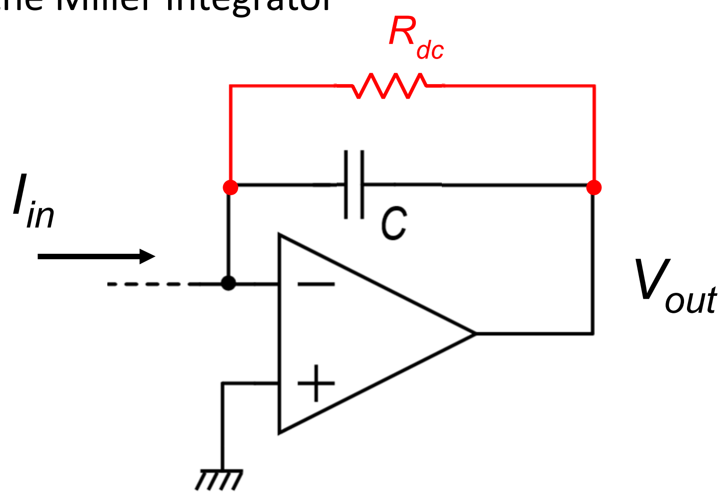
An interface for capacitive sensors based on the SC charge amplifier

Charge amplifier

Invented by Walter Kistler in 1950
It is based on the Miller Integrator



$$V_{out}(t_2) = -\int_{t_1}^{t_2} I_{in}\,dt + V_{out}(t_0)$$

Charge fed to the amplifier from t_1 to t_2

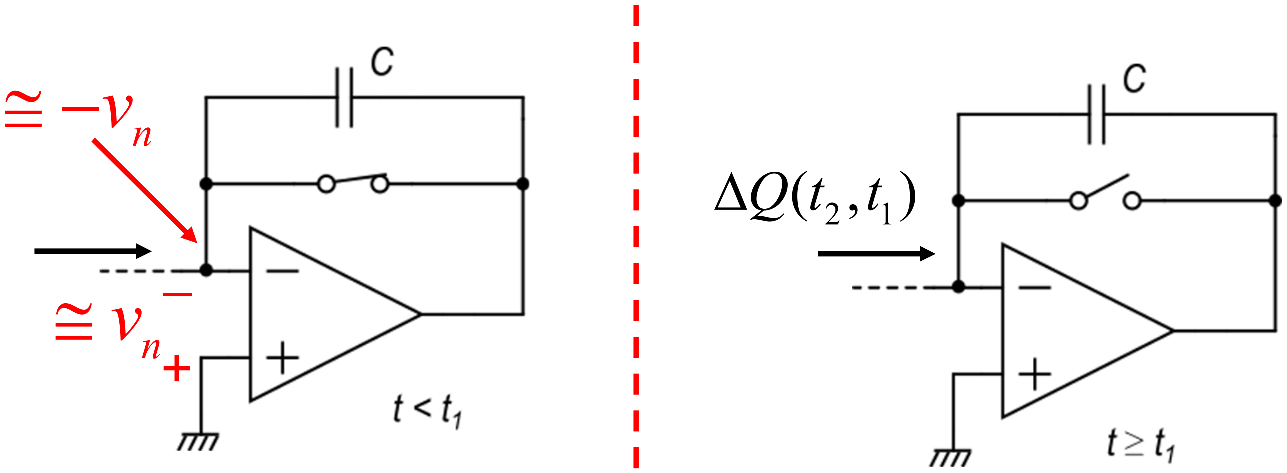
$$= \Delta Q(t_2, t_1)$$

This value is an uncertainty and may also cause saturation of the amplifier

The classical solution consists in placing a resistor of very high resistance (R_{dc}) in parallel with the capacitor

Unfortunately, this resistor also discharge the charge accumulated across C, imposing condition: $t_2 - t_1 \ll R_{dc}C$

