Politecnico di Milano
MSc Course - MEMS and Microsensors - 2024/2025

E19
Photon Transfer Curve and 4T APS

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Problem

An experimental Photon Transfer Curve of the 3T CMOS active pixel sensor analyzed in exercise E18 is provided in figure 1.

- Verify that the calculations you made for the sensor of E18 are correct in terms of number of bits, gain from photons to digital number, and in terms of noise, extracting also information about the PRNU.

Consider now a camera featuring a 4T CMOS APS, with a pinned diode structure. This specific pixel shows the same maximum full-well-charge and the same PRNU of the 3T case and the pinned implant reduces the dark current by a factor 10. Furthermore, correlated double sampling is exploited for the readout, reducing the reset noise by a factor 20.

- Trace the PTC in this new situation, evaluating graphically the dynamic range of the sensor. Then, comment about required changes in the ADC.

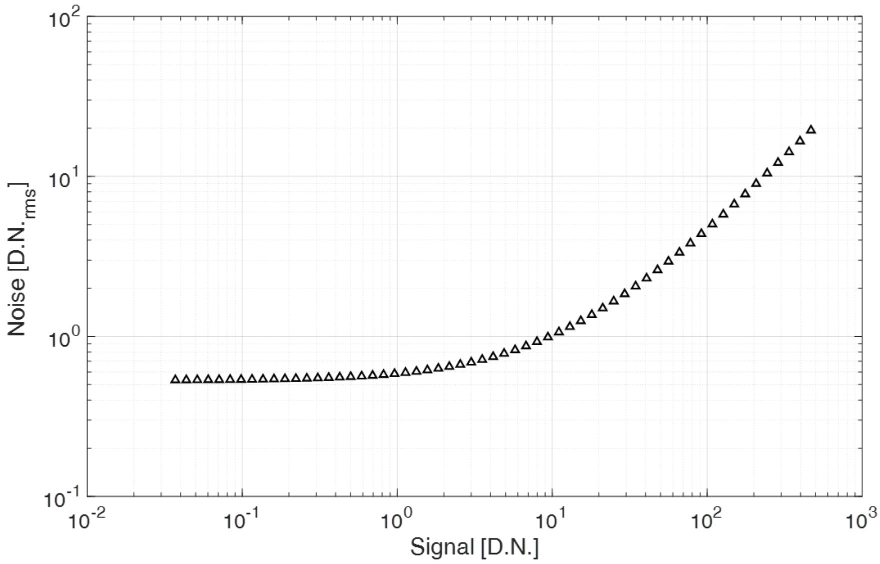

Figure 1: Measured PT curve.

Part 1: Photon transfer

Photon transfer is a valuable testing methodology employed in the characterization, optimization, calibration, and application of solid state image sensors and systems. Conceived in the 70s, the photon transfer technique is applicable to all imaging disciplines. Detector parameters, such as quantum efficiency, noise, charge collection efficiency, sense node capacitance, full charge, dynamic range, pixel responsivity, ..., can be extracted from a PTC. The PTC treats a camera system, no matter how complex it is, as a black box and determines the desired parameters with little effort. The user needs only to expose the camera to a light source and measure the signal and noise output responses. Fig. 2 shows a generic camera block diagram where the input exhibits Poisson shot noise. This means that the input is in non-dimensional units, photons in our case:

$$\sigma_A = \sqrt{A},$$

where A is the mean input signal level, and σ_A is the input noise standard deviation. For an image sensor, the only quantity with this feature is the photoelectrons number:

$$\sigma_{N_{el}} = \frac{\sqrt{2qi_{ph}\dfrac{1}{2t_{int}} \cdot t_{int}^2}}{q} = \frac{\sqrt{qi_{ph}t_{int}}}{q} = \sqrt{\frac{Q_{ph}}{q}} = \sqrt{N_{el}}.$$

Input and output signal and noise are related through a sensitivity constant K (e.g. in digital numbers / photons):

$$B = KA, \qquad \sigma_B^2 = (K\sigma_A)^2 + \sigma_{add}^2,$$

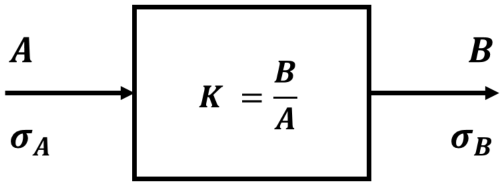

Figure 2: Black box camera system with a constant $K = B/A$ used to transfer the input A (photons) to the output B (digital numbers).

