Part III:
Noise
in
Image Sensors

Introduction

- **We have seen how pixels are designed to maximise the sensitivity to illumination**
- **However, this is only part of the story**
- **The overall performance of the sensor is ultimately limited by the noise that is added by the system to the signal**
- **In this sense, the noise figure of the detector system is a measure of its "perfection"**
- **Noise comes from numerous sources and its minimisation requires optimisation of many individual parts of the system**
- **Our discussion will not consider external noise sources, such as electrical pick-up**
  - » the only "external" noise we will include is noise in the optical signal itself
- **The treatment of noise is a complex subject, and it is even harder to measure the individual components accurately**
  - » the theoretical treatment is important, however, as a design tool for optimising the performance of specific stages in the system

Types of Noise

- **“Noise” in image sensors is typically separated into two categories**
  - random noise
  - pattern noise
- **Random noise is what you might call “real” noise**
  - it is temporally random and is not constant from frame to frame in the image
  - hence, it can be reduced by averaging successive frames
  - and is described by statistical distributions
- **Pattern noise is effectively a spatial noise as seen by the observer of the image**
  - it does not change significantly from frame to frame
  - and so cannot be reduced by frame averaging
- **Pattern noise is divided into two components**
  - fixed pattern noise (FPN)
  - photo-response non-uniformity (PRNU)

Pattern Noise

- **FPN is the component of pattern noise measured in the absence of illumination**
- **It is mainly due to variations in**
  - detector dimensions
  - doping concentrations
  - contamination during fabrication
  - characteristics of MOSFETs (V_T, gain, W, L, etc.)
- **PRNU is the component of pattern noise that depends on the illumination**
- **PRNU depends on**
  - detector dimensions
  - doping concentrations
  - thicknesses of overlayers
  - wavelength of illumination (spectral response)
- **Historically, pattern noise (FPN in particular) has been the factor limiting the acceptability of CMOS imagers**
  - PRNU is not often mentioned ...
  - shortly, we will see how FPN can be reduced

Describing Noise

- **Pattern noise is usually specified in terms of the variation in the signals from individual pixels under uniform illumination**
  - » usually as a percentage of the saturation output
- **Random noise is expressed in terms of parameters which describe the statistical distribution of voltage or current**
- **If there are n samples of the signal**
  - » $x_1, x_2, x_3, \ldots x_n$
- **then the mean is $x = (x_1 + x_2 + x_3 + \ldots x_n) / n$**
- **However, the mean for many noise sources is zero**
  - » leaving the DC level of the signal unaffected
- **So a more useful description of the noise is either the variance ($<x^2>$) or the standard deviation ($\sqrt{<x^2>}$, in rms units)**
  - » which measures the scatter of the data points about the mean

$$\left\langle x^2 \right\rangle = \frac{1}{n} \sum_{j=1}^{n} \left(x_j - x \right)^2$$

- **To sum noise sources, we have to add the variances**

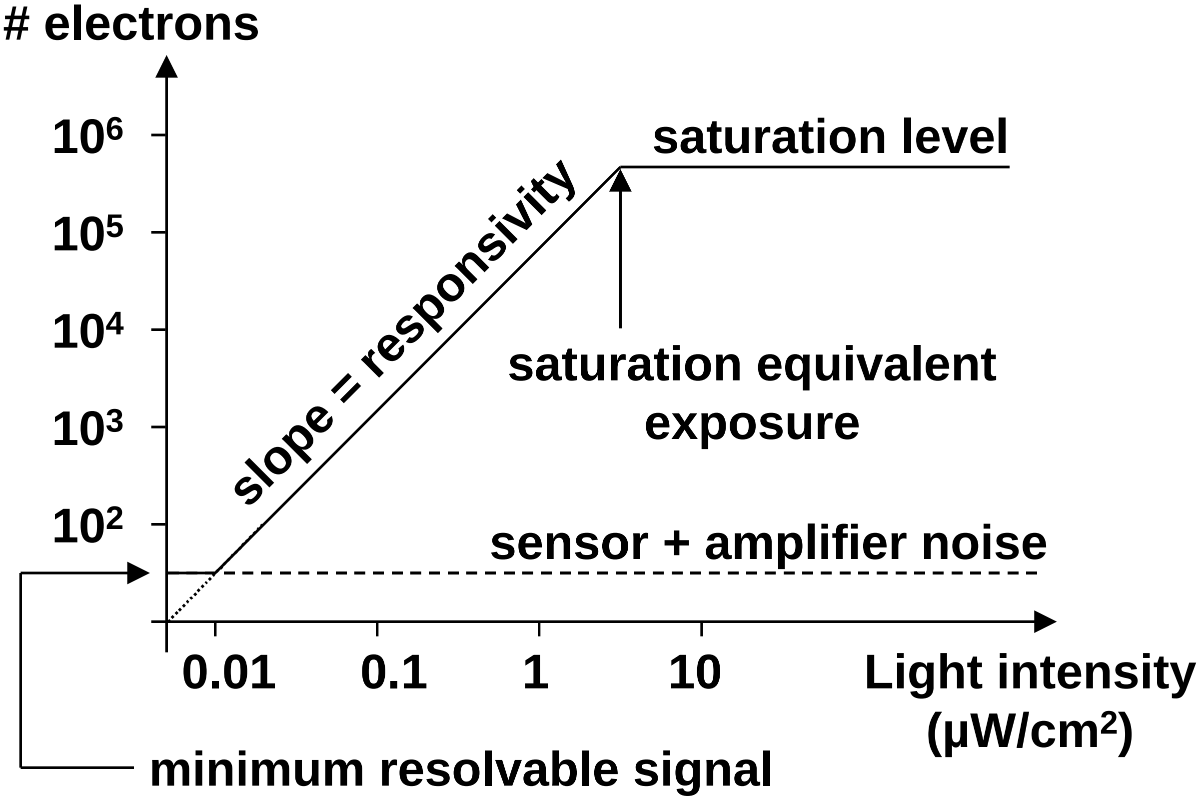
$$\left\langle \mathbf{x}^2 \right\rangle = \left\langle \mathbf{x}_1^2 \right\rangle + \left\langle \mathbf{x}_2^2 \right\rangle + \left\langle \mathbf{x}_3^2 \right\rangle + \ldots \left\langle \mathbf{x}_n^2 \right\rangle$$

- **or the standard deviation is given by**

$$\langle \mathbf{x} \rangle = \sqrt{\left\langle \mathbf{x}_1^2 \right\rangle + \left\langle \mathbf{x}_2^2 \right\rangle + \left\langle \mathbf{x}_3^2 \right\rangle + \ldots \left\langle \mathbf{x}_n^2 \right\rangle}$$

Importance of Noise

- We can illustrate the importance of the noise on the overall sensor performance as follows



- Dynamic range = (saturation signal / rms noise level)
  - saturation ≈ 200,000 e^-, noise ≈ 40 e^- rms
  - typical value is 5,000 for a PD (~75dB)
  - assuming dark current is not the limiting factor

- **Responsivity = (# electrons / light intensity)**
  - » in linear portion of the curve (electrons.cm^2/µW)
- **Provided that the dark current is small, the minimum resolvable signal is determined by the noise in the system**
- **Hence, a good responsivity is not enough to ensure a good signal at low light levels**
  - » a low “noise floor” is also required
- **In a convenient model, the rms system noise is**

$$\langle \mathbf{n}_{\mathbf{sys}} \rangle = \sqrt{\langle \mathbf{n}^2_{\mathbf{shot}} \rangle + \langle \mathbf{n}^2_{\mathbf{floor}} \rangle + \langle \mathbf{n}^2_{\mathbf{pattern}} \rangle}$$