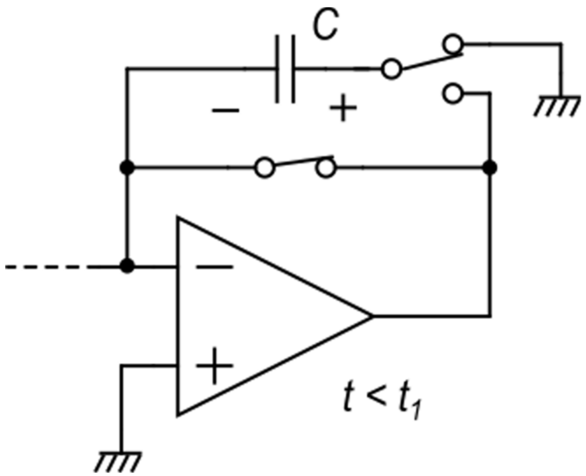
A Switched Capacitor (SC) charge amplifier



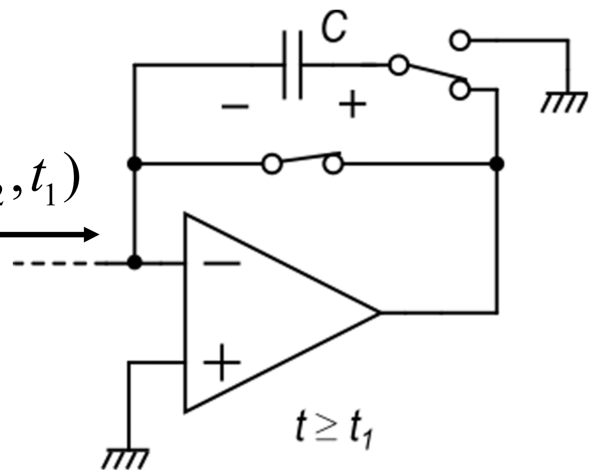
Note: ***$v_n(t)$*** includes the offset voltage, which can be quite large in CMOS circuits

$V_{out} = 0$	$V_{out}(t_2) = -\Delta Q(t_2, t_1)$	Ideal case
$V_{out} \cong -v_n(t)$	$V_{out}(t_2) = -\Delta Q(t_2, t_1) - v_n(t)$	Real case

SC charge amplifier with offset cancellation



$\Delta Q(t_2, t_1)$



Two noise samples are subtracted: This is the correlated **double** sampling (CDS)

