Equivalent Noise Charge of Monolithic Active Pixel Sensors for use in charged particle detection

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***Abstract*—The Equivalent Noise Charge (ENC) of Monolithic Active Pixel Sensors has been determined using an analytical approach. The ENC is an important characteristic when these sensors are used for charged particle detection as it determines the Signal to Noise ratio. This paper gives the dominant contributions to the temporal noise as a function of an observation time directly related to the clocking frequency of the pixel array. Measured data made on MIMOSA8 array confirms the validity of the approach. In addition both theoretical computation and experimental data show that the residual ENC is of the order of 10 e- and can be further reduced.**

***Index Terms*—Equivalent Noise Charge (ENC), temporal noise, Monolithic Active Pixel Sensors (MAPS), charged particle detection, International Linear Collider.**

I. Introduction

Monolithic Active Pixel Sensors (MAPS) have been the subject of intense research over the past decade[1-4]. For charged particle detection, which is of dramatic importance in high-energy physics, the signal to noise ratio should be increased to a level compatible with the requirements such as high detection efficiency for minimum ionizing particles and fake events rejection. Computation of the equivalent noise charge (ENC) is necessary to specify which parameters are dominant in the residual noise level. In this paper we present an analytical approach which allows a literal expression of the ENC to be introduced.

II. Noise calculation

A. Front End

The schematic of the frontend used for the computation is given in Fig. 1. The capacitance at the output is due to the transistor that acts as a switch to output the signal onto the readout column line. We assume that permanent biasing of the readout transistor is not very different from the switch biasing that occurs in real MAPS pixels, so that the switch-on/switch-off noise is not taken into consideration. In this case we consider that the noise is observed during a duration T_{obs}, which is the time in the real case which separates two successive samples (called the observation time). No reset ever occurs during the observation time so that we can assume continuous operation is valid. As the detecting element is a partially depleted diode, its parallel noise must be considered whatever its origin (shot noise or parallel thermal noise). In addition, the channel thermal noise of the source-follower transistor contributes to the total noise.

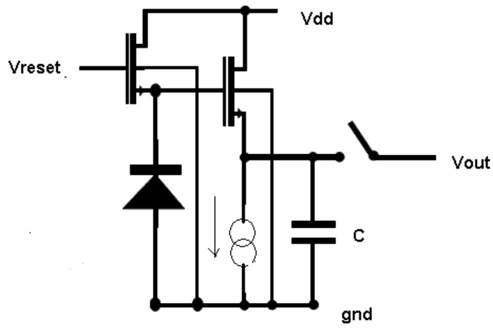

Fig. 1: schematic of the simplified pixel used for the analytical calculation of the noise. The signal is sampled through the output switch.

We will compute the two terms of the ENC using the Campbell theorem as the noise at the output of the readout circuit cannot be determined from the sole spectral densities. We can write:

$$ENC^2=ENC^2_{series}+ENC^2_{//} \quad (1)$$

B. Calculation

For the series noise which is due to the thermal noise of the channel:

$$<V^2_{out}>=2k\theta g_m (1+C_{gd}/C_{gs})^2/B^2 \int \exp(-2tg_mC_{gd}/BC_{gs})dt \quad (2)$$

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Where θ is the absolute temperature g_m the transconductance of the source follower, C_{gd} and C_{gs} the gate/drain and gate/source capacitance of the follower (including the sensing diode capacitance).k is the Boltzmann constant. The limits of the integral are 0 and T_{obs}, the observation time. B is given by:

$$B=C+ C_{gd} +C\, C_{gd}/C_{gs} \quad (3)$$

C represents the output capacitance, which is due to the load column strip connected at the source of the follower, or amplifying element. It may dominate the other capacitance terms.

We implemented the Campbell theorem by calculating the response of the circuit due to an channel current (i_c) impulse:

$$V_{out}/i_c=(1+ C_{gd}/C_{gs})/(Bs+ C_{gd}g_m/C_{gs}) \quad (4)$$ is the transfert function.