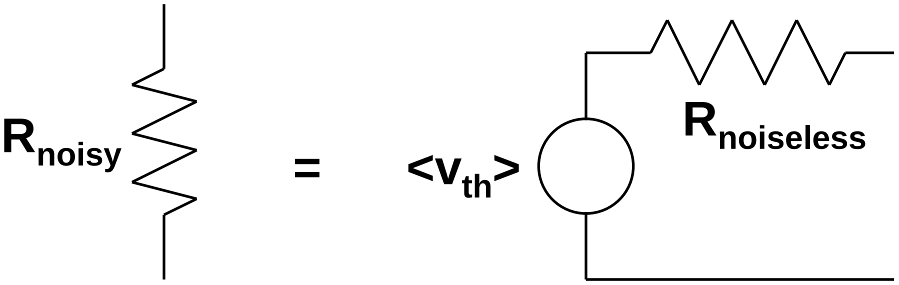
  - » where the floor is determined by the amplifier noise, the reset noise, and the analog-to-digital converter noise
  - » the noise floor is often referred to as the read noise
- **The other noise included above is called the shot noise, which arises because of the statistical arrival of electrons**
  - » due to the photo-generation of the electrons
  - » and the thermal generation of electrons
- **We will now examine some of the noise sources present in image sensors**

Thermal Noise

- **Thermal noise is a white noise**
  - the noise power is constant over all frequencies
- **For a resistor, the thermal noise root mean square voltage is given by**

$$\langle \mathbf{v_{th}} \rangle = \sqrt{\mathbf{4kTBR}}$$

  - where R is the resistance, and B is the noise equivalent bandwidth
- **Since the thermal noise covers the entire frequency range, the bandwidth determines the actual amount measured**
- **So the <u>open circuit</u> equivalent circuit is**



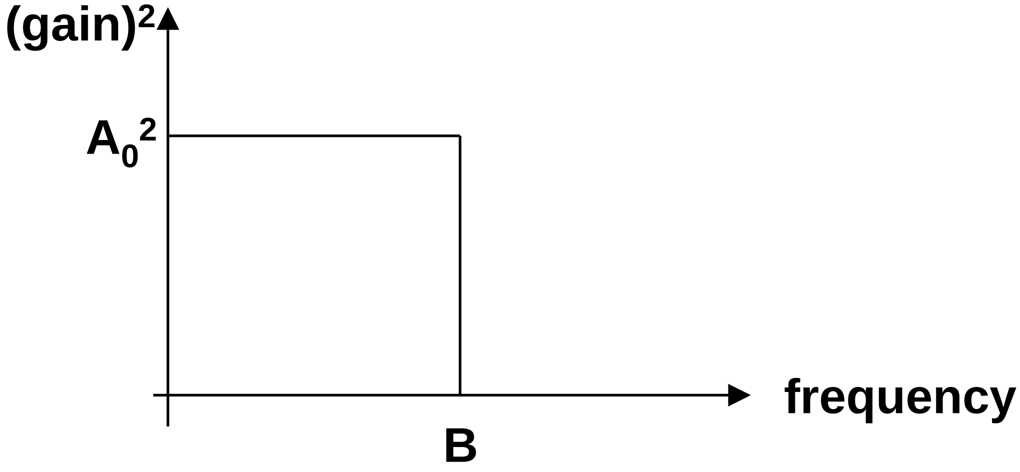
- **Alternatively**

$$\langle \mathbf{i_{th}} \rangle = \sqrt{\frac{\mathbf{4kTB}}{\mathbf{R}}}$$

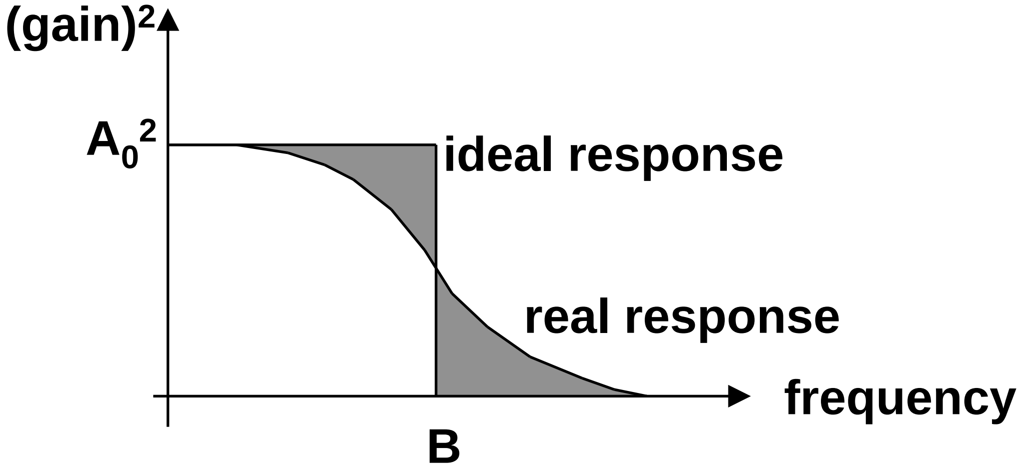
- **However, an important factor is the noise equivalent bandwidth for use in the calculation**

Noise Equivalent Bandwidth

- This is defined as the voltage-gain-squared bandwidth of the circuit
- The ideal case is that the (gain)^2 is constant at a value of A_0^2 up to the bandwidth (A_0 = voltage gain)



- But, the behaviour of a real circuit is not abrupt



- The NEB is defined as the point at which the two shaded areas equal

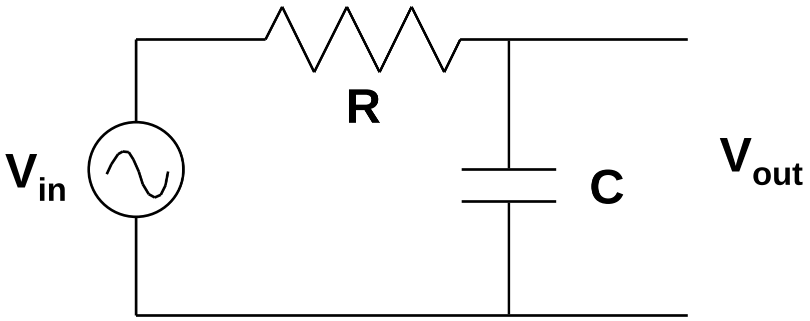
- **Mathematically, this is given by**

$$B = \frac{1}{|A_0|^2}\int_0^\infty \left|A(f)^2\right| df$$

- **So in the ideal case**

$$\text{bandwidth} = \frac{1}{A_0^2}\int_0^\infty |A|^2\, df = \frac{A_0^2 B}{A_0^2} = B$$