$$V_{out} \cong -v_n(t)$$

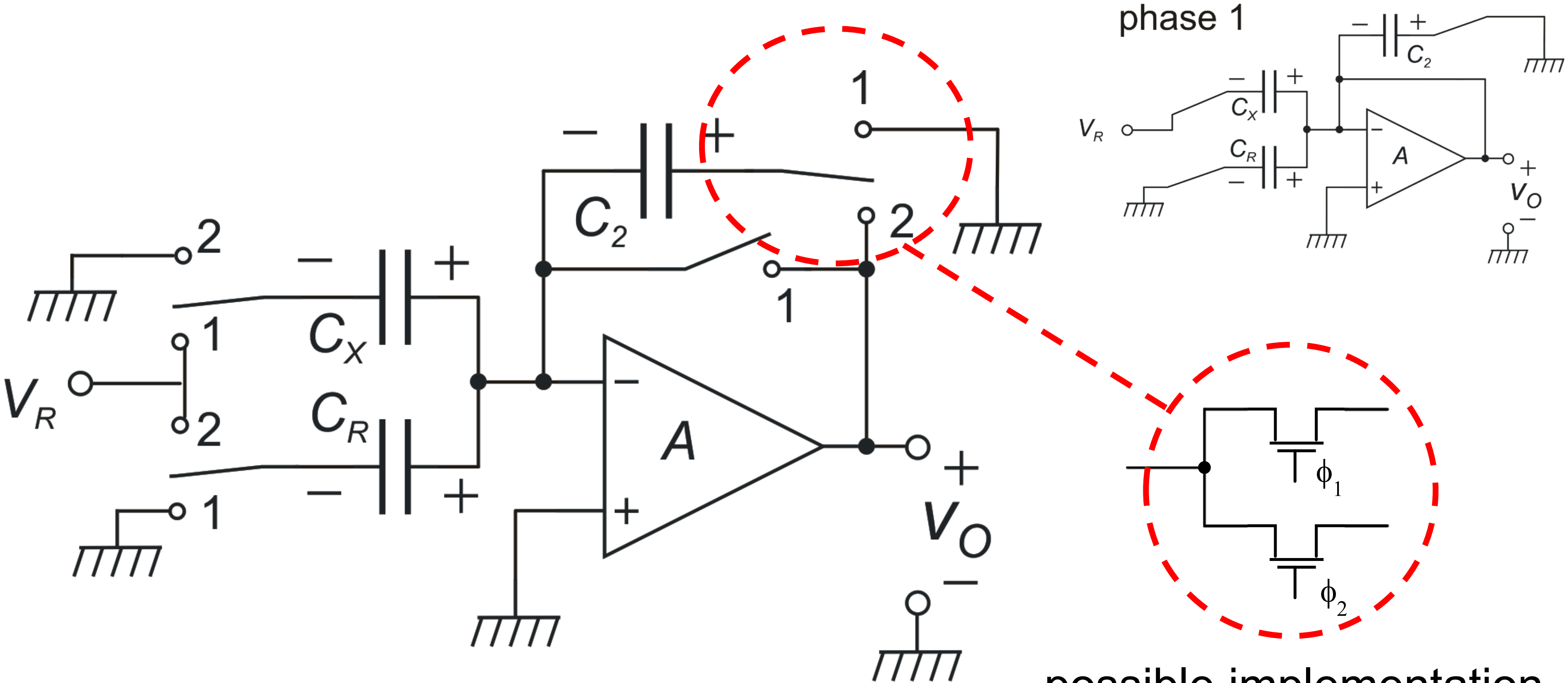
$$V_c \cong 0-(-v_n(t)) = v_n(t)$$

The feedback capacitor is pre-charged with $-v_n(t)$

$$V_{out}(t_2) \cong -v_n(t_2) + V_C\left(t_2\right) = \underbrace{-v_n(t_2) + v_n(t_1)} - \Delta Q(t_2, t_1)$$

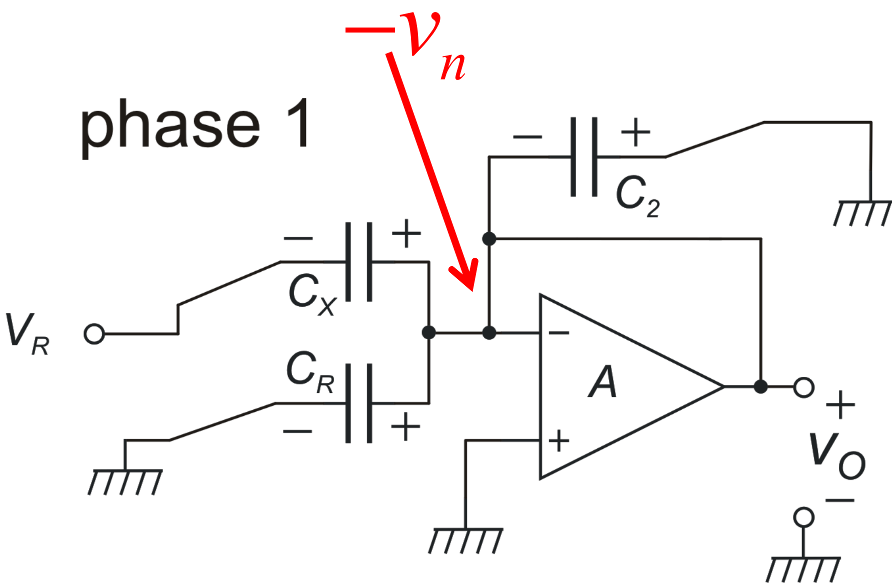
All $\boldsymbol{v_n}$ components (offset, low freq. noise) that do not change across the t_1,t_2 interval are cancelled

