Characterization of building block imagers with respect to linear dynamic range.

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Abstract

CCD imagers from the mK×nK building block family have been characterized with respect to linear dynamic range, which is defined as the ratio of the maximum linear response and the total noise. A very good linear response has been found, up to 400 kel, by using a 3-level clocking scheme. For the 3K×2K full-frame sensor this results in a linear dynamic range of 14,400 at an optimal read-out frequency of 7.2 MHz and a chip temperature of 35 °C. The pixel to pixel non-uniformity of the linear dynamic range is estimated by the random non-uniformity as determined from a homogenous nominal illuminated image.

Introduction

The dynamic range of a solid-state image sensor is one of the main characteristics if the device is used in (professional) digital still photography. The dynamic range (DR) should give the user an idea of the range in output voltage which is available in the application compared to the noise floor. In this paper DR is defined as the ratio of the maximum charge handling capability (Q_{max}) and the noise (read-out noise and shot noise on dark current).

In the case of a colour imager with on-chip colour filters the sensor is preferably used in the linear range since non-linear response will lead to colour artefacts or to complex image processing. Therefore it is useful to specify, in addition to DR, the linear dynamic range (LDR). The linearity of the imagers is characterized by Q_{lin}, the number of electrons at which during integration the collected charge starts to deviate more than 1% from linear. The linear dynamic range (LDR) is defined as the ratio of Q_{lin} and the total noise.

This paper focuses on the characterization of mK×nK building block CCD imagers [1] with respect to the linear dynamic range. The building block imagers have 12μm × 12μm pixels with four non-overlapping gates and a vertical anti-blooming structure. Measurements have been performed at a 3K×2K full-frame sensor (FTF3020) and an 1K×1K frame-transfer sensor (FTT1010).

The dynamic range is very much depending on various parameters which have to do with the driving of the CCD. We will focus on:

- the clocking scheme for optimization of the saturation level,
- the read-out frequency for optimization of the linear dynamic range at different temperatures.

The light sensitivity (kel/lux·sec), Q_{lin} and Q_{max} (kel) of the imagers are determined from measurements of the sensor output current (reset-drain current) for different integration times at constant homogenous illumination.

Besides the linear dynamic range, the uniformity of this quantity over the sensor is of great importance too. In this work we will present a description of the distribution of Q as function of illumination which covers the full range, $0 < Q(L) < Q_{max}$.

Saturation level

In a four-phase pixel with two-level clocking (e.g. between 0 V and 10 V) the charge is collected under three gates which are biased to a high voltage (10 V), while during vertical transport the charge is periodically stored under two gates. Therefore, the maximum charge handling capability (Q_{max}) is limited by the capacity of two biased gates.

An increase of Q_{max} can be realized by increasing the clock swing on the image and storage gates. However, this will cause an increase of dark current (Idark) and fixed pattern noise (FPN) due to an increase of the electric field between the gates and the p^+ channel stops. E.g. an 70% increase in dark current is measured going from 10 V to 15 V gate voltage [2].

To minimize the increase in dark current we have introduced a three-level clocking scheme. With this method the clock swing is only increased during vertical transport, while during integration and storage the high level remains 10 V.

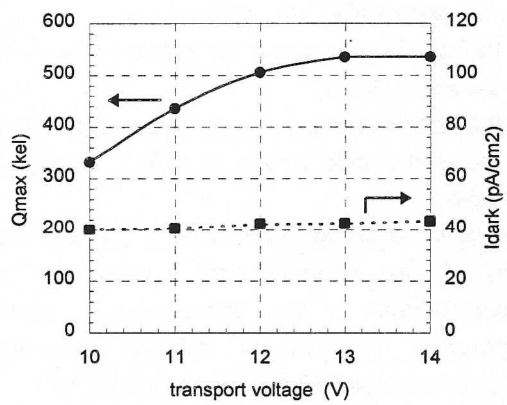

Figure 1. Measurements of Q_{max} (dots) and dark current (squares) of a 3K×2K full-frame imager versus the clock swing during transport with integration under three gates at 10 V. Dark current is measured at 35 °C.

Figure 1 shows a 60% increase in Q_{max} by increasing clock swing for transport from 10 to 14 V. The dark current remains almost constant.

Another big advantage of this three-level clocking can be seen in figure 2, where the output signal of a single line from a saturated image is shown for two different clocking conditions. With two level clocking (dotted line) saturation gives rise to the so called "bathtub effect". This effect is a consequence of the reduced clock swing in the middle of a line during transport due to the RC-time of the long poly gates. As can be seen in figure 1, an increase of the transport voltage from 13 to 14 V does not result in a further increase of Q_{max}. This means that Q_{max} is no longer limited by vertical transport and the bathtub effect has disappeared (solid line in figure 2).