- **If we take the example of an RC low pass filter**



- **Calculating the transfer function**

$$A(\omega) = \frac{v_{out}}{v_{in}} = \frac{\frac{1}{j\omega C}}{\frac{1}{j\omega C} + R}$$

$$= \frac{1}{1 + 2\pi fRC} \text{ since } \omega = 2\pi f$$

$$= \frac{f_0}{jf + f_0} \text{ where } f_0 = \frac{1}{2\pi RC}$$

- **At f = 0, $A(f) = A_0 = 1$ for this circuit**
- **Now we can calculate the noise equivalent bandwidth, using $A_0 = 1$**

$$B = \int_0^\infty \left(\frac{f_0}{\sqrt{f^2 + f_0^2}} \right)^2 df$$

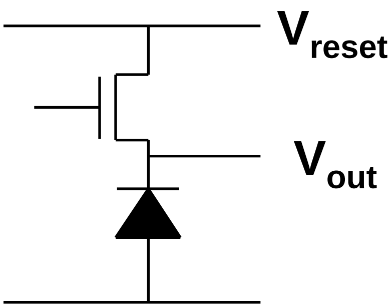
$$= f_0^2 \int_0^\infty \left(f_0^2 + f^2 \right)^{-1} df$$

$$= \frac{\pi}{2} f_0$$

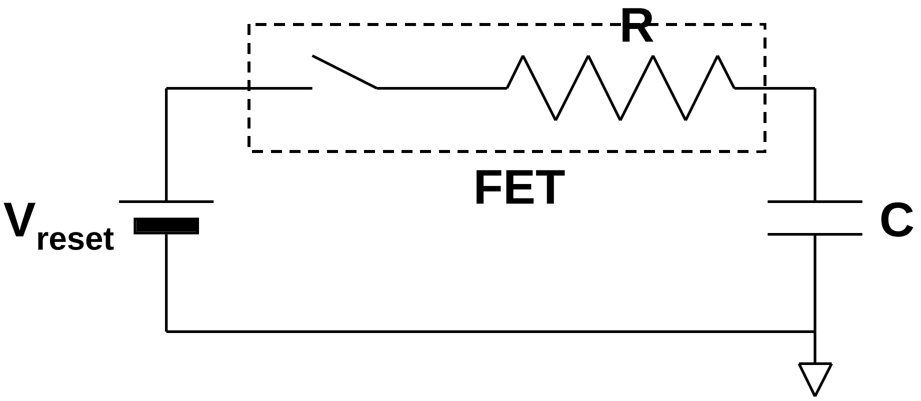
- **The reason for choosing this example is that it is directly applicable to the resetting of photodiodes and the output nodes of CCD and photogate pixels**

Reset Noise

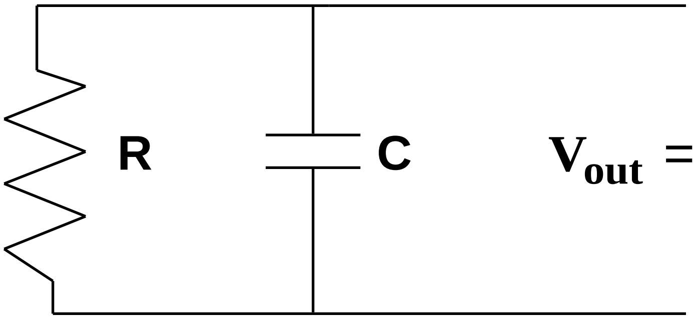
- If we consider a diffusion (either a floating diffusion or a photodiode) being reset through a MOSFET



- Effectively, this is a capacitance being charged through the resistance of the MOSFET channel



- So the ac-equivalent circuit is



$$V_{out} = \sqrt{4kTBR}$$

- **From before, the bandwidth is**

$$B = \frac{\pi}{2} f_0 = \frac{1}{4RC}$$

- **So we find the rms noise voltage**

$$\langle v_{out} \rangle = \sqrt{\frac{kT}{C}}$$

- **Usually, the noise voltages is expressed in terms of electrons, in order to compare directly with the electrons in the well**
- **In which case the reset noise on the capacitor is calculated from Q = nq = Cv_{out}, and the rms noise electrons is given by**

$$\langle n_e \rangle = \frac{C}{q}\sqrt{\frac{kT}{C}} = \frac{\sqrt{kTC}}{q}$$

- **This noise is generally called “kTC noise” or, in this case, reset noise**
- **Calculating this out at room temperature gives**

$$\langle n_{kTC,RT} \rangle = 400\sqrt{C(pF)}$$

- **For a floating diffusion C ~ 20fF, so n_{kTC} = 55 e^-**
- **For a $(10\mu m)^2$ photodiode, C ~ 60pF, so n_{kTC} = 100 e^-**
  - » currently, reset noise limits the read noise in PDs

Shot Noise

- **Shot noise is another white noise that arises from the discrete nature of the electrons themselves**
  - » i.e. the random arrival of particles of charge
- **This is the result of the random generation of carriers**
  - » either by thermal generation within a depletion region (i.e. shot noise of the dark current)
  - » or by the random generation of photo-electrons, caused in turn by the random arrival of photons
- **The rms signal is given by**

$$\langle i \rangle = \sqrt{2qI_{dc}B}$$

- **If the noise statistical distribution is described by a Poisson distribution**
  - » the variance is equal to the mean
  - » so $<i^2> = i$
- **So, if electrons are generated with a current density, J_{dark},in a sensor of area, A, over an integration time, t_{int}, the shot noise variance is**

$$\langle n_{dark}^2 \rangle = n_{dark} = \frac{J_{dark}At_{int}}{q}$$

- **Similarly, the photo-electron shot noise variance is given by**

$$\langle n_{pe}^2 \rangle = n_{pe} = \eta I_0 A t_{int}$$

  - » where I_0 is the photon flux (photons/cm^{2}s) and η is the quantum efficiency

- **So the total rms shot noise contribution from the sensor is**

$$\langle n_{shot} \rangle = \sqrt{\langle n_{dark}^2 \rangle + \langle n_{pe}^2 \rangle} = \sqrt{n_{dark} + n_{pe}}$$

$$= \sqrt{\frac{J_{dark} A t_{int}}{q} + \eta I_0 A t_{int}}$$

- **For example, with**
  - » J_{dark} = 200nA/cm^2
  - » A = (10μm)^2
  - » t_{int} = 30ms
  - » $I_0 = 10^{13}$ photons/cm^{2}s
  - » and η = 0.5

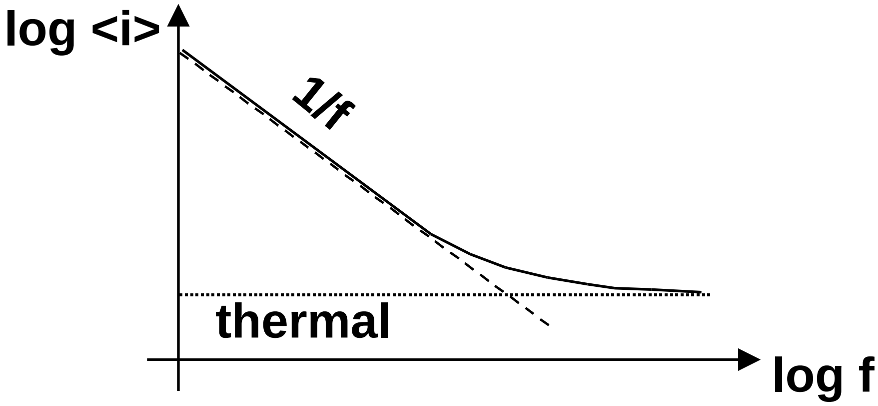
- **we find $\langle n_{shot} \rangle = \sqrt{(37{,}500_{dark} + 150{,}000_{pe})} = 430\ e^-$**