SC interface for capacitive sensors



possible implementation

Phase 1: Capacitor voltages

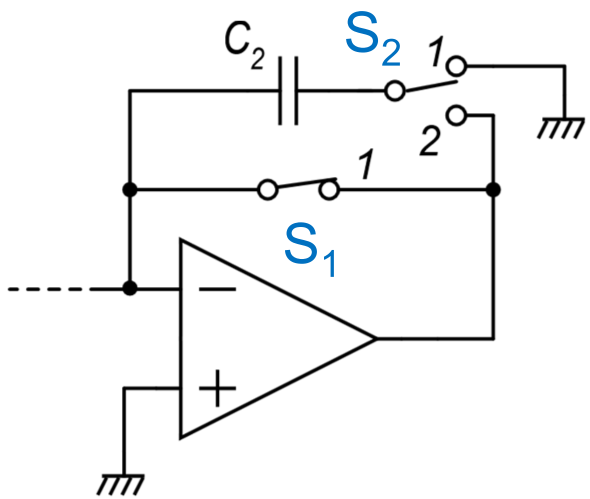


$$v_O = -v_n^{(1)}$$

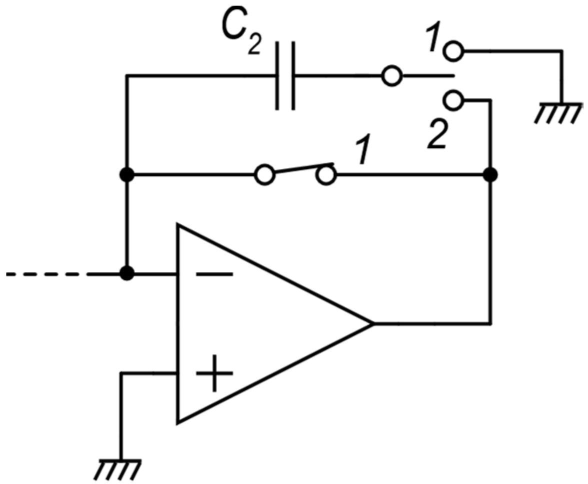
$$\begin{cases} V_{CX}^{(1)} = -v_n^{(1)} - V_R \\ V_{CR}^{(1)} = -v_n^{(1)} \\ V_{C2}^{(1)} = v_n^{(1)} \end{cases}$$

Transition to phase 2

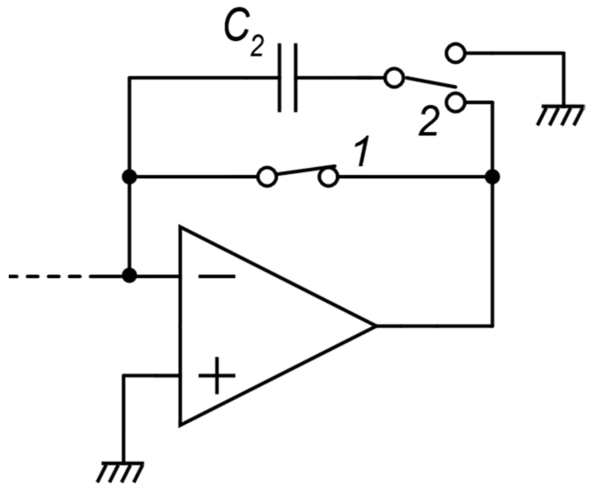
In SC circuits, timing of the switches is critical, due to the risk to alter the charge stored into the capacitors



S_2 opens and C_2 samples $v_n^{(1)}$



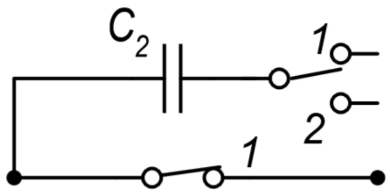
If S_1 is still closed in the previous position (phase 1), when S_2 closes to phase 2 position, C_2 is short circuited



The intermediate phase "*i*"

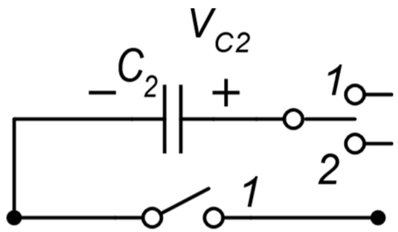
In order to avoid the occurrence of unwanted temporary short-circuits the transition from phase 1 to phase 2 occurs according the following steps:

Switches are closed in position 1



phase 1

All switches opens (capacitors sample their voltages)

