The source-to-gate capacitance of the in-pixel source follower: a positive feedback during charge sensing which increases column settling time and noise voltage.

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Abstract
The gate-to-source capacitance of the in-pixel source follower, forms a capacitive attenuator with the floating diffusion capacitance. Voltage changes at the source are feedback to the gate: a positive feedback. It is effective when the resetfet is turned off. This is during charge sensing and reset level sensing for CDS. The positive feedback increases the output impedance at the source of the source follower and the noise voltage increases just as the settling time at the column.

Pre-amble: Simplifications
To focus on the main topic many simplifications have been applied. E.g. select and reset transistor are switches, simple MOS-transistor model for SF, no gate current noise, no bulk effect, noise excess factor of 2/3. Stationarity of the noise. The floating diffusion capacitance as a lumped form of the detection node capacitance. Column capacitance (pF) much larger than floating diffusion or SF gate-to-source capacitance (fF), one dominant pole. CDS applied. The intended approach is to keep it simple within reasonable restrictions that always apply when one has an imager that works.

Feedbackfactor
During charge sensing, the resetfet is off and the gate of the in-pixel source follower (SF), Figure 1, is floating, Figure 2 with RST=low. The gate-to-source capacitance (Cgs) has now an effective positive feedback to the detection node (Cfd), Figure 3. Consequently, any changes in the source voltage also changes the gate voltage. The amount of feedback from source to detection node depends on the ratio between gate-to-source capacitance Cgs and the floating diffusion capacitance Cfd,

$$\beta := \frac{Cgs}{Cfd}$$

During pixelreset (RST high, Figure 1,2) the gate of the source follower SF, and the capacitances connected to it, are clamped to a reference voltage, VDD-PIX. The gate of the source follower SF sees a low impedance. The capacitance between source and gate is a load for the source of SF and there is no feedback.

In an early paper on noise optimization [1] an optimal value for the gate-to-source capacitance was found Cgs=Cfd, or β=1. In a recent paper [2] a SF in a 45nm process with Cfd=1.34fF and Cgs=1.9fF had a slightly larger value of β=1.39. In general values of β=1/3 to β=2 will be found depending on the type of optimization [3,4,5] employed, eg 1/f, thermal, rtn.

Outputimpedance
In figure 4 the noise small signal equivalent diagram's are given for the reset state and charge sensing state. During the charge sensing state and seen from the SF source the positive feedback increases the output impedance with (1+β), Figure 2, 4

$$\frac{1+\beta}{gm}$$

In which gm is the SF transconductance.

Timeconstant
Figure 4 rightpart, with β=1 the RC-timeconstant for charging the column capacitor (Ccol) is doubled (1+ β=2), an important aspect in highspeed applications and for settling behavior

$$\tau := \frac{Ccol}{gm} \cdot (1+\beta)$$

Noisebandwidth

For a single pole network the noise bandwidth Bn [6] relates to the timeconstant. Due to the positive feedback the timeconstant is increased with (1+β) compared to the resetfet-on state

$$Bn := \frac{1}{4 \cdot \tau} = \frac{1}{4} \cdot \frac{gm}{1+\beta} \cdot \frac{1}{Ccol}$$

Noise

Assuming that the resetnoise is suppressed with e.g. CDS, the noise at the column is mainly caused by the source follower (in_sf) and the current source CS (in_cs), Figure 3,4. Due to the positive feedback the noise voltage at the SF source increases to:

$$en^2 = \left(in\_sf^2 + in\_cs^2\right) \cdot \left(\frac{1+\beta}{gm}\right)^2$$

with β=1 the noise spectral density increases 4 times. Irrespective if the noise is thermal, 1/f, RTN etc.

Thermal noise

The SF thermal noise current density is: $in\_sf^2 = 4kT*\gamma*gm$ and for the current source: $in\_cs^2 = 4kT*\gamma*gcs$ where γ is the noise excess factor, γ=2/3 will be used even though larger values can be found [4,7]. It equates to:

$$en^2 = 4 \cdot kT \cdot \frac{2}{3} \cdot (gm + gcs) \cdot \left(\frac{1+\beta}{gm}\right)^2 = 4 \cdot kT \cdot \frac{2}{3} \cdot \left(1 + \frac{gcs}{gm}\right) \cdot \frac{1}{gm} \cdot (1+\beta)^2$$

with respective transconductances for the source follower (SF) gm and for the current source (CS) gcs.
The noise spectral density has a multiplier $(1+\beta)^2$ and the noise bandwidth Bn has a devisor (1+β). The noise variance (σ^2) at the column is then

$$\sigma^2 = Bn \cdot en^2 = \frac{kT}{Ccol} \cdot \frac{2}{3} \cdot \left(1 + \frac{gcs}{gm}\right) \cdot (1+\beta)$$

Even though σ^2 is the noise power at the column, only at the first sample and hold after the column it will show up and will have this noise variance in each sample! Practically the transconductance of the current source is smaller than that of the SF and the product of 2/3*(1+gcs/gm) will be close to 1. Using the optimal value for Cgs=Cfd, β =1, the noise variance simplifies into

$$\sigma^2 = 2\,\frac{kT}{Ccol}$$

A bit larger than the often-expected kT/Ccol, or after CDS 4*kT/Ccol.