where B and σ_B are the *measured* output mean signal level and noise standard deviation, respectively, and σ_{add} is the standard deviation of all the other noise contributions due to the non-idealities of a real image sensor.
Actually, the sensitivity of an image sensor is a function of the wavelength. In this context a linear gain K (instead of an integral law over the visible spectrum) can be precisely defined only if the radiation spectrum is monochromatic. In the exercises, even if the radiation spectrum is not monochromatic, we will assume it as characterized by its dominant wavelength - unless differently specified.
At this point in the analysis K is unknown. However, assuming to find a operation region where the term σ_A is dominant (and thus σ_{add} is negligible), by re-arranging the K-equation with proper substitutions we get the result:

$$K = \frac{B}{A} = \frac{B}{\sigma_A^2} = \frac{B}{\frac{\sigma_B^2}{K^2}} = \frac{K^2 B}{\sigma_B^2}.$$

Hence:

$$K = \frac{\sigma_B^2}{B}$$

This is called the PT relation, the equation that is the basis of the PT technique. Note that K is simply found by *measuring output statistics* (mean and noise variance) without knowledge of neither the individual camera transfer functions nor on the input characteristics (except for the requirement to measure the output in a shot-noise limited region).

Let us have a look at the typical noises at the output of the sensor. We have (i) *shot noise*, that increases with the square root of the signal, (ii) *PRNU*, associated with pixel-to-pixel response differences and whose standard deviation increases linearly with signal, (iii) the so-called *read noise*, that encompasses all noise sources that are *signal independent*. These three noise sources can be summed up (quadratically), giving the total output noise

$$\sigma_{TOT} = \sqrt{\sigma_{read}^2 + \sigma_{shot}^2 + \sigma_{PRNU}^2}.$$

An ideal photon transfer curve (PTC) response from a camera system exposed to a uniform light source is illustrated in Fig. 3. Noise (rms) is plotted as a function of average output signal. Four distinct noise regimes are identified in a PTC. The first regime, read noise, represents the random noise measured under dark conditions, which includes several different noise contributors; they can be both temporal and FPN: dark shot noise, kTC noise, DSNU, quantization .... As the light illumination is increased, read noise gives way to photon shot noise, which represents the middle region of the curve. Since the plot in Fig. 3 is on log-log coordinates, shot noise is characterized by a line with a slope of 1/2. The third regime is associated with pixel PRNU, which produces a characteristic slope of unity because signal and FPN scale together. The fourth region occurs when the matrix of pixels enters the full-well regime. In this region noise typically decreases as saturation is approached (yet, the signal looses any meaning).

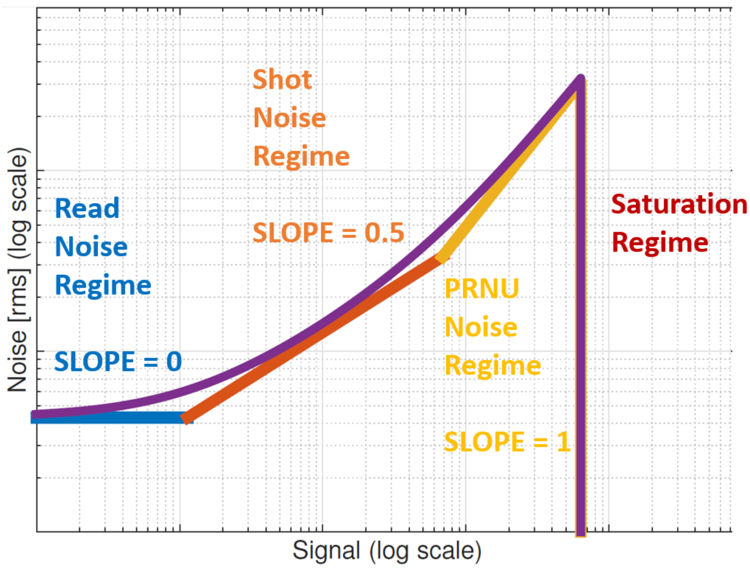

Figure 3: Ideal total noise PTC illustration showing the four classical noise regimes.

