Improvement of Fluorine to Photo Response Non-Uniformity and Random Telegraph Signal of Pinned Photodiodes

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Abstract—**The simultaneous effects of fluorine (F) injection of various energy and dose on the characteristics of the photo response non-uniform noise (PRUN) and random telegraph signal (RTS) in the CMOS image sensor were investigated. A 2M sensor product with pixel size 3um was fabricated using 90nm CMOS image sensor technology on 8" 4μm epi wafer as an experimental platform. In order to optimize the performance of PRNU and RTS noise, the process of F ion was implanted in the poly loop and LDD loop steps separately. The measurement results show that the transfer gate and source follower with F implanted compensation, the PRNU could be improved by more than 30% and the number of blinking pixels (random noise >10e-) was reduced by ten times.**

Keywords- Image sensor, fixed pattern noise, fluorine implantation, photo response non-uniformity noise (PRNU), random telegraph signal (RTS), blinking pixels

I. INTRODUCTION

There are two main components of the pattern noise are the fixed pattern noise (FPN) and the photo-response non-uniformity noise (PRNU) (see Fig. 1) [1]. The pixel wise fixed pattern noise (P-FPN) is caused by dark currents. It primarily refers to pixel-to-pixel differences when the sensor array is not exposed to light. Because the P-FPN is an additive noise, some middle to high end consumer cameras suppress this noise automatically by subtracting a dark frame from every image they take. P-FPN also depends on exposure and temperature.

In natural images, the dominant part of the pattern noise is the photo-response non-uniformity noise (PRNU). It is caused primarily by pixel non-uniformity (PNU), which is defined as different sensitivity of pixels to light caused by the inhomogeneity of silicon wafers and imperfections during the sensor manufacturing process. The character and origin of the PNU noise make it unlikely that even sensors coming from the same wafer would exhibit correlated PNU patterns. As such, the PNU noise is not affected by ambient temperature or humidity. Light refraction on dust particles and optical surfaces and zoom settings also contribute to the PRNU noise. The PRNU limits the image quality after 3D dynamic noise reduction in the IP camera applications. With good PRNU, there will be good image clarity as image recognition.

A general study of the RTS phenomena in semiconductor devices can be found in a recent book [2], covering a wide range of experimental and theoretical topics. For CMOS image sensor (CIS), the most reported RTS originate from the source followers (SF) of the active pixels [3]–[7]. Although other sources, such as dark current RTS, have been reported [8, 9]. The main objective of this paper is to highlight that the RTS comes from the SF device. The low-frequency noise also constitutes a critical technology parameter [10]. It can be used to determine the quality of the gate stack when the sources of the current fluctuations are charge trapping/de-trapping events [11, 12]. To solve these problems, incorporating fluorine (F) into the gate oxide has been suggested and investigated because F atoms that diffuse into the gate dielectric react with the silicon dangling bonds within the gate dielectric, and these passivate the traps at the Si/SiO_2 interface [13]–[17]. Also, *Si-F* bonds are less likely to be broken than *Si-H* under electrical and thermal stress because of their higher binding energy [13]–[17].

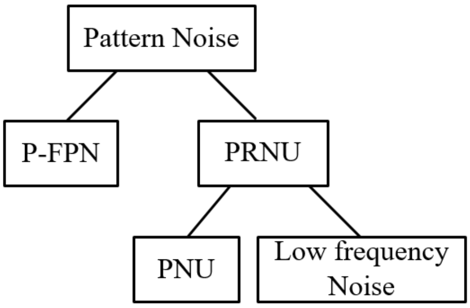


Fig. 1. Pattern noise of imaging sensors.

II. EXPERIMETAL AND RESULTS

The PRNU is limited by potential barrier, pocket, interface state trap, and charge spill-back of the transfer gate [18]. Fig. 2 shows the cross-sectional view of the pinned photodiode of the 2M sensor. The signal charge transfer of the pinned photodiode with interface state trap is shown in Fig. 3. Fluorine was introduced through ion implantation into polysilicon and diffused into the gate oxide at following the annealing process and, consequently, this F atoms passivated the dangling bonds in the Si-SiO2 interface and so the SiO2 imperfection is mitigated. The experimental results show that F can compensate oxide interface traps of the transfer gate and source follower device. The PRNU of the charge transfer with fluorine implantation was greater than without fluorine implantation. The measurement results show that PRNU can be improved by three times under the condition of pinned skip and F injection compensation of the transfer gate. PRUN is affected by potential barrier and interface state of the transfer gate. In this case of pixel, the silicon surface is covered with a P layer over the transfer gate. Therefore, the silicon surface can be accumulated by holes. The negative bias of the transfer gate can protect the silicon surface of transfer gate when the P layer is skipped. Fig. 4 and Fig. 5 show the pixel-wise fixed pattern noise comparison of twenty electron signal level at 32X sensor gain in low light illumination. The FPN is 0.5e under the F compensation. The P-FPN process variation can also be improved.