The relation between the output voltage and the deposited charge is straightforward, $Q=C_{gd}V_{out}$, so that the Equivalent Noise Charge is given by

$$ENC^2_{series}=<V^2_{out}>C_{gd}^2 =k\theta(1+C_{gd}/C_{gs})^2C_{gd}C_{gs}/B(1-\exp(-2T_{obs}g_mC_{gd}/BC_{gs})) \quad (5)$$

The parallel noise results from a similar calculation and leads to:

$$<V^2_{out}>=2qI_{leak}T_{obs}/C_{gd}+(1-\exp(-2g_mC_{gd}T_{obs}/A))\, qI_{leak}\beta^2/(g_mAC_{gd}) \quad (6)$$

Where: $A=BC_{gs}$ **(7)** and $\beta=C_{gs}-A/C_{gd}$ **(8)**

Therefore, the ENC is given by:

$$ENC^2_{//}=<V^2_{out}>C_{gd}^2=2qI_{leak}T_{obs}C_{gd} + (1-\exp (-2g_mC_{gd}T_{obs}/A))\, xC_{gd}qI_{leak}\beta^2/(g_mA) \quad (9)$$

We have obtained the two dominant noise terms. In addition the 1/f noise term can be estimated. First order approximation gives:

$$<V^2_{out}>=T_{obs}(1+C_{gd}/C_{gs})^2\pi A_\omega/4\alpha B^2 \quad (10)$$

where: $\alpha = g_mC_{gd}/(BC_{gs})$ is a cut-off frequency. **(11)**

Relation (10) is valid when αT_{obs} is much greater than 1.

$$ENC^2_{1/f} = T_{obs}C_{gd}^2(1+C_{gd}/C_{gs})^2\pi A_\omega/4\alpha B^2 \quad (12)$$

The ENC due to 1/f noise is negligible compared to the thermal noise when the noise corner frequency is higher than $1/T_{obs}$: $f_{corner} < 1/T_{obs}$ which is often the case when T_{obs} is greater than a few µs. This is true at moderate to high speed operating conditions. At low speeds, it varies proportionally to the observation time.

From these calculations, it may be deduced that the ENC squared varies linearly with the observation time at high observation times (or at low operating frequencies); this is due to the parallel noise first term and the 1/f noise contribution. At higher operating frequencies, the ENC reaches a plateau until the cut off frequency α is overtaken, above which the ENC should vanish. Fig 2 summarizes the behavior.

For instance if we take $B= 10^{-12}$ F; $g_m=10^{-5}$ A/V; $C_{gd}= 10^{-15}$F; $C_{gs}= 10^{-15}$ F this leads to: $\alpha = 10^7$ Hz.

In MAPS the clocking frequency determines the duration between which pixels are read-out. The observation time should then be inversely proportional to the clocking frequency. In expressions, (5) and (9) the last terms are independent of observation time and reasonable orders of magnitude show that the series noise is dominant at moderate clocking frequencies. The series thermal noise is dominant as long as the C (the output capacitance) << $16x10^3\, C_{gs}$, which is a valid assumption. In this case, the series noise equals:

$$ENC^2_{series}=<V^2_{out}>C_{gd}^2=k\theta(1+C_{gd}/C_{gs})^2C_{gd}C_{gs}/B \quad (13)$$

$ENC^2_{series}=1.65x10^{-50}/B$ with the previous values this leads to:

$$ENC_{series} =1.28x10^{-25}/B^{0.5},\ ENC_{series}\ (e) =8x10^{-7}/B^{0.5} \quad (14)$$