The photon transfer curve (PTC) is a commonly used test procedure to characterize digital sensors parameters, i.e. from output data, we can infer a lot of system and pixel parameters of the sensor. This is done without knowing anything of the camera system, i.e. by assuming the camera as a black box. In fact, given a certain photon flux impinging on the sensor, you can measure the output signal of each pixel. From this data, you can calculate the average output signal, DN, its standard deviation, σ_{DN}, and you can draw your PTC with the average signal on the x-axis and its standard deviation on the y-axis. This can be repeated for different photon fluxes, i.e. for different average output signals, and a complete PT curve is built. In Fig. 4, a measured photon transfer curve is displayed. On the x-axis we have the digital output number corresponding to the signal (B), while on the y-axis we have the output rms noise expressed in rms digital number (σ_B). PTC measurements are usually made (initially) in digital number (DN) units that will be later converted to electron units, if needed.

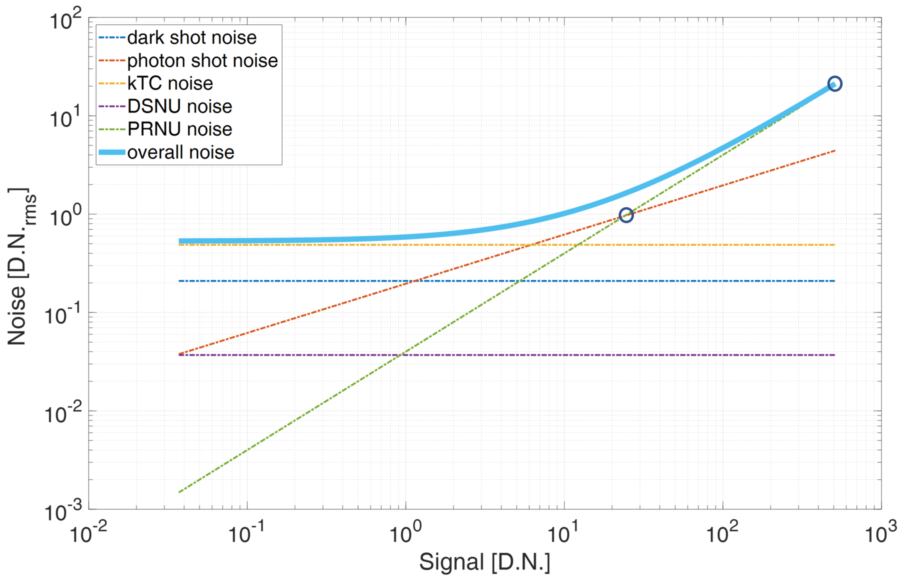

Figure 4: Measured PT curve and extracted parameters.

There exist a precise mathematical routine that helps you to calculate each noise contribution alone: read, shot and PRNU. This can be easily (and quickly) done in a graphical way, by drawing the asymptotic curves, with 0, 1/2 and 1 slopes, respectively, in the log-log plot. Reminding that:

$$K = \frac{\sigma_B^2}{B}$$

The equation states that one could extract the transfer function of the camera system, by taking the ratio between the output variance and the output signal, assuming that the system is shot noise limited, i.e. if $\sigma_A = \sqrt{A}$. Hence, from measured data, we can immediately infer the transfer function of the system from the number of photons/electrons to the digital output. This is be practically done by simply calculating the ratio between the variance and the average output signal. Things are even easier: K can be found graphically by extending the slope 1/2 shot noise line back to the signal axis. The signal intercept with the 1 DN rms noise line represents the inverse of the transfer function:

$$K = \left[\frac{\sigma_B^2}{B}\right]_{\sigma_B=1} = \frac{1}{DN_{shot}} = \frac{1}{25} = 0.04\,\text{DN/photons}$$

From theory, the expected value is:

$$K = \frac{DN}{N_{ph}} = \eta\frac{2^{N_{bit}}}{FWC} = 0.65\frac{2^9}{8650} = 0.0389\,\text{DN/photons}$$

well in line with measured data.