Flicker (1/f) Noise

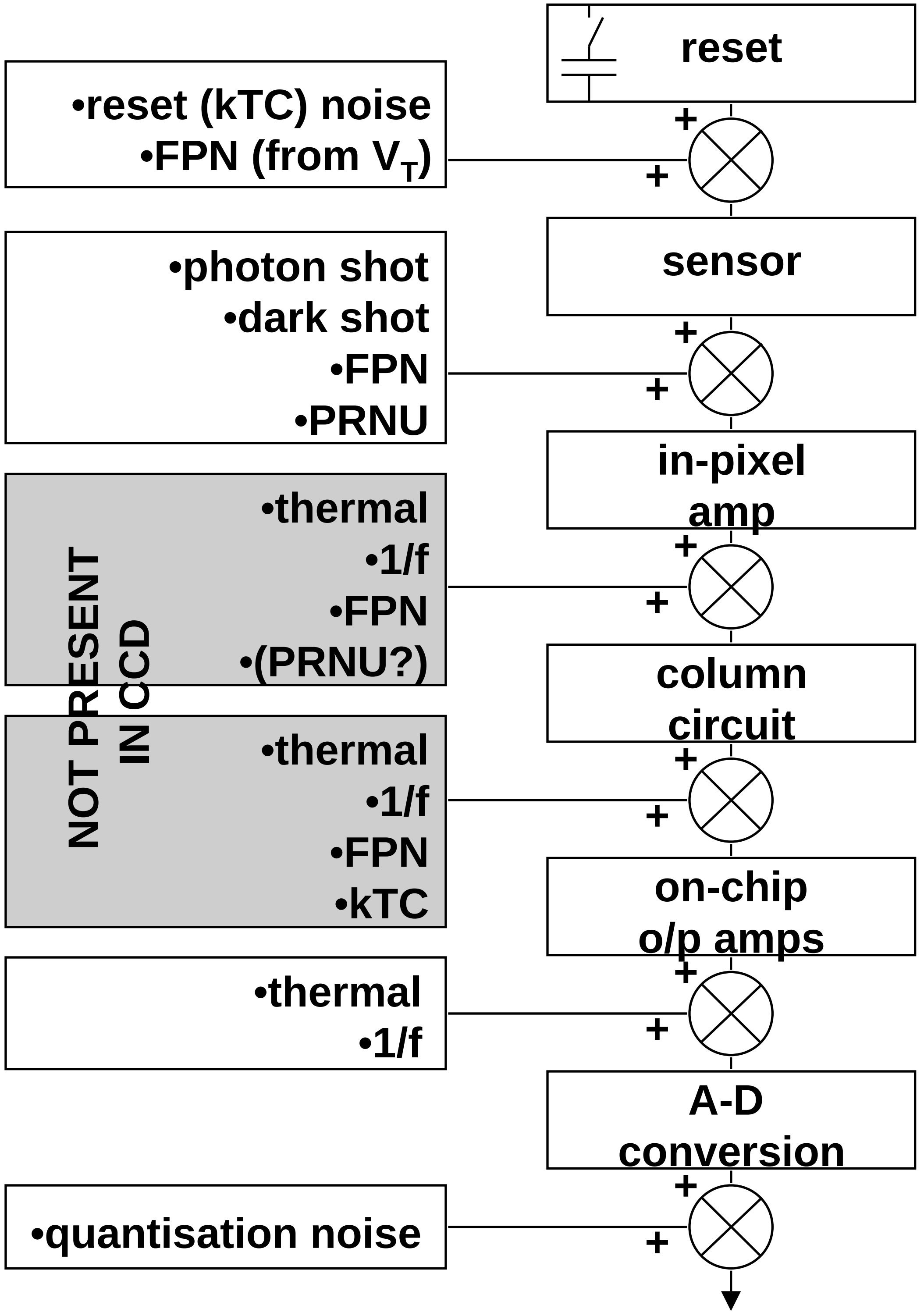
- **At any junction, including metal-to-metal, metal-to-semiconductor, and semiconductor-to-semiconductor, conductivity fluctuations occur**
  - » the causes of these are still not completely understood
- **The rms 1/f noise current is given by**

$$\langle \mathbf{i}_{1/f} \rangle \quad \mathbf{I}_{dc}\sqrt{\frac{\mathbf{B}}{\mathbf{f}}}$$

- **1/f noise arises mainly in amplifier circuits where there are numerous such contacts**
- **At low frequencies, 1/f noise can be the dominant component**
  - » but, at higher frequencies, the 1/f noise drops below the thermal noise
  - » the frequency at which this happens depends on the situation



Array Noise Components



reset

- reset (kTC) noise
- FPN (from V_T)

sensor

- photon shot
- dark shot
- FPN
- PRNU

in-pixel amp

- thermal
- 1/f
- FPN
- (PRNU?)

column circuit

- thermal
- 1/f
- FPN
- kTC

NOT PRESENT IN CCD

on-chip o/p amps

- thermal
- 1/f

A-D conversion

- quantisation noise

to noisy off-chip amps!

“Referred” Noise Figures

- **Conventionally, the noise figures are referred either to the final output or to the output of the optical detector**
  - » i.e. to be compared directly with the number of electrons generated by the detector
  - » called <u>input referred noise</u>
- **For input referred noise, the noise of later stages must be divided by the gains of the intermediate stages**
- **Or vice versa for output referred noise**
- **Usually, authors in CMOS circles use the input referred figure**
  - » but this is tough to obtain for intermediate stages in the circuit owing to uncertainties in the gains of each stage
  - » only the overall figure in electrons is practically feasible because the appropriate inverse-conversion efficiency (e^- per µV) is only known for the entire output circuit

Typical Noise Figures

- From Mendis, the calculated and measured input referred noises for a 128x128 element photogate array are

Noise source	Calculated rms	Measured rms
kTC from reset of FD	negligible	negligible
In-pixel amp. 1/f	111µV	
kTC from column sample & hold	93µV	
Column source follower 1/f	46µV	
Total column noise	86µV	120µV
Total noise	152µV	151µV
Total noise electrons	41 e^-	41 e^-

- Mendis also reported a photodiode read noise of ~80 e^- rms
- Typical read noises for CMOS sensors

Technology	RMS read noise
Photodiode APS	50 - 80 e^-
Photogate APS	20 - 40 e^-
Logarithmic APS	700 e^-
Passive pixels	200 - 300 e^-

- Remember that this does not include shot noise or pattern noise

Fixed Pattern Noise

- **Fixed Pattern Noise is due to pixel-to-pixel variations in the absence of illumination**
- **The main cause of FPN in CMOS imagers is variations in V_T**
  - » between reset and buffer MOSFETs in the pixel
  - » and between MOSFETs in the column circuits
- **FPN can also arise from repeating irregularities in the array clocking**
  - » allowing small variations in integration time etc.
- **In very large arrays, resistive drops in reset buses may lead to a “droop” in the voltage to which the pixels are reset,**
  - » but this is not usually significant in CMOS imagers
- **FPN is just as valid as a “noise” as the temporal variety**
  - » both affect the actual output voltage that the pixel produces
  - » in a way that is not directly related to the illumination to be measured

PRNU

- **The issue of photo-response non-uniformity has not historically received much attention in the CMOS imager community**
  - » although there is now some occasional mention of “gain nonuniformity”
- **Like FPN, PRNU is essentially time-independent, but it is signal-dependent**
- **Both types of pattern noise can be specified in terms of either an rms or a peak-to-peak value, referenced to an average value**
  - » e.g. the full-well capacity
- **A histogram of output signals is built up in the dark or light, as appropriate**
  - » PN_{rms} = rms of distribution / average value
  - » $PN_{p\text{-}p}$ = peak-to-peak variation / average value
- **Since PRNU is signal dependent, it is often expressed as a multiplier of the number of photons**
  - » $\langle n_{PRNU} \rangle = U n_{pe}$