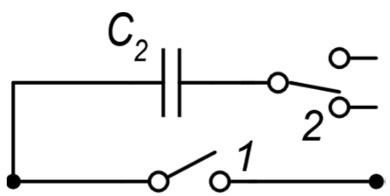


phase "i"

$$V_{C2}^{(i)} = v_n^{(1)} + v_\varepsilon$$

kT/C noise

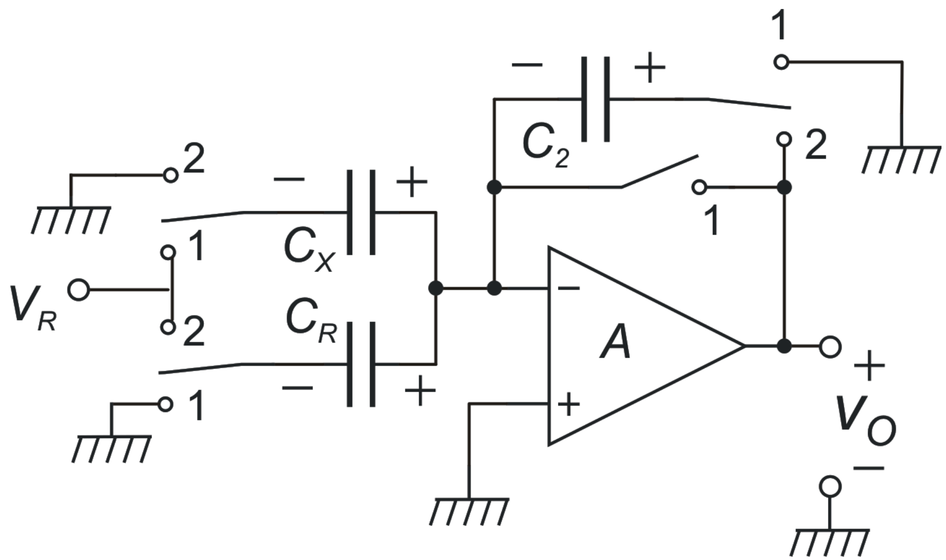
Switches close in position 2

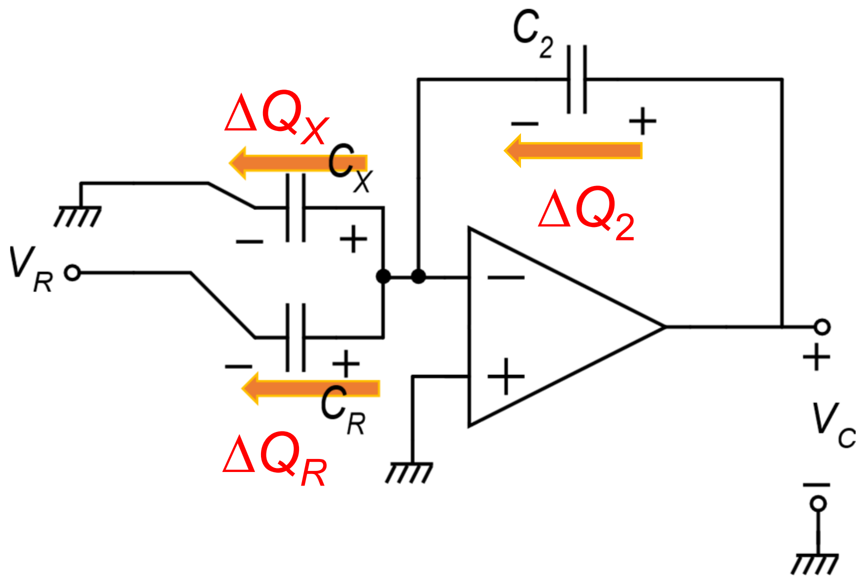


phase 2

Phase 1 to phase 2 transition

$$\begin{cases} V_{CX}^{(i)} = -v_n^{(1)} - V_R + v_{\varepsilon X} \\ V_{CR}^{(i)} = -v_n^{(1)} + v_{\varepsilon R} \\ V_{C2}^{(i)} = v_n^{(1)} + v_{\varepsilon 2} \end{cases}$$



