Charge-Sensitive Preamplifier
Continuous Reset

Requirements:
- discharge $C_F$
- source $I_{\text{leak}}$ (variable)
- minimum noise
- linear
- insensitive to process, temperature, and supply variation
- low capacitance

Simplest: FET
Drawback:
Nonlinear
Needs biasing
Nonlinear Pole-Zero Compensation

Classical

\[ RF \cdot CF = RC \cdot CC \]

Zero created by RC, CC cancels pole formed by RF, CF

IC version

\[ CC = N \cdot CF \]
\[ (W/L)_{MC} = N \cdot (W/L)_{MF} \]

Zero created by MC, CC cancels pole formed by MF, CF

Rely on good matching characteristics of CMOS FETs and capacitors
In more detail…

\[ V_{gs1} = V_{gs2} \]
\[ V_{in1} = V_{in2} \]
\[ V_{T1} = V_{T2} \]
\[ I_{d1} = I_{DET} \]
\[ I_{d2} = N \cdot I_{DET} \]
\[ Q_{inj} = N \cdot Q_{DET} \]

Composite amplifier is a charge (current) amplifier with gain of N.
DC Analysis

M1, M2 in saturation, strong inversion

\[ V_{\text{OUT}} \approx V_{\text{GG}} - V_{T1} + \sqrt{\frac{2 L_1}{k' W_1}} (I_{\text{DET}} + I_B) \]

- Leakage current up to 100 nA can be sourced with modest increase in output voltage
Dynamic Analysis

First stage alone

$$v_{out}(t) = \frac{2(V_{GSI} - V_{T1})}{K \frac{C_F}{V_{GS1} - V_{T1}} \frac{L_1}{k'} \frac{W_1}{C_F \frac{L_1}{k'} \frac{W_1}{V_{GSI} - V_{T1}}} + 1}$$

- Decay time constant $\sim C_F/gm_1$
- Effective feedback resistance of M1: $R_{F,eff} = 1/gm_1$
- Strong variation with $Q_{DET}$

With compensation

- Linearity is recovered
- Time constant no longer depends on injected charge

$V'_{DET} = 25.8\mu A/V$, $V_{T1} = -1.37V$, $L = 60\mu m$, $W = 1.8\mu m$, $V_{GO} = -1V$

$I_{DET} = 1nA$, $C_F = 100fF$

$Q_{DET} = 1fC$, $10fC$

$Q = 1fC$, $10fC$
Noise Analysis

Parallel noise:
M1, M2 bias condition at minimum $I_{DET}$:
$V_{DS} > V_{GS} – V_T$ Saturation
$(V_{GS} – V_T) >> kT/q$ Strong Inversion

M1 contributes thermal noise < shot noise of detector leakage

\[ ENC^2 = 2kTA_3t_m \left[ \gamma g_{m1} \cdot \left(1 + \frac{g_{m1}}{g_{mA}}\right) + \left(\gamma g_{m2} + \frac{1}{R_{F2}}\right) / N^2 \right] + \text{series} + 1/f \]

Non-stationary noise:
Due to increase in M1's drain current during the reset.
Signal-dependent $ENC_{NS} \sim \sqrt{Q_{DET}}$
Responsible for minor (< 2%) degradation of S/N.
Layout

Two-stage compensation circuit
$N_1 = 24$ (PMOS), $N_2 = 6$ (NMOS)
$N_{tot} = 144$

0.14 x 0.78 mm
Parallel Noise

![Graph showing parallel noise with frequency and parallel noise as axes.](image-url)
Nonstationary Noise

\[ \delta\text{ENC} = 750\text{pA} \]

- Theoretical assuming full shot noise
- Theoretical assuming full thermal noise
- Approx. Eq.(1)
- Measured

\( I_{\text{det}} = 750\text{pA} \)
Nonstationary Noise

\[
\delta \text{ENC rms } [\text{e}^-] = \frac{q}{\sqrt{2}} \left( \frac{\tau_p}{C_{\text{in}}} \right)^{1/2} \sqrt{\frac{Q_{\text{DET}}}{\tau_p}}
\]

- **Gain** = 30mV/fC
- **\(\tau_p\)** = 1µs
- **\(C_{\text{in}}\)** = 1.5pF
- **\(\text{ENC}_0\)** = 350e⁻
Nonlinearity

- $\tau_p \approx 1\,\mu s$
- Gain $\approx 200\,\text{mV/fC}$
- $C_{IN} \approx 1.5\,\text{pF}$
- $I_{DET} \approx 1\,\text{nA}$

Channel Integral Linearity Error [%]

Injected Charge [C]
Leakage Current Handling

Dual Stage N = 24x6

$C_{\text{IN}} \approx 3\, \text{pF}$

$Q_{\text{IN}} \approx 11\, \text{fC}$

Gain $\approx 200\, \text{mV/fC}$

$I_{\text{det}} \approx 250\, \text{pA} \div 70\, \text{nA}$
Summary

- New reset system for DC-coupled detectors
- Self-adaptive to wide range of leakage current
- No tweaking or switching
- Excellent noise and linearity
- Versatile

<table>
<thead>
<tr>
<th>Shaping</th>
<th>5th order compl. unip.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>≈ 200mV/fC</td>
</tr>
<tr>
<td>Peaking time</td>
<td>≈ 400ns</td>
</tr>
<tr>
<td>ENC</td>
<td>≈ 30+37/pF+0.4√(Q/q)</td>
</tr>
<tr>
<td>Integral linearity error</td>
<td>&lt; 0.2% @ 13fC</td>
</tr>
</tbody>
</table>