Minimum Noise

- **In principle, the noise floor and dark current can be reduced so that the system is photon shot noise limited**

$$\langle \mathbf{n_{sys}} \rangle = \langle \mathbf{n_{pe}} \rangle = \sqrt{\mathbf{n_{pe}}}$$

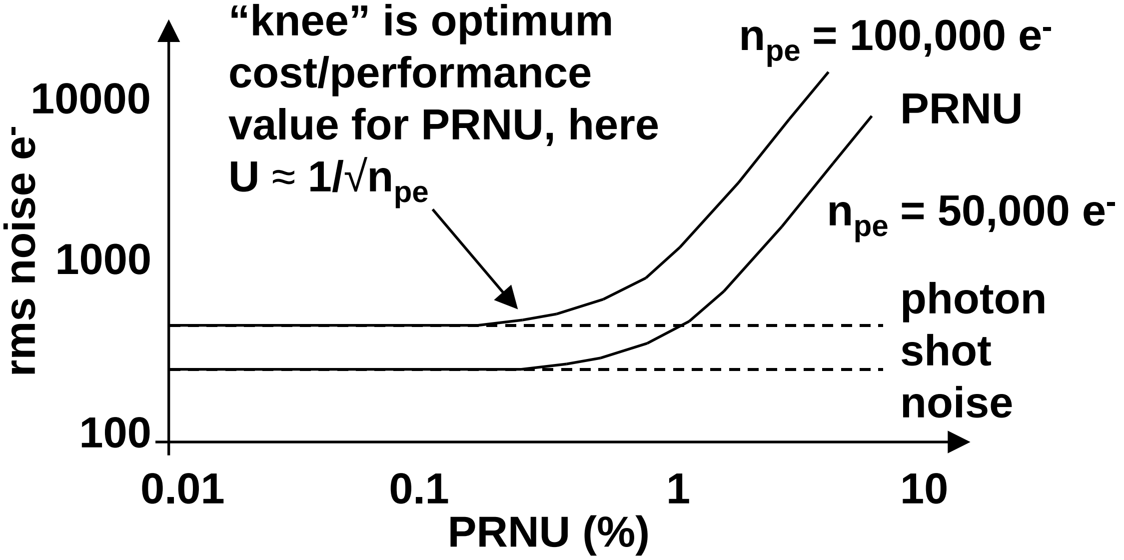
  - » this approximation is sometimes used to calculate the pixel sensitivity (µV/e^-)

- **But there will never be zero PRNU, so a more achievable value would be**

$$\langle \mathbf{n_{sys}} \rangle = \sqrt{\mathbf{n_{pe}} + \left(\mathbf{U n_{pe}}\right)^2}$$

  - » The worst case when $n_{pe} = n_{full\text{-}well}$

- **If we plot out this limiting noise as a function of PRNU, it looks like**



Noise Reduction Techniques

- **Having seen some of the common sources of noise in CMOS imaging systems, how might we go about reducing them?**
- **Essentially, there are three classes of noise**
  - » those we can do nothing about, such as photon shot noise
  - » those we can reduce by careful design of circuit components, such as thermal noise
  - » those we can reduce by circuit design, such as FPN
- **These techniques are inter-dependent**
  - » we shall see that adding extra circuitry to reduce FPN also introduces extra 1/f and kTC noise
  - » so the optimisation of noise is a system issue, not just a question of optimising each element individually
- **We will look at the general techniques for reducing noise in electronic devices, as well as circuit techniques for pattern noise etc**
- **The study of noise is a specialised topic, and we will only look at the essentials**

Shot Noise

- **As we remarked earlier, photon shot noise is dependent on the illumination level, and there is not much we can do about it**
  - » except reduce the QE of the detector, which we don't want to do!
- **Shot noise also arises from the pixel dark current**
  - » which we ***can*** alter
- **By changing doping levels, we can reduce the dark current**
  - » but, in a regular photodiode, at the expense of QE
- **And by removing the collection area away from the surface**
  - » this is another advantage of the pinned photodiode
- **The magnitude of the dark current is, of course, dependent on the pixel area**
  - » so the shot noise will be smaller for smaller pixels
  - » although the perimeter component of the dark current means that S/N still gets worse as pixel dimensions are reduced
- **But shot noise is not usually the limiting factor**

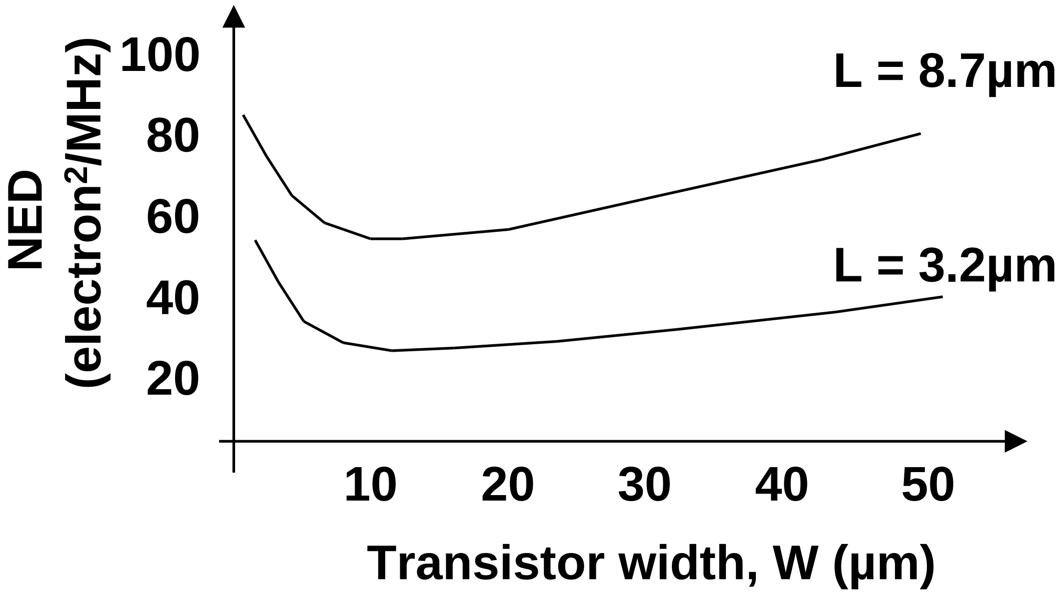
Thermal Noise

- **Thermal noise is important mainly in the input stages of amplifiers**
  - because of the √(4kTB$R_{channel}$) from the MOSFETs
- **In general, the power spectrum of the thermal noise will be proportional to (W/L)$^{-1}$**
- **But it is also dependent on the current through the devices**
- **A common way of expressing thermal noise is the noise electron density (NED)**

$$\mathbf{NED(f)} = \left[\frac{\mathbf{e_n(f)C_t}}{\mathbf{q}}\right]^2$$

  - where $e_n(f)$ is the total equivalent noise voltage at the output stage (e.g. a floating diffusion)
  - and C_t is the total capacitance present at the input, including diffusion capacitance, gate capacitance, and everything else (to convert to electrons)
- **$e_n(f)$ represents the device noise, referred to the input**
  - and so includes all factors such as the transistor geometry, i_{DS}, device area etc. that affect the gain

- **NED, expressed in electrons^2/Hz, is sketched below for a bias current of 100μA**