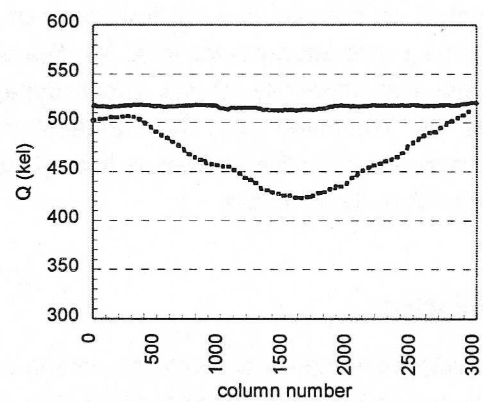

Figure 2. Output signal of a single line from a saturated image as observed by transport at 11 V (dotted line) and 14 V (solid line).

Using the three-level clocking not only results in a high Q_{max} but also a very good linear response is found, up to Q_{lin} = 400 kel for the 1K×1K frame-transfer sensor.

Linear dynamic range

In general the device noise spectrum *N(f)* consists of a thermal and the 1/f portion of the on-chip output amplifier and the shot noise of the dark current. In most full frame, mK×nK, imager applications the integration time is much smaller than the read-out time. Neglecting the integration time, a simple relation can be found for the optimal read-out frequency at which the maximum linear dynamic range (LDR) is reached.

N(f) can be described as [3]:

$$N^2(f,T) =$$

(1) $$C_1(T) \cdot \left(1 + \left(\frac{f_c}{f}\right)^{\gamma}\right) \cdot f + C_2(T) \cdot \frac{m \cdot n}{f}$$

with f the pixel read-out frequency, f_c the cross-over frequency of 1/f and thermal noise, γ the exponent of the 1/f noise, $m{\cdot}n$ the size of the imager (in number of K-blocks). The first two terms of the equation represent the amplifier noise (thermal and 1/f) and the last term is the dark current. The constants C_1 and C_2 are both a function of temperature. C_1 is proportional to the absolute temperature while C_2 is an exponential function of temperature. The temperature behaviour of C_1 is weak and therefore neglected in this analysis.

For γ=1 a simple analytical solution is found for the optimal read-out frequency.

(2) $$f_{opt} = \sqrt{\frac{m \cdot n \cdot C_2(T)}{C_1}}$$

At this frequency *N(f)* has its minimum and so the LDR will have its maximum value.

As an example, figure 3 shows the LDR of a 3K×2K full-frame imager as a function of the read-out frequency for different temperatures. The crosses indicate the optimal read-out frequency per temperature .

At a low read-out frequency the dynamic range decreases because of an increase in dark current and therefore an increase of the shot noise of the dark current. At high frequencies the dynamic range is determined by the amplifier noise. This value is proportional to C_1 and therefore nearly the same for the three curves. The optimal read-out frequency depends on the temperature as can be seen in equation 2.

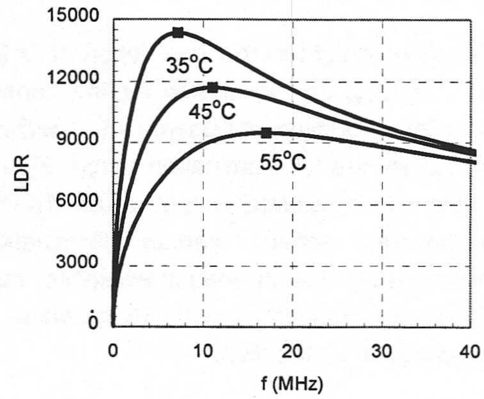

Figure 3. Linear dynamic range of a 3K×2K full-frame imager as a function of the read-out frequency for different temperatures. Squares indicate the optimal read-out frequency per temperature.

Non-uniformity

Besides the sensor characteristics as sensitivity and (linear) dynamic range, the pixel to pixel uniformity over the sensor of these quantities is of great importance too. Therefore, the possible deviation of a pixel from the mean sensitivity is specified by the random non-uniformity (RNU), which is determined from a homogenous nominal illuminated image by:

(3) $$RNU_{nom} = 100\% \cdot \frac{\sigma(HP)}{\mu(LP)}$$

where $\sigma(HP)$ is the standard deviation of the high pass filtered image and $\mu(LP)$ is the mean of the low pass filtered image. In the same way the non-uniformity of a saturated image can be defined (RNU_{max}). For the mK×nK building block imagers the non-uniformity is typical around 0.6% and 1.5% for RNU_{nom} and RNU_{max}, respectively.

From Q_{max} and RNU_{max} the mean dynamic range with standard deviation can be derived, with $DR=Q_{max}$/noise. Since Q_{lin} is defined as the point where Q starts to deviate from linear, its non-uniformity can be approximated by RNU_{nom}. The distribution of the linear dynamic range is calculated by $LDR=Q_{lin}$/noise.