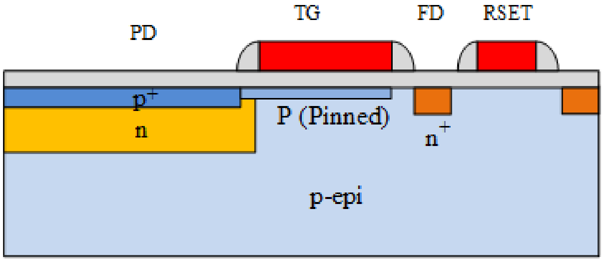


Fig. 2. Cross-sectional view of the pinned photodiode.

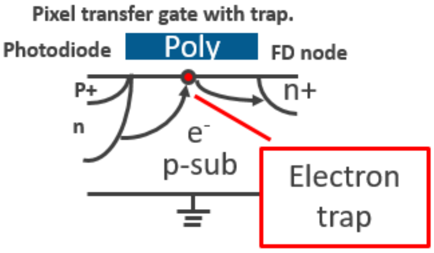


Fig. 3. The signal charge transfer of the pinned photodiode with interface state trap.

The random telegraph signal (RTS) noise of the source follower device was greatly reduced compared with that of a baseline pixel without fluorine implantation. The dose and energy of fluorine ion implantation were varied to optimize the effect of fluorine incorporation on PRNU and RTS noise characteristics. The normalized energy was split into Energy 1.0, Energy 1.33 and Energy 1.5 and the dose was split into Dose 1.0, Dose 2.0 and Dose 3.0 (1.5 means 1.5 times greater energy than 1.0 and 2.0 means 2 times greater dose than 1.0). The implantation energy and dose are expressed as relative magnitudes because it's not convenient to reveal the exact situation of the implant. Medium concentrations have been found to have improved interface characteristics as shown in Fig. 6. The measurement results show the number of blinking pixels (RN >10e-) is reduced by ten times. The result of Fig. 7 indicate that high concentrations of fluorine can cause deterioration of the bulk gate oxide, although the interfacial region is improved. High doses of fluorine will also cause an increase in oxide thickness which can be monitored [14].

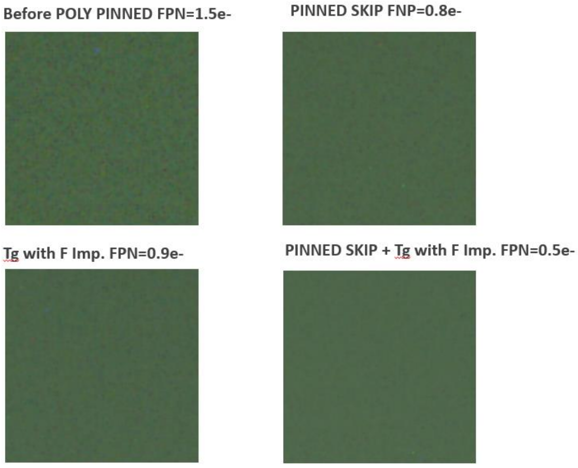


Fig.4. The PRNU comparison of twenty electron signal level at 32X sensor gain in low light illumination

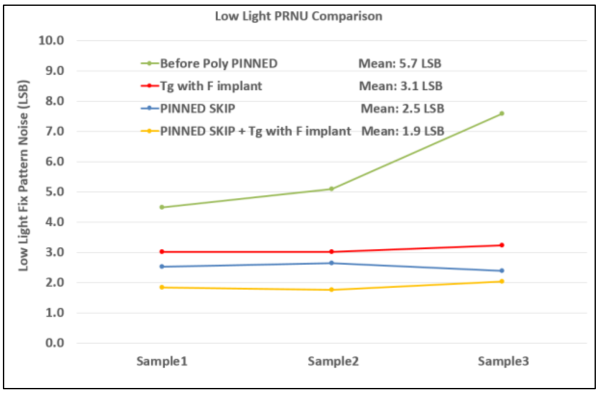


Fig. 5. The PRNU average comparison of three sample dies of twenty electron signal level at 32X sensor gain.

Table 1 and Table 2 are the numbers of blinking pixel of different F implanted energy. The blinking pixel is important. The ISP chip must have a strong defect compensation or de-noise to remove it if there are too many blinking pixel. This will cause the image sharpness to drop.