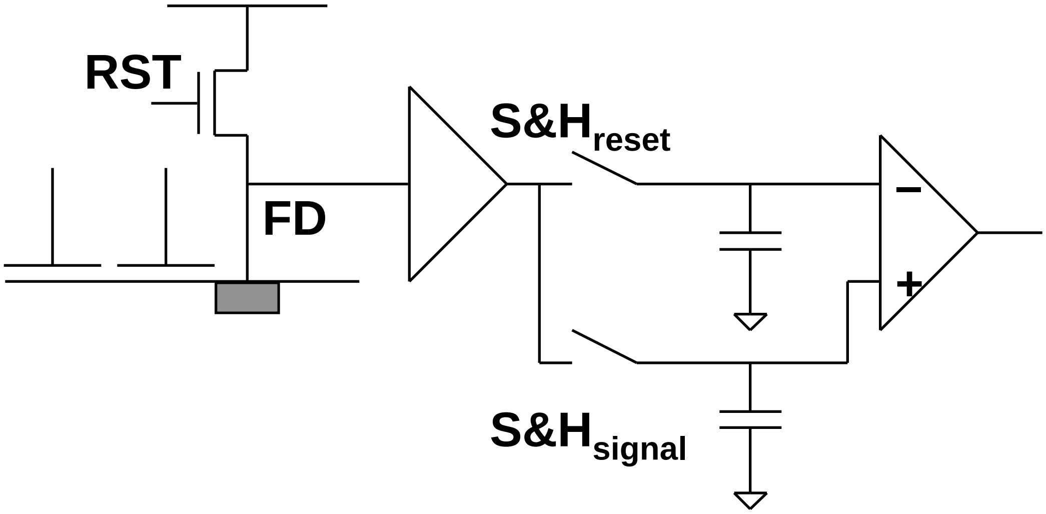
- **Increasing W, for a fixed L, increases C_t because of the device area**
- **But increased W decreases $e_n(f)$**
  - » because the current i_{DS}, and the gain of the circuit, are increased
  - » therefore reducing the input referred noise
- **So the optimum condition is to keep W ≈ 15μm in these transistors**
  - » too small a W reduces the gain
  - » and too large a W increases the C
- **Also the NED decreases with L, which makes smaller devices advantageous**

1/f Noise

- **1/f noise arises mainly from trapping de-trapping of electrons at the Si-SiO$_2$ interface**
- **So we can do two things to minimise 1/f noise**
  - » reduce the device area, W x L
  - » use a buried channel device to separate the channel from the interface
- **While in standard CMOS we cannot do much about the second option, we could reduce W x L**
  - » but the gain of the amplifier is dependent on W/L
  - » so reducing L is the best choice!
- **In the pixel, this is a good thing since we want to minimise the areas of the transistors anyway, to achieve a high fill factor**
  - » although care is needed to ensure that the pixel source follower can adequately drive the column capacitance (i.e. enough W/L)
- **Note that we need the noise added at early stages of the process to be minimised**
  - » since this is amplified at all subsequent stages

Correlated Double Sampling

- **Reset noise is difficult to design out of the system**
  - » since the properties of the transistor cancel out
  - » although reducing the capacitance of the node is useful for both kTC and conversion efficiency
- **So the most common solution is to measure the value of the reset noise and then to subtract it from the signal**
- **A generic circuit for achieving this in a CCD or floating gate APS would be**



- **During the sample and hold period, the appropriate switches are pulsed on & off**
  - » to leave the voltages stored on the capacitors

- **The sequence of events for a CCD or photogate would be**

Reset pixel

Sample & hold value of reset signal
(charge = reset)

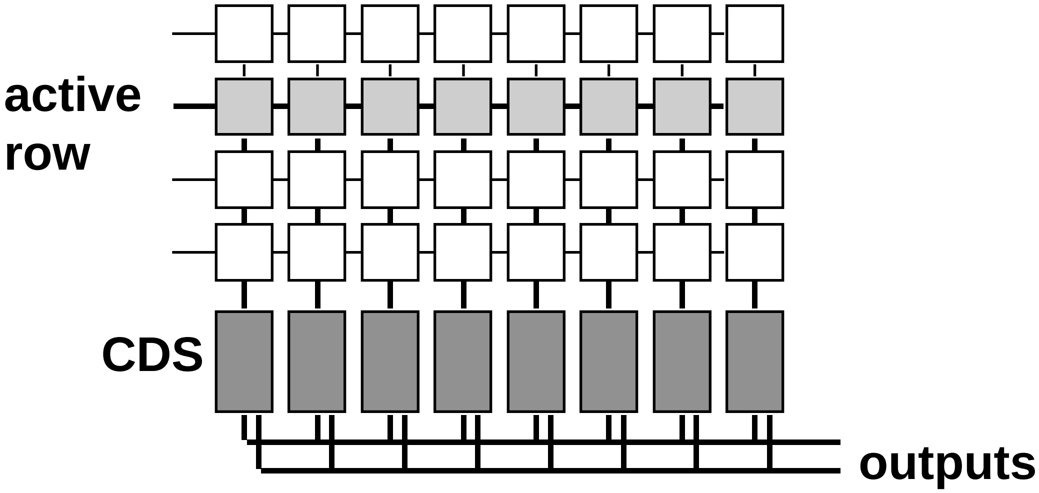
Transfer signal charge
(charge = signal + reset)

Sample & hold signal charge

Subtract two stored values
output = (signal + reset) - (reset) = signal

- **Here, the reset signal is given by**
  - » $V_{reset} = [V_{DD} - (V_T \pm \Delta V_T)] \pm (V_{kTC}) \pm (V_{part})$
- **Here the ΔV_T is the component of FPN arising from mismatches between the reset transistors**
  - » and is approximately the same for each frame
- **V_{kTC} is the reset noise**
  - » and is different from frame to frame
- **Note that we are considering voltages (not electrons) at this stage**
  - » so the “kTC” noise is given by $\sqrt{(kT/C)}$, and is therefore reduced for larger C

- **V_{part} refers to what is called the partition noise**
  - » when the reset FET turns off, the channel charge moves either to the source (= FD) or to the drain
  - » but we do not know exactly how much goes to each
- **This type of sample-and-hold technique is known as correlated double sampling (CDS)**
- **The “correlated” part comes about because the noise component of the two signals is correlated, and can therefore be subtracted out**
- **In a CCD, a single CDS circuit is needed because there is only one floating diffusion output node**
- **In CMOS APS, there is an output node per pixel**
  - » but practically, we need only one CDS circuit per column of the array
  - » and the S&H is carried out for all columns in parallel



CDS for Photodiode APS

- **This form of CDS works very well for pixels with a floating diffusion output node**
  - photogate, and pinned photodiode with transfer gate
- **Indeed, the main advantage of using the photogate structure is to facilitate the removal of reset noise**
  - since the improvement in conversion efficiency is offset by the lower QE
- **In photodiode designs, double sampling can only remove the FPN that results from mismatches**
  - this is because the double sampling is not correlated
- **In FD designs, the signal was added to the existing (and stored) reset value**
  - so the subtraction was of exactly the same noise signals
- **In the photodiode, there is no separate output node, so the signal must be read out first**
  - and this signal includes the original reset voltage on the photodiode
  - which in turn includes FPN and kTC noise

- **We can now reset the pixel again and subtract this value**
  - » the FPN will be much the same as that which was included when we sampled the signal
  - » but the kTC noise will be different, i.e. not correlated
  - » remember kTC is the rms value of a distribution
- **So now the sequence of events is**