We can then extrapolate the PRNU of the camera system. As $\sigma_{PRNU} = \%_{PRNU} \cdot DN$, we have

$$\%_{PRNU} = \frac{\sigma_{PRNU}}{DN}.$$

The PRNU factor $\%_{PRNU}$ can be found from a single data point for the PRNU asymptotic curve; or, as before, we can do it in a graphical way, by denoting that

$$\%_{PRNU} = \left[\frac{\sigma_{PRNU}}{DN}\right]_{\sigma_{PRNU}=1} = \frac{1}{DN_{PRNU}},$$

where DN_{PRNU} is the signal where the PRNU line intercepts the 1 DN rms noise. From Fig. 1, we find that $\%_{PRNU} = 1/25 = 0.04 = 4\%$.
Another parameter that can be extracted from the PT curve is the full-well charge, that corresponds to pixel saturation, which can be found where noise begins to decrease when increasing signal. The maximum digital number is about 510 levels, effectively matching the expected $2^N_{bit} = 512$ levels. Hence, the maximum number of electrons that can be integrated can be estimated as:

$$N_{sat} = \frac{DN_{sat}\eta}{K} \approx \frac{510\,\mathrm{DN} \cdot 0.65}{0.04\,\mathrm{DN/photons}} = 8320\,\mathrm{electrons}.$$

Read noise can be also extracted:

$$\sigma_{read,N} = \frac{\sigma_{read,DN}\eta}{K} = \frac{0.5 \cdot 0.65\,\mathrm{DN}}{0.04\,\mathrm{DN/photons}} = 8.2\,\mathrm{electrons}.$$

The dynamic range of the sensor corresponding to the integration time used to acquire the PTC can be finally be determined:

$$DR = \frac{N_{sat}}{\sigma_{read,N}} = \frac{8320}{8.2} = 1014,$$

that corresponds to 60 dB. All these numbers are, with a reasonable error due to the extrapolating procedure, the same that we obtained during the last exercise class.
Note that from the PTC you can also extract the minimum measurable signal including the effect of the photocurrent shot noise by finding the point on the PTC where signal and noise are equal (i.e. SNR = 1).
The most important thing related with PT is that all these parameters were extrapolated *without knowing anything about neither the input light source nor the camera/pixel parameters*! This is the greatest strength of the photon transfer technique.

Part 2: 4T APS and correlated double sampling

Two significant challenges exist in conventional *pn* photodiode pixels: dark current reduction and reset noise reduction. To address these problems, the pinned photodiode structure was introduced and has become very popular in most recent CMOS image sensors. The basic pinned photodiode pixel configuration is shown in Fig. 5a. The pixel consists of a pinned photodiode and four transistors that include a transfer gate (MTX), a reset transistor (MRS), an amplifier transistor (MRD), and a select transistor (MSEL). Thus, the pixel structure is often called a four-transistor (4T) pixel in contrast to the conventional 3T one.