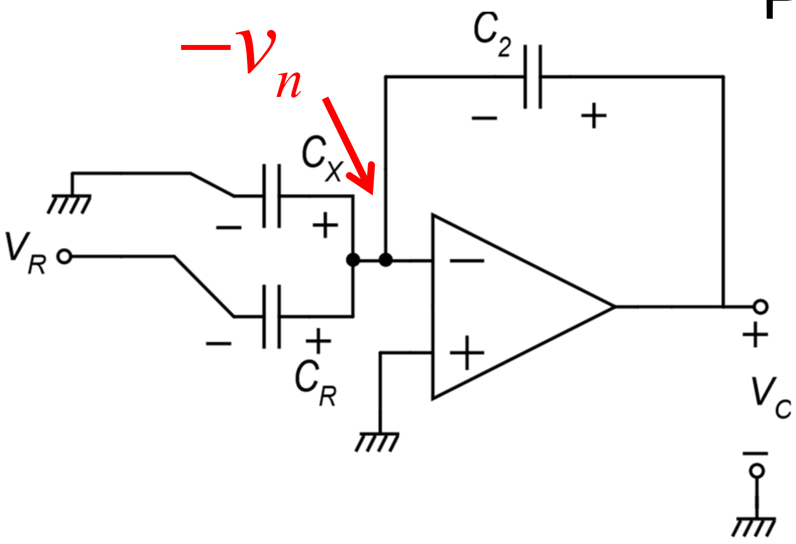


$$\Delta Q_X = C_X\left(V_{CX}^{(2)} - V_{CX}^{(i)}\right)$$

$$\Delta Q_R = C_R\left(V_{CR}^{(2)} - V_{CR}^{(i)}\right)$$

$$\Delta Q_2 = \Delta Q_X + \Delta Q_R$$

Phase 2 voltages



$$V_{CX}^{(2)} = -v_n^{(2)}$$

$$V_{CR}^{(2)} = -v_n^{(2)} - V_R$$

$$V_{C2}^{(2)} = V_{C2}^{(i)} + \frac{\Delta Q_2}{C_2}$$

$$V_o^{(2)} = -v_n^{(2)} + V_{C2}^{(2)}$$

$$\Delta Q_2 = \Delta Q_X + \Delta Q_R \; = C_X\left(V_{CX}^{(2)} - V_{CX}^{(i)}\right) + C_R\left(V_{CR}^{(2)} - V_{CR}^{(i)}\right)$$

$$V_o^{(2)} = -v_n^{(2)} + V_{C2}^{(i)} + \frac{1}{C_2}\left[C_X\left(V_{CX}^{(2)} - V_{CX}^{(i)}\right) + C_R\left(V_{CR}^{(2)} - V_{CR}^{(i)}\right)\right]$$

Phase 2 output voltage

$$V_o^{(2)} = -v_n^{(2)} + V_{C2}^{(i)} + \frac{1}{C_2}\left[C_X \left(V_{CX}^{(2)} - V_{CX}^{(i)} \right) + C_R \left(V_{CR}^{(2)} - V_{CR}^{(i)} \right) \right]$$

$$\begin{cases} V_{CX}^{(1)} = -v_n^{(1)} - V_R \\ V_{CR}^{(1)} = -v_n^{(1)} \\ V_{C2}^{(1)} = v_n^{(1)} \end{cases} \qquad \begin{cases} V_{CX}^{(i)} = -v_n^{(1)} - V_R + v_{\varepsilon X} \\ V_{CR}^{(i)} = -v_n^{(1)} + v_{\varepsilon R} \\ V_{C2}^{(i)} = v_n^{(1)} + v_{\varepsilon 2} \end{cases} \qquad \begin{array}{l} V_{CX}^{(2)} = -v_n^{(2)} \\ V_{CR}^{(2)} = -v_n^{(2)} - V_R \end{array}$$

$$V_o^{(2)} = -v_n^{(2)} + v_n^{(1)} + v_{\varepsilon 2} + \frac{1}{C_2}\left[C_X \left(-v_n^{(2)} + v_n^{(1)} + V_R - v_{\varepsilon X} \right) + C_R \left(-v_n^{(2)} - V_R + v_n^{(1)} - v_{\varepsilon R} \right) \right]$$

$$V_o^{(2)} = \frac{C_X - C_R}{C_2} V_R + \left(-v_n^{(2)} + v_n^{(1)} \right) \left(1 + \frac{C_X}{C_2} + \frac{C_R}{C_2} \right) + v_{\varepsilon 2} - \frac{C_X}{C_2} v_{\varepsilon X} - \frac{C_R}{C_2} v_{\varepsilon R}$$