Sample & hold signal value
charge = new signal + old reset value

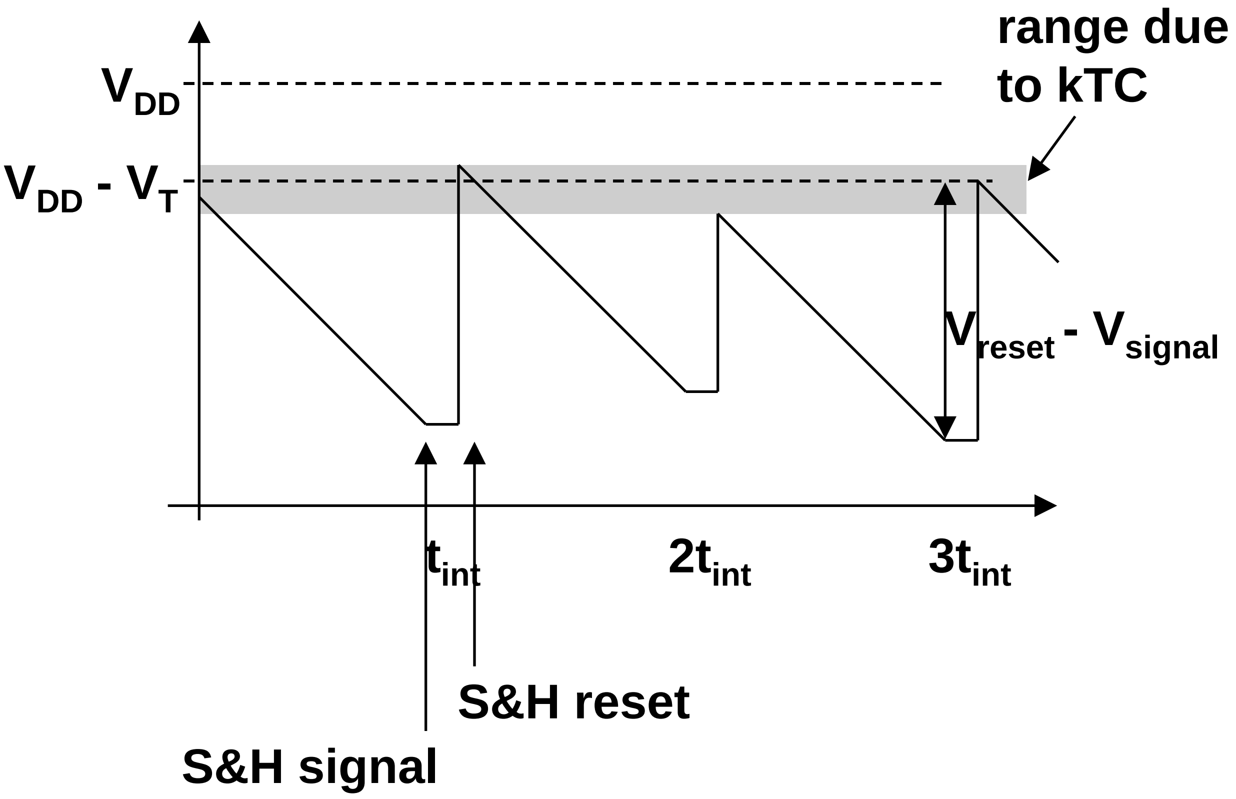
Reset pixel

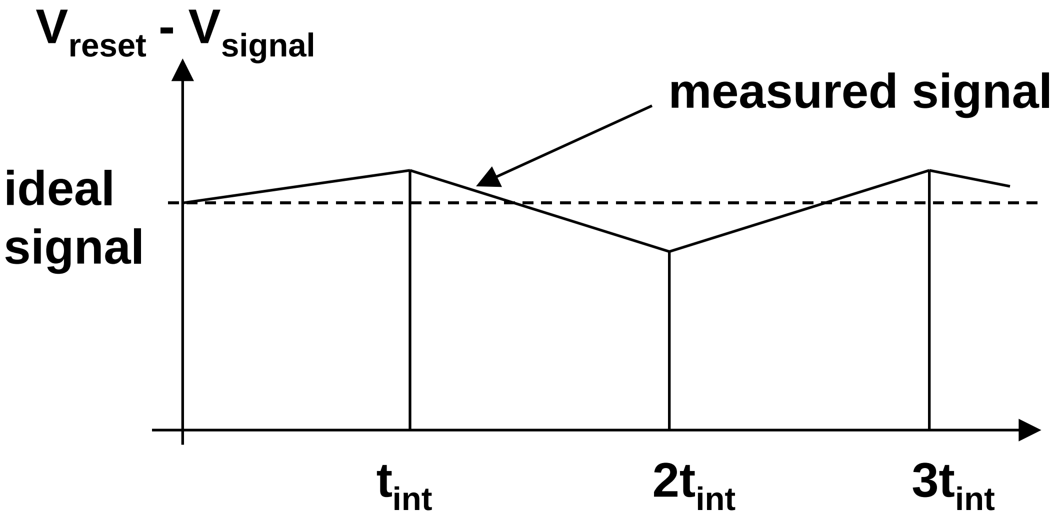
Sample & hold reset value
charge = new reset value

Subtract two values
output = (new signal + old reset) - new reset

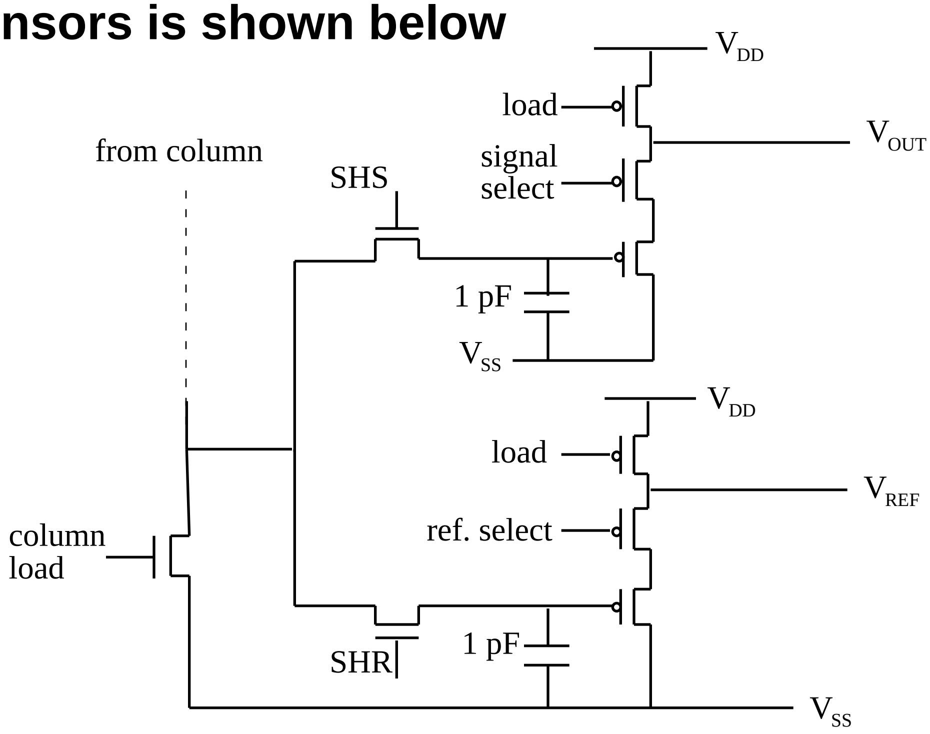
- **This would be better termed pixel double sampling**
- **Or, alternatively, a graphical representation is as follows ...**