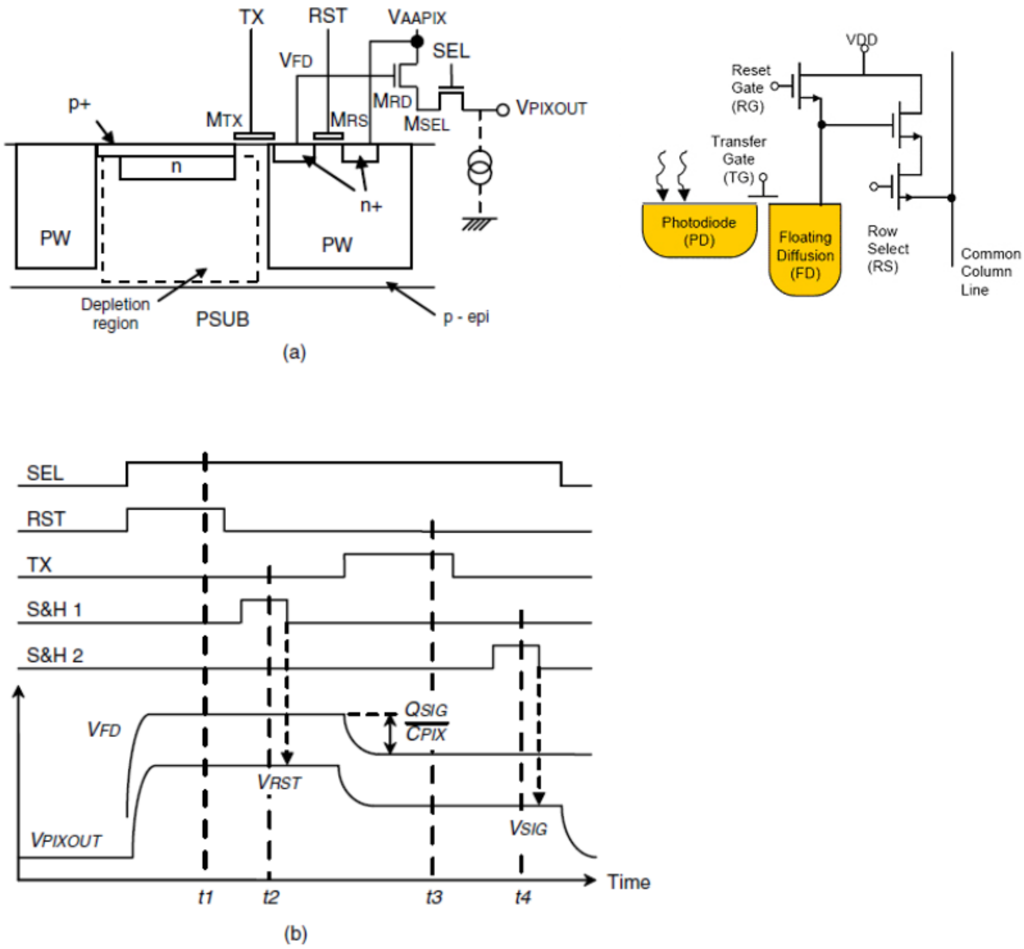

Figure 5: Pinned photodiode pixel (4T pixel): (a) pixel structure and (b) timing diagram.

The time diagram of the image acquisition in a 4T pixel is illustrated in Fig. 5b. At the beginning of the pixel readout, the floating diffusion (FD) node is reset at the supply voltage by the reset transistor (MRS). Then the pixel output (VPIXOUT) is read out once, as a reset signal (VRST), and stored. VRST includes both inherent pixel offsets and reset noise at the FD node. Next, the transfer gate (MTX) turns on so that the accumulated charge in the pinned photodiode is transferred completely to the FD node. Because of the complete charge transfer, no reset noise is generated during the transfer operation. The transferred charge drops the potential at the FD node, and VPIXOUT decreases. After the transfer operation, VPIXOUT is read out again as VSIG. By subtracting VRST from

VSIG, pixel FPN and reset noise are removed, resulting in a reduced overall noise. Since noises (both FPN and kTC) in VRST and VSIG signals are *correlated*, this operation is called *correlated double sampling* (CDS).
Which is the capacitance seen by the integration node (FD) to ground? In principle, we have the parallel of the physical diffusion capacitance and the input capacitance of the MRD transistor: $C_{int} = C_{FD} + C_{in,MRD}$. With respect to a standard 3T pixel, with a pinned photodiode topology the physical diffusion capacitance can be made very small. As it is not responsible of photons collection, there is no need to make it wide. Assuming a floating diffusion area corresponding to minimum-size transistors, $A_{diff} = W_{min}L_{min}$, and assuming a depletion width of 1 μm, we get a physical floating diffusion capacitance of

$$C_{FD} = \frac{\epsilon_0 \epsilon_r WL}{x_{dep}} = 6.8\,\text{aF},$$

while the input capacitance of MRD transistor can be estimated as

$$C_{in,MRD} = C'_{ox}WL = 0.5\,\text{fF},$$

which is much higher than the physical diffusion one. With 4T pixel, it is a common property that the integration capacitance is dominated by the input capacitance of the source follower, MRD. This leads to huge benefits in terms of linearity of the pixel, as the integration capacitance is now independent from a physical depletion capacitance, whose value, as we learned in previous classes, depends on the signal itself.
Another important benefit obtained from the adoption of the pinned photodiode (with respect to standard *pn* photodiodes) is the lower dark current. Since the surface of the pinned photodiode is shielded by a p^+ layer, dark current is highly reduced.
In order to trace the PTC in this new situation, we calculate again noise contributions:

- The dark current is lowered by the pinned implant: from 0.2 fA of the 3T APS of exercise E19 we reached 0.02 fA in the 4T architecture. Consequently, we can quantify the dark shot noise improvement as follows:

$$\sigma_{dark,N} = \frac{\sqrt{q i_{d,4T} t_{int}}}{q} = 1.1\,\text{electrons} \tag{1}$$

- The KTC rms value is improved by a linear factor 20, resulting in 0.4 electrons noise. The CDS (performed following the timing scheme of figure 5) ideally cancels the KTC noise term, sampling the reset just before the transfer gate opening. In a real situation, a residual contribution is present, e.g. given by a discharge of the sample & hold capacitance or other spurious effects.

One can trace the PTC curve noting that:

1. for the sake of simplicity, we can assume that the whole system is somehow adjusted in order to obtain the same K gain of the 3T topology;

2. the full-well-charge is unchanged with respect to the 3T analyzed topology;

3. also the PRNU and the photocurrent shot noise will not change;

4. the only PTC improvement happens at the low-end. Indeed, the flat portion of the curve given by the reset and dark noise, will be shifted downwards reaching:

$$DN_{read} = \sqrt{(\sigma_{dark,n}^2 + \sigma_{KTC}^2)} \cdot K/\eta = 0.07DN \tag{2}$$

The PTC of this new situation is plotted in Fig. 6, compared to the 3T APS.

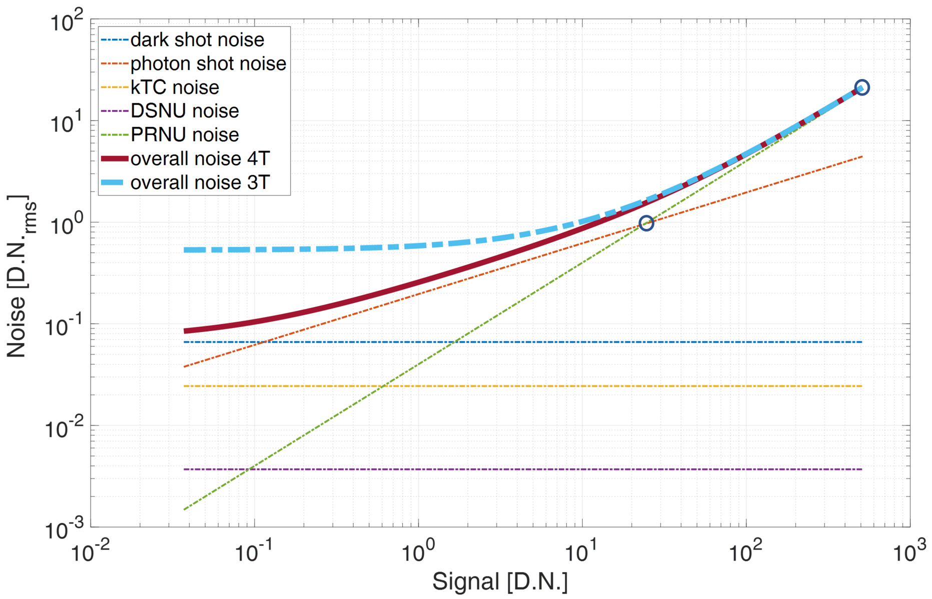

Figure 6: PTC for the 4T APS with CDS.

The maximum dynamic range its evidently increased:

$$DR = 20 \cdot \log_{10}\left(\frac{512}{0.07}\right) = 77dB \tag{3}$$

Some final remarks: the correlated double sampling nulls the source follower transistor voltage spread. Any other out-of-pixel electronic stage can introduce its own threshold spread, but can be realized with larger MOS since the fill factor depends only on in-pixel transistors. So, their voltage spread will be lower, given the Pelgrom relation:

$$\sigma_{V_t} = \frac{\text{const.}}{\sqrt{WL}} \tag{4}$$

Furthermore, the gain in DR actually requires a larger n. of bit of the ADC. Quantization noise was indeed ignored in this exercise, but using 9 bit (as for the 3T case) would become the dominant noise source.