Solid-State Electronics 114 (2015) 111–114

Contents lists available at ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

Letter

Random telegraph signal transients in active logarithmic continuous-time vision sensors

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ARTICLE INFO

Article history:
Received 23 May 2015
Received in revised form 24 August 2015
Accepted 25 August 2015
Available online 11 September 2015

Keywords:
Random telegraph signal
Address event representation
Selective change driven vision
Logarithmic pixel

ABSTRACT

Random Telegraph Signal (RTS) is a well-known source of noise in current submicron circuits. Its static effects have been widely studied and its noise levels are in the order of other noise sources, especially for moderate submicron transistors. Nevertheless, RTS events may produce transients many times larger than the RTS itself, and this problem seems to have not yet been addressed. In this article we present results on the transients produced by RTS events in a smart vision sensor. RTS transients in closed-loop amplifiers can be many times greater than static RTS. The duration of the RTS transient may last for several milliseconds, and can be considered almost stationary for some conditions. The RTS transient effect has been modelled, and its impact on event-based vision sensors has been studied. This analysis may be also useful for many circuits based on closed-loop amplifiers. Some hints on how to reduce RTS transient effects on these sensors are also given, which may help with the design of current and future event-based vision sensors.

1. Introduction

Random Telegraph Signal (RTS) is caused by the trapping/un-trapping of a single carrier at the interface between the Silicon and the Oxide in any MOS transistor gate. This signal is the main component of $1/f$ noise in CMOS circuits. In current submicron technologies, it is possible to find transistors with very few traps in the gate, or even just one, which allows the study of single charge trapping effects.

The consequence of a single charge being trapped (captured) or un-trapped (emitted) is a change in the transistor threshold voltage [1]. The threshold voltage variation amplitude ΔV_{th} follows a log-normal distribution [2] with median at:

$$\Delta V_{th} = \Delta V_{RTS} = \frac{q}{C_{ox}WL} \quad (1)$$

where ΔV_{RTS} is the RTS amplitude, q is the elementary charge, C_{ox} is the dielectric capacitance per unit area, and W and L are the effective transistor gate width and length respectively. The obtained value supposing standard 180 nm technology with a transistor gate of 1 μm^2 is in the order of 0.04–0.08 mV. The log-normal distribution of the RTS amplitudes explains the high ΔV_{RTS} found in some transistors [2], with values many times larger than the median. Even for these abnormal cases, the ΔV_{th} is usually lower than 1–2 mV in medium sized submicron transistors (180 nm technology), and can be negligible depending on the application.

The problem of RTS has already been studied in CMOS image cameras based on light integration, where a 1 mV output difference may have an impact on the high aimed image quality [3]. Nevertheless, the objective of other CMOS vision systems is the implementation of a specific task, where image quality is usually not so important; moreover, some of these vision systems do not deliver images at all, just the results of some processing (say, the position of a target in the scene). For these systems, a change of just 1 mV is not usually important, and little attention has been focused on studying the RTS impact in these smart vision systems.

Address Event Representation (AER) [4,5] and Selective Change Driving (SCD) [6], are vision strategies based on sending pixels (not images) according to their temporal illumination level change. Most of these vision systems are based on the same continuous-time logarithmic transduction cell with the two variants [7,8] shown in Fig. 1. In both cases, the gate-source voltage V_{gs} of transistor M_n has a logarithmic dependence with the photodiode generated current I_{ph} of the form $V_{gs} = V_{DC0} + n\frac{kT}{q}\ln\frac{I_{ph}}{I_0}$, where V_{DC0} is a constant offset voltage, n and I_0 are the sub-threshold slope and current factors, respectively, k is the Boltzmann constant, and T is the Temperature. M_{na} and M_{pa} form a high-gain inverter amplifier. The output of this amplifier is fed-back to the initial stage, thus V_D remains almost constant, increasing the overall circuit reaction

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http://dx.doi.org/10.1016/j.sse.2015.08.025

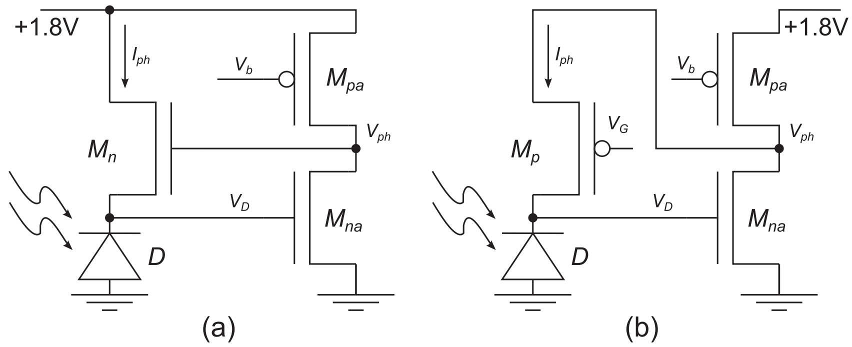

Fig. 1. Typical active continuous-time logarithmic light-transduction cells: (a) *n*-gate feedback and (b) *p*-gate feedback.

speed to light changes. The output voltage V_{ph} is then $V_{ph} = V_{DC1} + A_a \frac{nkT}{q} \ln \frac{I_{ph}}{I_0}$, where V_{DC1} is a constant offset Voltage, and A_a is the closed-loop amplifier gain ($A_a \approx 1$).

