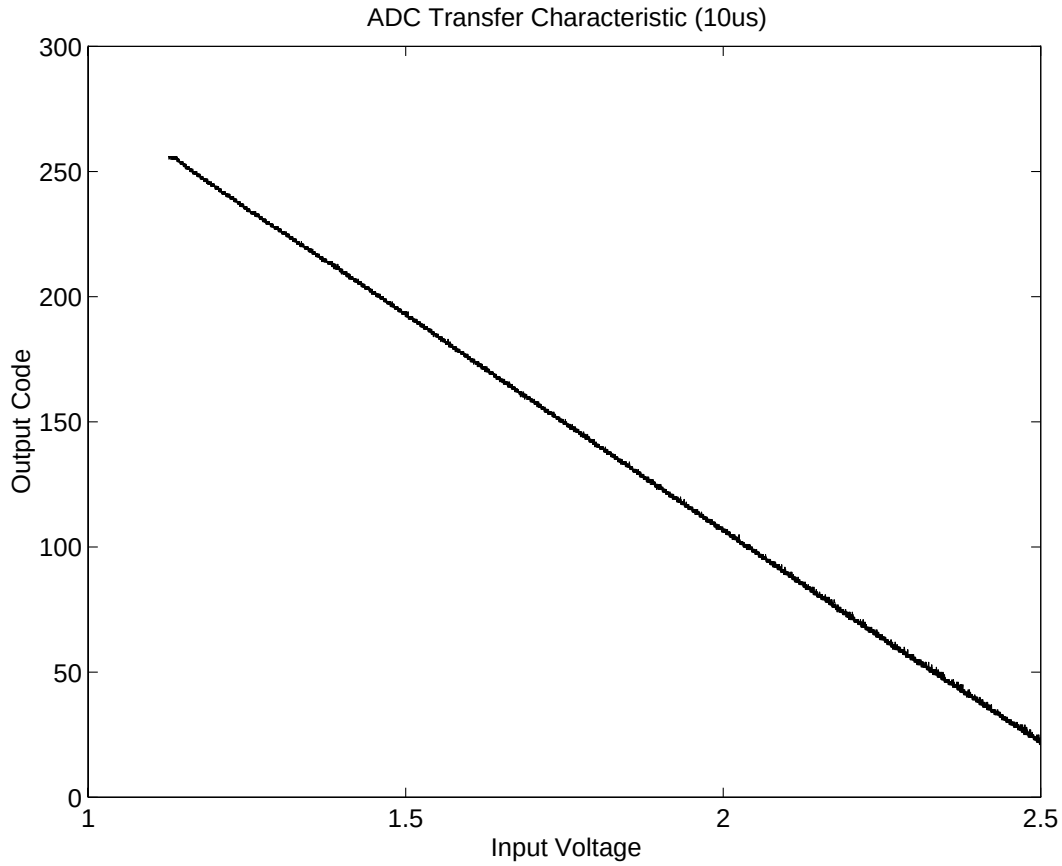



PIXEL OUTPUT




**SNR = 43dB with OSR = 64, Gain FPN = 1%**

# Measured MCBS ADC Transfer Function




**INL = 2.3 LSB, DNL = 1.2 LSB, Gain FPN = 0.24%, and Offset FPN = 0.2%**

# Outline

- **Architecture**
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$\Rightarrow$ • **Comparision**

# Pixel Level ADC Comparison

| | $\Sigma\Delta$ ADC | MCBS ADC |
|---|---|---|
| **Size** | **4.25 transistors per pixel** | **4.5 transistor per pixel** |
| **Conversion mode** | **Charge to bits** | **Voltage to bits** |
| **Charge handling Capacity** | **Large** | **Small** |
| **FPN** | **Moderate** | **Small** |
| **Transistor noise sensitivity** | **Small** | **Moderate** |
| **Date rate** | **Large** | **Small** |
| **Quantization** | **Nonuniform – fixed by $L$** | **Programmable** |
| **External processing** | **Decimation Filtering** | **None** |
| **Required memory** | **Large** | **Small** |
| **Power Dissipation** | **Moderate** | **Small** |

# Conclusions

- $\Sigma\Delta$ ADC is better suited to IR sensors
  - Large charge handling capacity
  - Fine quantization near the center of the range (i.e. small difference between large charge value can be determined)
- MCBS ADC is better suited to visible range sensors
  - Low output data rate
  - Programmable quantization
  - High sensitivity