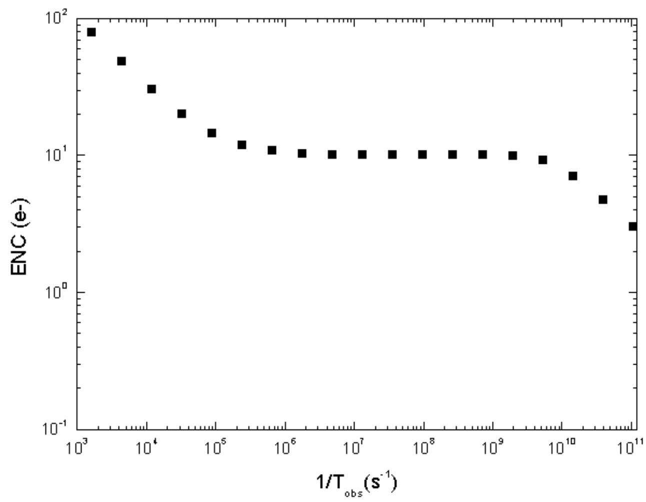


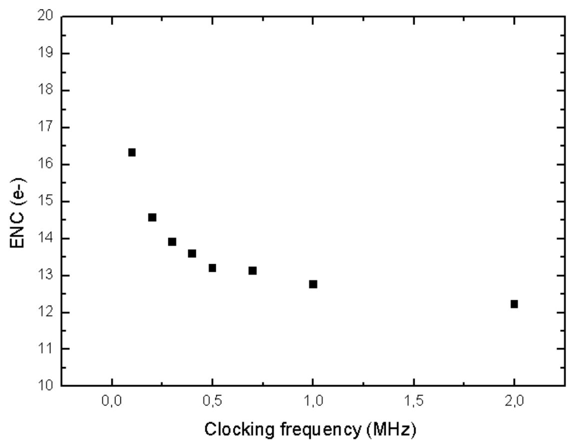
Fig 2. : ENC versus reverse of the observation time, a plateau is reached above a value, which experimentally corresponds to a relatively low clocking frequency.

III. Noise measurements

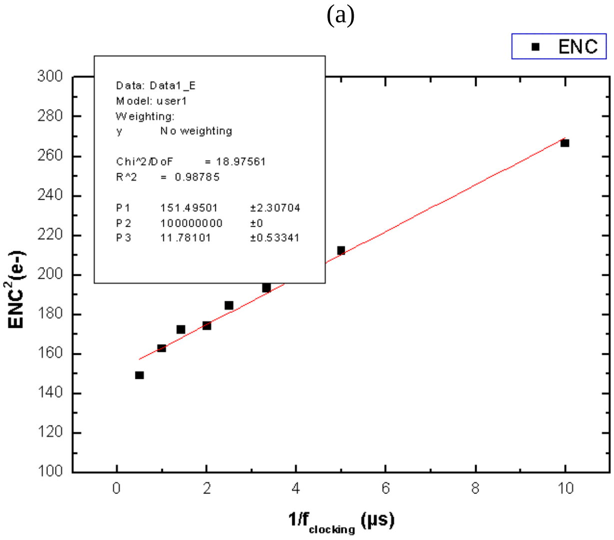
In practice, the MIMOSA8 pixel array was used for noise measurements. It differs from the classic 3T scheme by the fact that a voltage gain stage is introduced. This voltage gain stage only adds a contribution to the series noise, that can be reduced to a similar term as (13).The treatment should give similar results and differ only slightly from the original expression. The contribution of the detecting element to the noise is identical. The schematic of the pixel readout circuitry can be found in [5]. The clocking frequency determines the time between successive readouts. $T\sim A/f_{clocking}$. Experimental results of measured Noise Equivalent Charge are represented in Fig. 3. It is clear that the ENC increases at low clocking frequencies. A fit of the measured data is made with the expression:

$$\mathbf{ENC^2 = K_1(1\text{-}exp(\text{-}K/f)) + K_2/f = K_1\ (1\text{-}exp(\text{-}KT)) + K_2{}'T}\ ,$$

this leads to K_1 =152, K_2=12 , K is difficult to determine from the fit, but a high value can be assumed to obtain a satisfactory fit.



(a)



(b)

Fig 3. : Experimental ENC measured on the MIMOSA8 array (a), with the corresponding fit (b).At higher clocking frequencies the ENC levels off.

One can easily see that the expression gives a good fit to the experimental results, especially at low clocking frequencies. This proves that the assumptions leading to the ENC expressions described here are valid. The low frequency contribution to the ENC is due to the parallel noise and the low frequency flicker noise, although their respective contributions cannot be estimated through this simple fitting procedure. When the plateau is reached the residual noise equivalent charge is approximately ~ 12 e- which is consistent with the series noise magnitude (13). $ENC^2 = K_1$ when f is sufficiently high, sqrt (K1) i.e. 12 e- .From expression (14) it may be deduced that $B\sim(8x10^{-7}/12)^2$ =$4.4x10^{-15}$ F which is very reasonable. Moreover the results obtained on MIMOSA15 and further [3] are consistent with our approach. The results are also consistent with the temporal noise measurements made in [3].

IV. Conclusions

The Equivalent Noise Charge of Active Pixel Sensors has been treated both theoretically and experimentally. A good fit is obtained between the prediction and the experimental data. They show that ENC only increase at very low clocking frequencies that are not to be used in arrays implemented for charged particle detection. In addition, the residual temporal noise estimated at medium clocking frequencies could be scaled down and go below 10 e- using smaller design features.

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