The worst theoretical static impact of RTS in this circuit is in the order of $\Delta V_{RTS} \approx 1$–2 mV at the output, according to the equations shown above. This amplitude is already in the order of the thermal noise generated by the photodiode and the M_n transistor. As a first approach, it may seem that static RTS has little impact on this circuit. Nevertheless, the experimental results obtained with an SCD sensor show RTS amplitudes of 20–40 mV (see Fig. 3 in next section) that do not fit in any RTS static model.

In this paper we present an explanation for these abnormally high levels of noise, based on the transient effects of RTS itself.

2. RTS transient amplitude

The static RTS amplitude ΔV_{RTS} has been summarized in the introduction. It has been shown that its impact on the output is not very large, and in its worst case, it is in the order of the already present thermal noise. This static RTS impact is even less important if we consider that the probability of just one transistor presenting the worst RTS is roughly in the order of 0.1% (this depends on many factors).

However, the temporal effects of an RTS event are not so negligible. Fig. 2 shows the basic circuit with the addition of a voltage source V_{RTS} in the gate of M_{na} to model the RTS at M_{na}. A sudden change ΔV_{RTS} in the V_{RTS} source, produces a change in both the voltage at the photodiode V_D, and the voltage at the M_{na} gate V_g. This change in the gate (ΔV_g) generates an amplified change in the drain voltage of M_{na} ($\Delta V_d = V_{ph}$). This change is proportional to the inverter amplifier open-loop gain A_n, thus $\Delta V_d = A_n \Delta Vg$. The change in V_d also influences the change in V_D closing the loop. The new voltages at V_D, V_d and V_g are coupled by the capacitors C_D (photodiode capacitance) Cna_{gd} (M_{na} gate-drain capacitance) and Cn_{gs} (M_n gate-source capacitance). The contribution of the

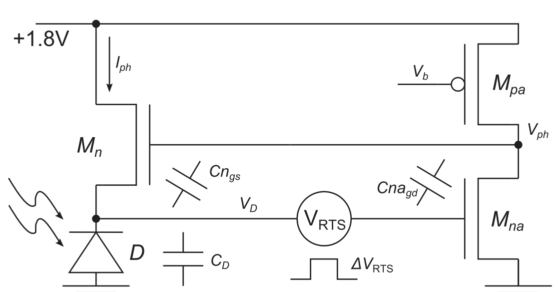

Fig. 2. Model of the *n*-gate feedback circuit for RTS transient analysis.

M_{na} gate-source capacitance is low, and it has been removed from the following equation which models the initial transient effect in the output produced by a sudden RTS change ΔV_{RTS}:

$$\Delta V_d = A_{tran} \Delta V_{RTS} \tag{2}$$

$$A_{tran} = \frac{A_n C_D}{C_D + A_n (Cna_{gd} + Cn_{gs})} \tag{3}$$

where A_{tran} can be defined as the RTS transient amplification factor. The capacitances Can_{gd} and Cn_{gs} are proportional to the gate width W, and they are not very dependent on the gate length or gate area, because M_n is always in weak inversion and M_{na} is never in the triode region. These capacitances are $Cna_gd = W_{na} C_{ov}$ and $Cn_{gs} = W_n C_{ov}$, where C_{ov} is the gate overlay capacitance, W_{na} is the M_{na} gate width, and W_n is the M_n gate width.

The experimental set-up is based on the Selective Change Driven (SCD) sensor described in [6]. The open-loop amplifier gain A_n is 60, the photodiode size is $6 \times 6\ \mu m^2$ with $C_D \approx 44$ fF (standard *n*-Well over p-substrate diode with *n* + contact). The gate widths of *Man* and M_n are 1.2 and 1.0 μm, respectively, thus $Can_{gd} + Cn_{gs} \approx 0.72$ fF. With these values, $A_{tran} \approx 30$. This means that any RTS event will be multiplied by 30 in this pixel.

The duration of the RTS transient depends on many factors. Since the photodiode capacitor is charged by the photogenerated current, it may take a long time (up to several milliseconds) to recover its steady state depending on the illumination level. In dark conditions, and with an RTS with periods in the order of 1 ms, the transient and the static RTS have the same squared shape as shown in Fig. 3(a), though the amplitude of the RTS transient is many times larger (30 in the analyzed circuit). Fig. 3(b) shows the output of the same pixel under intense illumination (10 Klux); the initial pulse voltage amplitude ΔV_{ph} is the same, but it rapidly decays. Even in very well illumination conditions, the time constant of the RTS transient is in the order of half a millisecond, which is still a long time.

These experiments have been performed for the pixel showing the largest RTS transient level among the 4096 pixels in the sensor array. In this worst case scenario, the measured $\Delta V_{ph} = \Delta V_d$ is 38 mV. Taking into account that the calculated A_{tran} for this circuit is 30, the actual static RTS is about $\Delta V_{RTS} = 1.27$ mV, which is in accordance with the expected RTS worst value due to the log-normal RTS amplitude distribution. The RTS transient amplitude of this pixel represents more than half a decade of illumination change, and it has a noticeable impact on the output. Fortunately, the chance of such a high level RTS is very low. The analysis of the worst pixels in a given sensor shows around 12 pixels with ΔV_{ph} linearly distributed between 4 mV and 40 mV; all other 4 K pixels show RTS transient levels below 4 mV, or even no RTS effects at all. Approximately 1/3 of the total pixels show no RTS effects (or they are too small to be seen), another 1/3 have a measurable single trap