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Localization of Dark Current Random Telegraph Signal Sources in Pinned Photodiode CMOS Image Sensors

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Abstract—This work presents an analysis of Dark Current Random Telegraph Signal (DC-RTS) in CMOS Image Sensors (CIS). The objective is to provide new insight on RTS in modern CIS by determining the localization of DC-RTS centers and the oxide interfaces involved. It is shown that DC-RTS centers are located near the transfer gate. In particular, it is demonstrated that both gate oxide and Shallow Trench Isolation (STI) contribute to this parasitic dark current variation.

Index Terms—Random Telegraph Signal, CMOS image sensors, Pinned Photodiode, Dark current, RTS, RTN, Random Telegraph Noise, Transfer Gate, STI, Shallow Trench Isolation

I. INTRODUCTION

Dark Current Random Telegraph Signal (DC-RTS) is a parasitic random process which limits the performance in many modern solid state photodetector (silicon based and others) in low light conditions. Indeed, as the noise impact is reduced and CIS are able to detect low flux, RTS phenomenon tends to be highlighted. Such signal which trend is given in Fig. 1, corresponds to discrete variations of the photodiode leakage current (see Sec. II for the photodiode cross section), and leads to random blinking pixels. This junction leakage current may be similar to the variable retention time observed in DRAM [1][2].

This parasitic fluctuation is different from the well-known RTS mechanism in MOSFET [3][4], which has already been widely analyzed and is due to a channel carrier capture/emission by a trap. The RTS signal studied here is different, because the metastable states can be observed directly at the output of the CIS (it is not the case of MOSFET RTS due to the correlated double sampling stage [5]), it is proportional to the integration time, and time constants between transitions are far longer (the order of magnitude at room temperature is about 120 s [6]). It has been demonstrated that in modern CIS, DC-RTS comes from metastable generation centers which probably change their geometrical configuration with time and induce discrete levels in the dark signal [6]. Previous work have shown that RTS centers are most likely situated at oxide interfaces [7][8] in unirradiated devices. However, the precise location of these sources and the influence of oxide composition on the phenomenon remain unclear.

Thus, two CIS with several pixel designs (change in the transfer gate length and shape) have been realized to determine RTS centers position and the different oxides contribution.

II. EXPERIMENTAL DETAILS

The two studied CIS are constituted of 256x256 4T-Pinned PhotoDiode (PPD)[9] pixels and manufactured using a commercially available 0.18 µm process. They contain respectively 10 and 24 areas of 2560 to 6528 pixels, but for the sake of clarity, only 9 designs will be discussed.

Fig. 2 represents the architecture of a 4T-PPD pixel. It shows that the source of the well known SF-RTS (which is not studied in this work) is located at the Source Follower transistor and may be modeled by a resistance because of the trap capture/emission rate.

Fig. 2 also depicts the cross section of the photodiode considered as the reference one. The photosensitive element, which corresponds to the N-doped volume, collects charges during the integration time. The applied gate voltage is thus
very low in order to separate the sense node and the photodiode (see left side of Fig. 3 for the potential diagram of this case). After the integration time, a high voltage is applied to the transfer gate, in order to decrease the potential barrier and transfer charges to the sense node so that the signal is collected (see right side of Fig. 3 for the potential diagram of this case). The different P-doped areas permit to enhance charge transfer performances, and the P⁺ implant isolates the photosensitive element from the oxides. This technique using different doping is commonly employed in CIS processes.

Fig. 4 represents the behavior of the space charge region extension when the applied transfer gate voltage $V_{LOTG}$ increases is shown. Indeed, as RTS centers are more likely to be near the oxide interface [7] [8], $V_{LOTG}$ variation permits to place the depleted volume in contact or not with the Si/SiO₂ interface, to highlight or not RTS centers contribution.

This assessment is illustrated Fig. 5 where the mean dark current is plotted as a function of $V_{LOTG}$ at room temperature. The layout used for this curve is the reference one given in Fig. 2. RTS contribution for negative voltage (0.075% of RTS pixels corresponds to 2 pixels in the area). This shows that RTS centers are not located in the bulk, because they participate to the dark current only when the depleted volume is in contact with Si/SiO₂ interfaces.