To get more insight in the distribution of Q for $Q_{lin} < Q < Q_{max}$ an expression for the sensor output (Q) as function of illumination is derived which covers the full illumination range. Figure 4 shows the measured output of an 1K×1K frame-transfer sensor versus illumination (markers). Note that the measured sensor output (reset-drain current) is equal to the mean of the pixel output distribution.

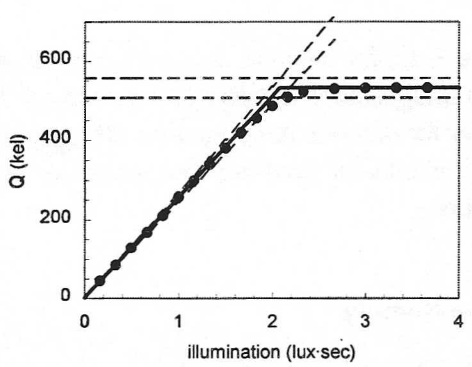

Figure 4. The measured response of a 1K×1K frame-transfer sensor shows a linear and a saturation domain (solid line). The sensitivity (S) and Q_{max} are statistically distributed; the dashed lines indicate the 3σ deviation limits.

A simplified relation of the output versus illumination shows the two different domains:

<u>linear domain</u>	$Q = S*L$, for $Q \le Q_{lin}$ and
<u>saturation domain</u>	$Q = Q_{max}$, for $Q > Q_{lin}$,

where L is the illumination and S the sensitivity (see e.g. ref. [4]). This is shown in figure 4 by the solid line. A better description is given by :

$$Q(L) = ((S \cdot L)^{-p} + Q_{max}^{-p})^{-1/p} \tag{4}$$

which smoothly links the linear and saturation domains and thereby covers the full illumination range (see figure 5). The parameter p defines the degree of bending and can be determined from the ratio of Q_{lin} and Q_{max}.
Based on equation 4 the pixel output distribution as function of L is estimated under the following assumptions:

- the sensitivity and Q_{max} are statistically distributed with standard deviations equal to RNU_{nom} and RNU_{max}, respectively.
- the illumination has no deviation which is a good approximation since shading is filtered out and the photon shot noise is small compared to the RNU.
- the deviations of S and Q_{max} are assumed to be independent. This is very likely because the deviation in the sensitivity is mainly due to small changes in the poly thickness, while the variance of Q_{max} is to a large extent caused by small changes in the doping profiles.

The calculation of the distribution of $Q(L)$ is simplified by the use of lognormal distributions which are a good approximation for the normal distributions for $\sigma/\mu < 0.1$ and can easy be calculated with a computer program like Mathematica.

In figure 5 the results of these calculations are shown together with the measurements. The input values for the model have been determined from these measurements, i.e. : Q_{max}=532 kel, Q_{lin}=405 kel, S=260 kel/lux·sec, RNU_{nom}=0.6% and RNU_{max}=1.5%. The mean of the distributions as calculated with the model fits the measurements very well over the whole range. The small decrease of sigma around L=1.5 lux·sec is due to the fact that by increasing illumination the pixels at the high Q side of the distribution starts to saturate first.

For $Q_{lin} \le Q(L) < Q_{max}$ the distribution is asymmetric with a tail to higher Q, which implies that the median < mean. For small values of RNU_{nom} and RNU_{max} this asymmetry is not very distinctly, e.g. for L=2 lux·sec we find: (mean – median) =13 e^-.

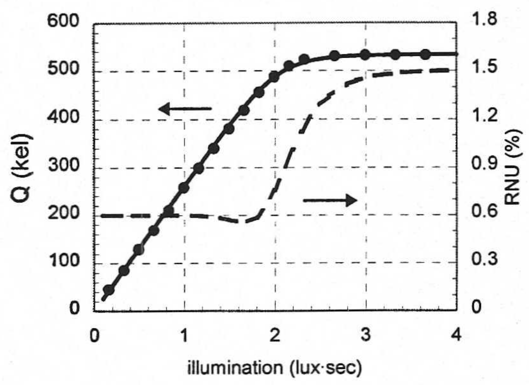

Figure 5. The measured response of a 1K×1K frame-transfer sensor (markers) can be described with an analytical expression (solid curve). The standard deviation of the distribution (dashed line) can be estimated under the assumption that the sensitivity (S) and Q_{max} are statistically distributed.

Conclusions

We have characterized the mK×nK building block family with respect to linear dynamic range. Using a three-level clocking scheme a linear response has been found up to 400 kel. Furthermore, due to the higher transport voltage the so called bathtub effect no longer appears in a saturated image. A simple relation has been found for the optimal read-out frequency at which the maximum linear dynamic range is reached. It is shown that the optimal read-out frequency increases with increasing temperature. The pixel to pixel non-uniformity of the linear dynamic range is estimated by the random non-uniformity as determined from a homogenous nominal illuminated image which is about 0.6%. The output distribution for $Q_{lin} < Q < Q_{max}$ is estimated using an expression for the output which links the linear and saturation domains.

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