Table 1 Number of blinking pixel (RN>10e-) under different F implant energies

	No F Imp.	F Imp. Energy 1.0	F Imp. Energy 1.3	F Imp. Energy 1.5
RN>10e-	6408	2334	398	244
RN>5e-	34688	12290	2262	1298

Table 2 Number of blinking pixel (RN>10e-) under different F implant dose

	No F Imp.	Energy 1.0 Dose 1.0	Energy 1.3 Dose 2.0	Energy 1.5 Dose 2.0	Energy 1.5 Dose 3.0
RN>10e-	4018	2401	376	242	144
RN>5e-	26475	14985	2920	1613	1337

The source follower device with zero threshold voltage can also minimize the RTS noise and the blinking pixel. Fig. 8 shows an additive effect of the zero threshold voltage and F ion implantation of the SF device. The F ion implantation has better trap passivation of the gate oxide in LDD loop than poly loop. This is because F ion penetrates into the gate oxide through the source and drain side.

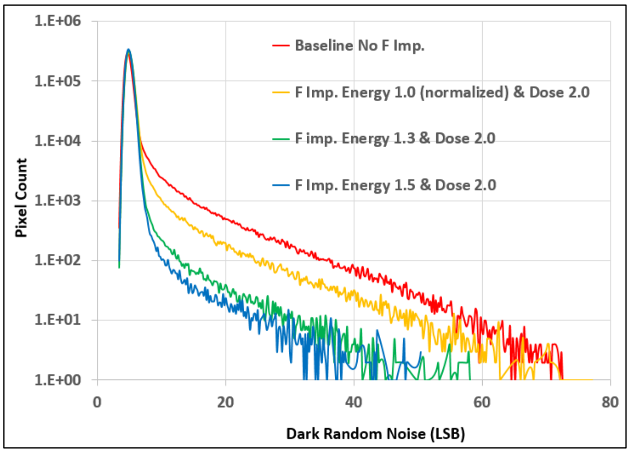


Fig. 6. Dark random noise histogram of 1920x1080 pixels of different F implant energies.

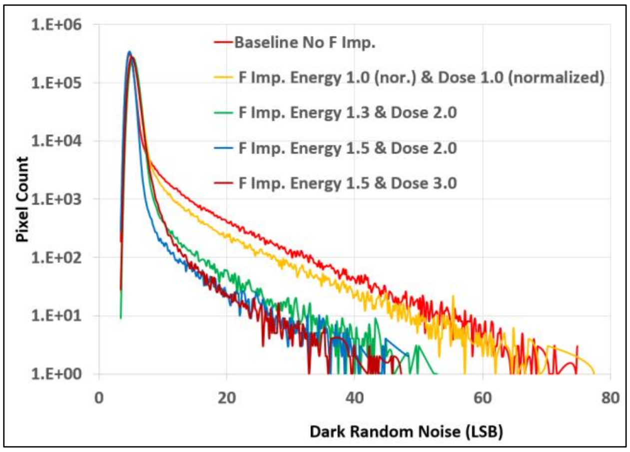


Fig. 7. Dark random noise histogram of 1920x1080 pixels of different F implant doses.

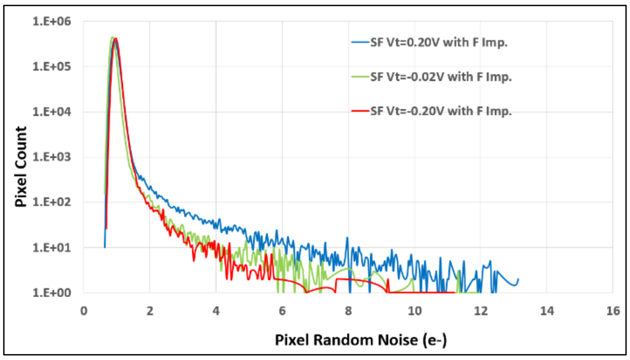


Fig.8. Dark random noise histogram of 1920x1080 pixels of F ion implantation of different source follower VT.

Fig. 10a and Fig. 10b show the dark random noise distribution with F ion implantation was performed by subtracting two frames with a sensor gain of 32 times. Compared with samples without F ion implantation, the noise distribution of F implant samples was relatively concentrated. The PRNU and RTS noise were reduced with increasing F ion implantation energy and dose. But, the PRNU was less dependent on F implantation dose. Medium-dose of F implantation are enough. Therefore, fluorine implantation is potentially significant for reducing random telegraph signal (RTS) as well as improving blinking pixel characteristics.

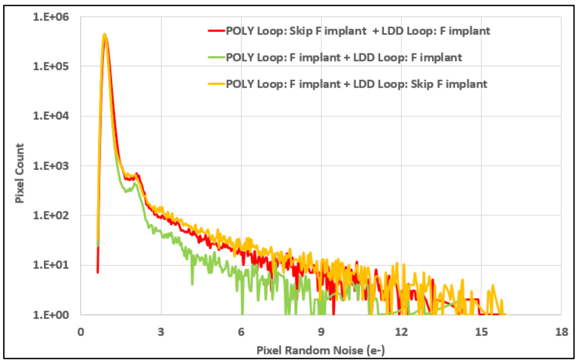


Fig. 9. Dark random noise histogram of 1920x1080 pixels on F ion implantation of poly loop or LDD loop.