Output voltage components

$$\Delta C = C_X - C_R$$

$$V_o^{(2)} = \frac{\Delta C}{C_2} V_R + \left(-v_n^{(2)} + v_n^{(1)}\right)\left(1 + \frac{C_X}{C_2} + \frac{C_R}{C_2}\right) + v_{\varepsilon 2} - \frac{C_X}{C_2} v_{\varepsilon X} - \frac{C_R}{C_2} v_{\varepsilon R}$$

useful signal ($\frac{\Delta C}{C_2} V_R$)

Amplifier noise (CDS): $\left(-v_n^{(2)} + v_n^{(1)}\right)\left(1 + \frac{C_X}{C_2} + \frac{C_R}{C_2}\right)$

kT/C noise: $v_{\varepsilon 2} - \frac{C_X}{C_2} v_{\varepsilon X} - \frac{C_R}{C_2} v_{\varepsilon R}$

sensitivity: $\frac{V_R}{C_2}$

Referred to the input diff. capacitance

$$\Delta C_n^{(2)} = \frac{\left(-v_n^{(2)} + v_n^{(1)}\right)}{V_R}\left(C_2 + C_X + C_R\right) + \frac{C_2 v_{\varepsilon 2} - C_X v_{\varepsilon X} - C_R v_{\varepsilon R}}{V_R}$$

Example: DR of the SC interface considering only kT/C noise

$$\Delta C_n = \frac{C_2 v_{\varepsilon 2} - C_X v_{\varepsilon X} - C_R v_{\varepsilon R}}{V_R} \qquad DR = \frac{\Delta C_{FS}}{\Delta C_{n-pp}} = \frac{\Delta C_{FS}}{4\Delta C_{rms}} \qquad \Delta C_{rms} = \sqrt{\left\langle \Delta C_n^2 \right\rangle}$$

$$< \left(\Delta C_n\right)^2 > \; = \; \frac{1}{V_R^2}\left(C_2^2 < \left(v_{\varepsilon 2}\right)^2 > + \; C_X^2 < \left(v_{\varepsilon X}\right)^2 > + C_R^2 < \left(v_{\varepsilon R}\right)^2 >\right)$$

$$< \left(\Delta C_n\right)^2 > \; = \; \frac{1}{V_R^2}\left(C_2^2 \frac{kT}{C_2} + \; C_X^2 \frac{kT}{C_X} + C_R^2 \frac{kT}{C_R}\right) = \frac{kT}{V_R^2}\left(C_2 + C_X + C_R\right)$$

$$DR = \frac{\Delta C_{FS}}{4\sqrt{\frac{kT}{V_R^2}\left(C_2 + C_X + C_R\right)}}$$

Example: DR of the SC interface considering only kT/C noise

$$DR = \frac{\Delta C_{FS}}{4\sqrt{\frac{kT}{V_R^2}\left(C_2 + C_X + C_R\right)}}$$

$$DR = \frac{1}{\frac{4}{\Delta C_{FS}}\sqrt{\frac{kT}{V_R^2}\left(C_2 + C_X + C_R\right)}}$$

$$= \frac{1}{4\sqrt{\frac{kT}{\Delta C_{FS} V_R^2}\frac{\left(C_2 + C_X + C_R\right)}{\Delta C_{FS}}}}$$

$$= \frac{1}{4}\sqrt{\frac{1}{\frac{kT}{\Delta C_{FS} V_R^2}\frac{\left(C_2 + C_X + C_R\right)}{\Delta C_{FS}}}}$$

$$DR = \frac{V_R}{4\sqrt{kT/\Delta C_{FS}}}\sqrt{\frac{\Delta C_{FS}}{\left(C_2 + C_X + C_R\right)}}$$

rms value of the kT/C noise associated to ΔC_{FS}