- **For example, if we read out a single pixel over several integration periods**
  - » assuming constant illumination (I.e. slopes parallel)





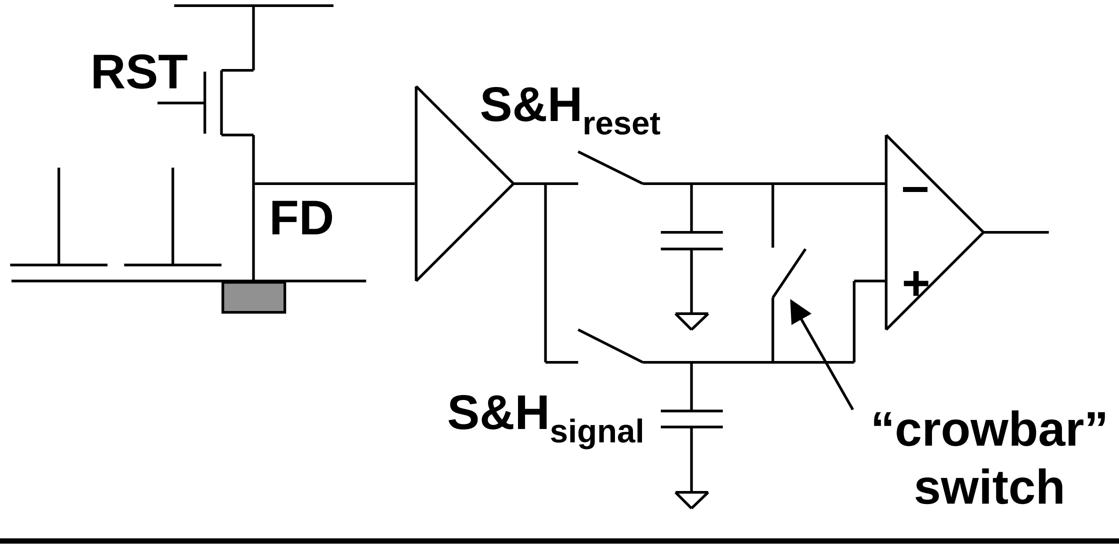
- **This is the reason why reset noise is now the limiting noise source in photodiode circuits**
- **Note that even this noise reduction is unavailable to the logarithmic pixels, hence their poor FPN characteristics**
- **The conventional CDS circuit used in CMOS sensors is shown below**



- **Of course, the additional circuitry required for the CDS implementation adds further noise to the signal**
  - » kTC from the sample-and-hold capacitors
  - » 1/f and thermal noise from the transistors
- **But usually in CMOS sensors, the FPN is the more critical issue**

Column FPN

- **The other issue with using column-wise CDS is that FPN is then added by the CDS circuits themselves**
  - » appearing as vertical streaks in the image
- **This can be removed by storing and subtracting column reference signals off chip**
- **Alternatively a second stage of double sampling is performed**
  - » where, after the readout of the differential signal, the S&H capacitors are shorted together
  - » this results in a differential output that is a measure of the mismatches between the two sets of output stages
  - » Mendis calls this a "crowbar" circuit and the process <u>delta difference sampling</u>

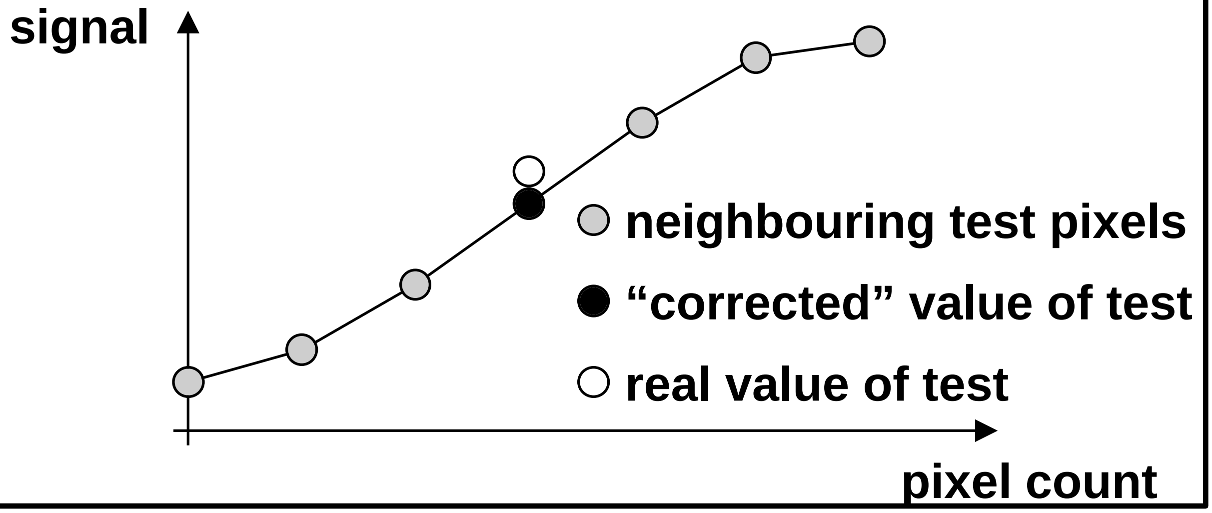


Typical Figures

- **Typical figures for FPN are hard to define because it depends so much on the precise process used**
- **For photogates with a 2µm CMOS process, Mendis reported a p-p FPN of 1% – 2.5% saturation with the CDS circuit**
  - » falling to ~0.1% sat. with the DDS as well
- **A photodiode fabricated similarly showed a p-p FPN of ~0.5% sat. after CDS, and ~0.1% after CDS + DDS**
  - » typical raw data are about 2 - 3% p-p sat.
- **For a 0.35µm process, the raw FPN for a PG array was 6% sat.**
  - » reducing to 0.4% after off-chip correction
- **Mansoorian et al. give a final FPN of 0.6% sat. p-p for both PG and PD using a 0.55µm process**
  - » using a similar DDS technique
- **For logarithmic pixels, IMEC report a raw FPN of ~100% of the useable signal range!**

Patent Issues

- **Other methods of reducing noise are possible, although probably not so good**
- **Hitachi have several patents which cover the idea of active pixel sensors and the use of CDS in these devices**
  - » in their CMOS digital still camera, VLSI Vision use a mechanical shutter in order to measure a true dark image for subsequent subtraction
- **One possibility is to smooth out large signal variations between neighbouring pixels**
  - » a smooth curve is fitted through points either side of the test point, and the test point moved to fit that curve
  - » the smoothing is improved if the number of neighbours is increased, but the “sharpness” of the image is lowered



Feedthrough & Crosstalk

- **We have considered here “natural” sources of noise such as 1/f, thermal, and shot noise**
- **And technological noise, such as FPN and PRNU**
- **In addition to these, there can be unwanted signals in one part of the circuit due to the operation of another part**
  - » these can be addressed in the design of the array and circuits
  - » although some sources are not easy to eliminated
- **Feedthrough of digital signals from control lines into the analog parts of the circuit can be a problem**
  - » analog and digital sections of the chip can be separated to some extent
  - » but the array itself, and much of the analog signal processing is intrinsically both analog and digital
- **The minimisation of these effects requires careful layout**
  - » and mixed signal design is currently a hot topic in many areas, such as A-D & D-A conversion, DSP etc.

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