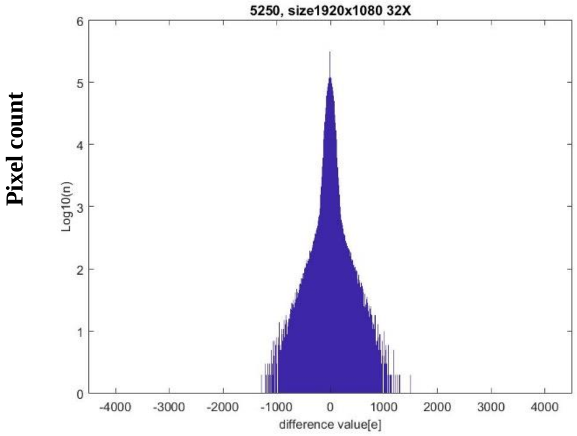


Fig. 10a. The dark random noise distribution without F ion implantation is performed by subtracting two frames with a sensor gain of 32 times.

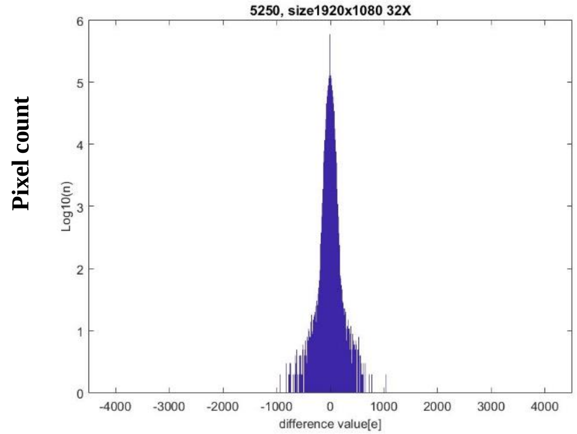
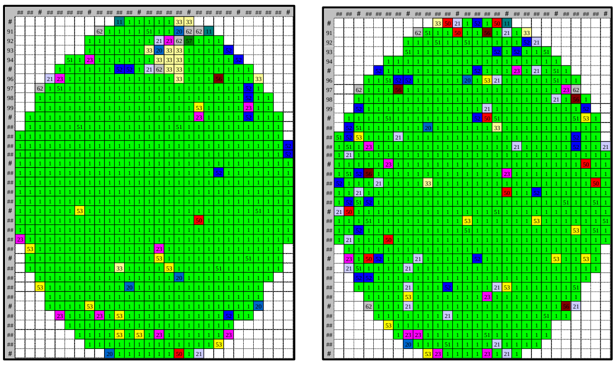


Fig. 10b. The dark random noise distribution with F ion implantation is performed by subtracting two frames with a sensor gain of 32 times.



(a) yield ~90% (b) yield ~84%

Fig. 11. Yield of 2 M sensor of (a) an F implant energy 1.5 and dose 2.0 and (b) an F implant energy 1.5 and dose 3.0.

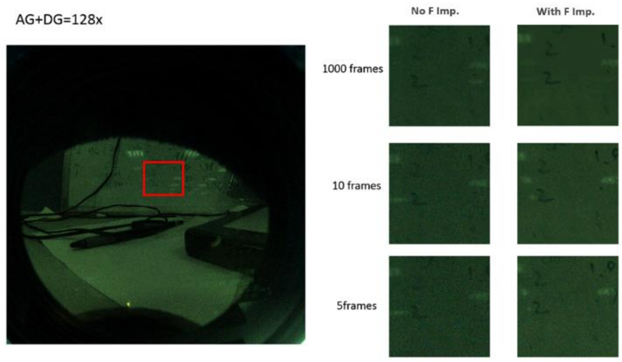


Fig. 12. PRNU of 2 M sensor of without and with F ion implantation in low light illumination. PRNU was stack after using 5 frames, 10frames, and 1000 frames of images to average random noise.

Figure 11 shows that the yield of 2M sensor products decreases with increasing F high implanted concentration. It is found that product yield is reduced by approximately 5% for every 0.5 times increase in F concentration. Figure 12 shows the difference before and after the improvement of the PRNU of actual image.

III. CONCLUSIONS

The fluorine ion implantation reduced the PRNU and RTS noise amplitude, which was believed to contribute to the effective passivation of the dominant traps within the gate oxide. But, high concentrations of fluorine can cause deterioration of the bulk gate oxide and suffer the product yield. Therefore, the medium implant dose of fluorine was recommended to improve PRNU and low frequency noise characteristics.

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