Moreover, Fig. 6 also reveals that the percentage of RTS pixels at a given $V_{LOTG}$ does not depend on the pinned photodiode length. This means that centers are not located at the interface with the Pre-Metal Dielectric (PMD), which increases when the photodiode size increases too. Consequently, RTS centers seem not to be located near the N doped photodiode, but rather located next to the transfer gate side.

Fig. 7 represents the percentage of RTS pixels for 4 designs, changing the transfer gate length, or the overlap between the P⁺ implant and the transfer gate ($L_1$). It can be seen that the transfer gate length influence on the number of RTS pixels is not significant. However, there is an influence of $L_1$.

The RTS pixels are detected thanks to a dedicated tool described in [10].

### III. EXPERIMENTAL RESULTS

#### A. Influence of $V_{LOTG}$, $L_{PPD}$, $L_{TG}$ and $L_1$

The CIS used for this section is the image sensor containing 24 areas. Fig. 6 and Fig. 7 represent the percentage of RTS pixels in 6 different areas for several $V_{LOTG}$. First of all, it can be seen that whatever the design is, there is no...
Fig. 6. Percentage of RTS pixels for several transfer gate voltages and 3 designs with different photodiode lengths. Each layout area contains approximately 2500 pixels.

increases too even if the transfer gate length remains the same.

Finally, it seems that RTS centers are more likely to be located under the TG, but the visible contribution to the dark signal comes from the overlap between the transfer gate and the P_{PPD-TG} implant.

B. Analysis of the transfer gate shape at a given $V_{LOTG}$

The CIS used for this section is the image sensor containing 10 areas. In this part, some variations in the transfer gate shape are analyzed, in order to better understand the precise location of RTS centers. Fig. 9 represents the three designs that will be studied. The first is the reference one, the second contains an annular transfer gate (no contact with the Shallow Trench Isolation (STI)) and the third one has one side of the annular gate which is extended to the STI. Tab. I sums up the designs parameters around the transfer gate. The overlap between the P_{PPD-TG} implant and the transfer gate will be called PTI (P_{PPD-TG} implant). Additionally, A_{TG-PTI} will be the surface shared by the transfer gate and the P_{PPD-TG} implant, and L_{STI-PTI} will be the distance where the STI and the P_{PPD-TG} implant are in contact under the transfer gate. As the STI depth is the same for each layout, the influence of this parameter (in this case, this would become $A_{STI-PTI}$) cannot be analyzed.

First of all, there are much more RTS centers in the third design (AnTG_STI). The main obvious difference is the extension of the transfer gate area and this should play a role in RTS phenomenon as mentioned in Sec.III-A. However, there are about 2.5 more RTS pixels between AnTG and AnTG_STI, and the ratio of the area parameter ($A_{PTI}$) is about 1.7. Thus, the AnTG_STI contribution seems important but not sufficient to explain the location of RTS centers.

Another difference between these two designs (AnTG and AnTG_STI) is the contact of the TG depleted region and the STI sidewall. Indeed, in the first layout, the transfer gate has no contact with this oxide. This leads to fewer RTS pixels, but some remain anyway. Consequently, this interface certainly plays a role but cannot be the only contribution.

Hence, there seems to be a combination of several contributions to RTS phenomenon. In order to estimate the influence of each of the two interfaces, one can divide the number of RTS pixels by the total interfaces on the CIS zone:

$$Nb_{RTS} = X_1 \times A_{PTI} + X_2 \times L_{STI-PTI} \quad (1)$$
TABLE I
PARAMETERS OF THE DIFFERENT DESIGNS USED. A_{PTI} IS THE AREA SHARED BY THE TRANSFER GATE AND THE PPD-TG IMPLANT, L_{STI-PTI} IS THE LENGTH WHERE THE STI, THE TRANSFER GATE AND THE PPD-TG IMPLANT ARE IN CONTACT. THE NUMBER OF RTS PIXELS IS GIVEN AT V_{LOTG} = 0.2 V.