Conclusion

During charge sensing, the reset-off state, settling is (Cgs/Cfd+1) ~ 2 times slower than what one would intuitively expect when using only the SF-transconductance and the column capacitor value. The same holds for the noise voltage at the column. The sampled thermal noise at the column is not the kT/Ccol but about (Cgs/Cfd+1)*kT/Ccol.

References

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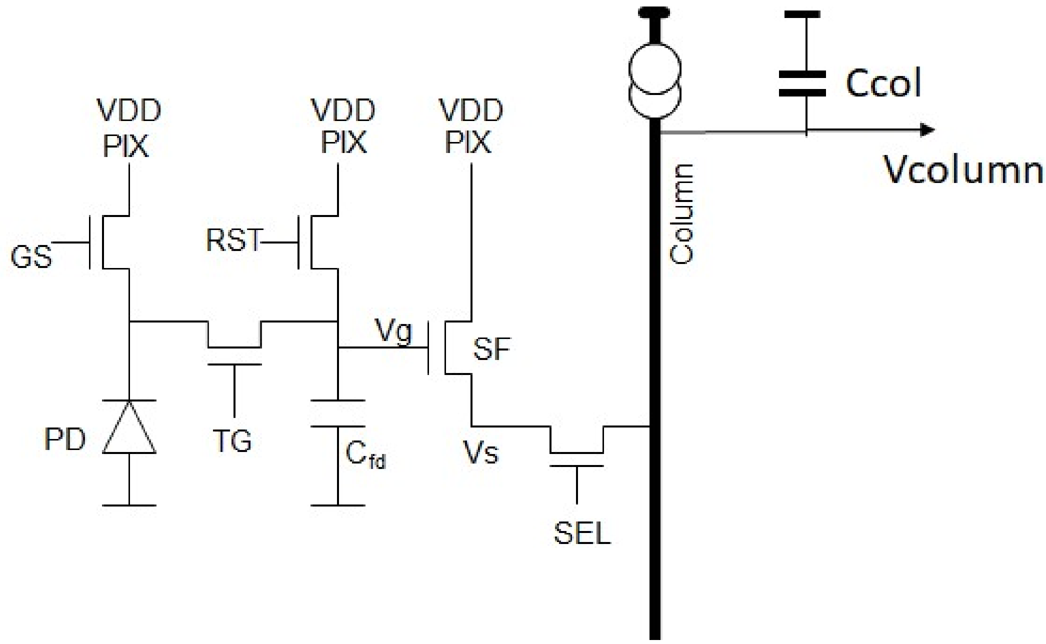

Figure 1 : 5T pixel

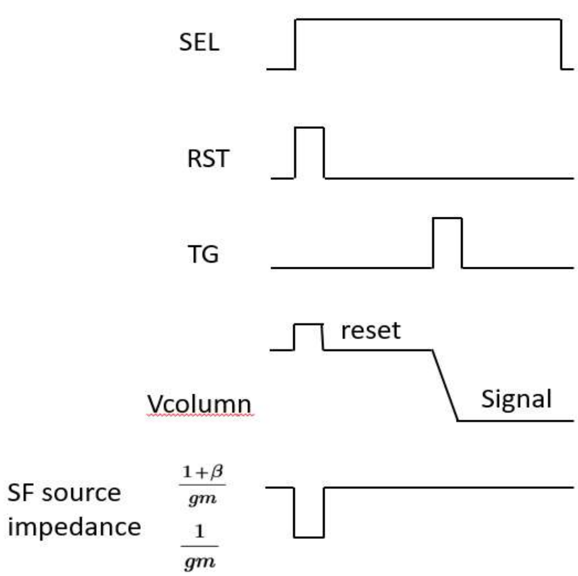

Figure 2: SF source impedance after reset and during charge sensing

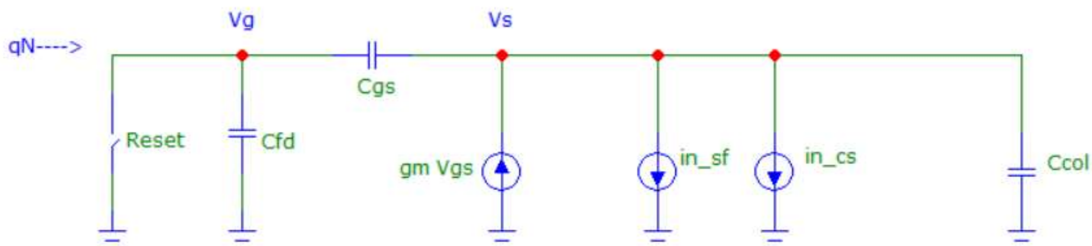

Figure 3: small signal diagram during charge sensing, reset-off

Figure 4: Noise small signal diagram. Left: reset-on, Right: reset-off