<table>
<thead>
<tr>
<th></th>
<th>A_{PTI} (µm²)</th>
<th>L_{STI-PTI} (µm)</th>
<th>Nb_{RTS}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref</td>
<td>1.1</td>
<td>0.7</td>
<td>40</td>
</tr>
<tr>
<td>AnTG</td>
<td>2.0</td>
<td>0.0</td>
<td>55</td>
</tr>
<tr>
<td>AnTG_STI</td>
<td>1.1</td>
<td>0.33</td>
<td>140</td>
</tr>
</tbody>
</table>

TABLE II
CALCULATED CONTRIBUTION OF A_{PTI} AND L_{STI-PTI} AT V_{LOTG} = 0.2 V. THE SIZE OF EACH DESIGN AREA IS APPROXIMATELY 6500 PIXELS, AND TOTAL SURFACES ARE GIVEN AS THE SURFACE IN A PIXEL MULTIPLIED BY THE NUMBER OF PIXELS IN THE AREA.

<table>
<thead>
<tr>
<th></th>
<th>Total A_{PTI} (µm²)</th>
<th>Total L_{STI-PTI} (µm)</th>
<th>Nb_{RTS predicted}</th>
<th>Nb_{RTS measured}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref</td>
<td>7000</td>
<td>4600</td>
<td>42</td>
<td>40</td>
</tr>
<tr>
<td>AnTG</td>
<td>13000</td>
<td>0</td>
<td>39</td>
<td>55</td>
</tr>
<tr>
<td>AnTG_STI</td>
<td>21700</td>
<td>7200</td>
<td>115</td>
<td>140</td>
</tr>
</tbody>
</table>

with X_1 and X_2 respectively the number of RTS centers per µm² and per µm for both contributions, and A_{PTI}tot and L_{STI-PTI}tot respectively the total A_{PTI} and L_{STI-PTI} on all pixels of the matrix zone (about 6500 pixels).

Tab. II represents the results obtained for the different contributions. It is found that there are about 0.0045 centers/µm² at the interface between the transfer gate and the PPD-TG implant, and 0.0022 centers/µm² for the one overlapping the PPD-TG implant and the STI under the transfer gate (if the depth of STI is considered to be about 0.3 µm and half of this depth is depleted, this would become 0.014 centers/µm² and in this case, this contribution would be more important than A_{PTI}). These results are given at V_{LOTG} = 0.2 V. For higher transfer gate voltages, both contributions are higher but the depleted volume increases too.

It can be seen that this model seems relevant, even if there are some differences between the values predicted and measured. Indeed, there are not enough statistics to be more accurate, because the overall ratio of RTS pixels is low.

Finally, Fig.10 gives the summary of this work. RTS centers appear to be located at the Si/SiO₂ interfaces, more precisely under the transfer gate because the photodiode size has no influence. Moreover, as the doping P_{TG-SN} is lower than the PPD-TG one, the electrons generated there go directly to the sense node (and do not participate to the dark current). Consequently, only RTS centers located under the transfer gate, AND in the PPD-TG implant contribute to the signal collected. Eventually, two main edges seem to be at the origin of RTS phenomenon: the first is the area A_{PTI} and the second is the distance in contact with the STI L_{STI-PTI} (it may also be an area if the depth is considered, but this parameter is difficult to estimate correctly in this work).

IV. Conclusion
The results of this work provide new insight on RTS in unirradiated modern CIS, and allow a better understanding of noise and electrical temporal fluctuations in photonic devices. It has been demonstrated that there are two major contributions to Dark Current RTS: the interface between the STI and the PPD-TG implant under the transfer gate, and the area of the transfer gate overlapping the PPD-TG implant. The first one can be removed with an annular transfer gate which has no contact with the STI. The density has been calculated at a given V_{LOTG} for both contributions and this reveals that the second contribution is responsible for twice more RTS pixels than the first source (in a standard pixel design for a 7 µm pixel pitch in the studied technology).

REFERENCES