Degradation of Spectral Response and Dark Current of CMOS Image Sensors in Deep-Submicron Technology due to γ-Irradiation

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***Abstract*—In this paper, a model for the spectral response of 4-T (4-Transistor) CMOS image sensors in deep-submicron technology is developed to study the sensor's sensitivity towards γ-ray irradiation. It is found that the spectral degradation due to γ-rays is mainly through changes in the top-layer material characteristics and Si/SiO_2 interface. There is a non-trivial contribution of STI (shallow trench isolations) towards the dark current of the sensor, and it turns out to be highly sensitive to radiation damage.**

I. Introduction

"Pinned" photodiodes utilize a p^+ pinning layer that shields the photodiode from surface effects that contribute to the leakage mechanism. The doping of the photodiode layers are chosen such that most of the photodiode is depleted. One of the most dominant dark current mechanisms in these structures are the defective sidewalls and the edges of shallow trench isolations (STIs) separating the photodiodes [1], [2]. The emission rate from the defects is also enhanced by local electrical fields via the Poole-Frenkel effect as well as the phonon-assisted tunneling [3], [10]. Shot noise and fixed-pattern noise (FPN) are also correlated to the dark current of a CMOS Image sensor (CIS) [1]. Since these sensors are utilized for applications involving the detection of signals as low as a few electrons, radiation tolerance of such devices is of primary concern. Ionization damage is the dominant mechanism when energetic photons (γ and X-rays) interact with solid-state matter. For main stream silicon CMOS, the major concern due to ionization damage are charge build-up in the gate dielectric and radiation induced interface levels. The introduction of discrete energy levels at the $Si\text{-}Si0_2$ interface leads to increased generation rates and thus higher surface leakage currents. Similarly, displacement of lattice atoms in the bulk leads to modified minority carrier life-times and increased bulk-generated leakage currents [4]. The spectral response of the detector is affected by an increased recombination at the $Si/Si0_2$ interface and changes to the top-layer material characteristics.

II. Experimental

A. Spectral response

A 4-T APS structure, shown in Fig. 1, is a popular and rapidly improving solution to high quality image sensing. The p^+ pinning layer is used on top of the photodiode to shield it from surface effects and hence minimize surface leakage currents. The charges that are collected in the photodiode are transferred to the floating diffusion node (FD) via the transfer gate (TX), and subsequently read-out through a source follower (SF). This pixel area is considered to be the most vulnerable to the effects of radiation.

An analytic model for the internal spectral response of such a pinned photodiode can be derived by solving the continuity equation of a usual p^+/n photodiode by using an equivalent diode reverse voltage V_d, that represents the depleted diode. The contribution from the p-type epitaxial region is included for the contribution from carriers collected through diffusion. Since the penetration of the depletion region into the highly doped pinning region is negligible, this solution is a very good approximation to the spectral response of the pinned photodiode. The p^+ region is considered to have a Gaussian profile for the solution. Standard CMOS process parameters have been used for the simulation. The diffusion length L_A may be considered to be small compared to the minority carrier (electrons) diffusion length $L_n = \sqrt{(D_n \tau_n)}$ where D_n is the diffusion coefficient and τ_n is the carrier life time, resulting in a simplified continuity equation,

$$\frac{\partial^2 \Delta n}{\partial r^2} - r\frac{\partial \Delta n}{\partial r} - \Delta n = -\frac{F_0 \alpha}{D_n} 2L_A^2 e^{-\alpha\sqrt{2}L_A r} \quad (1)$$

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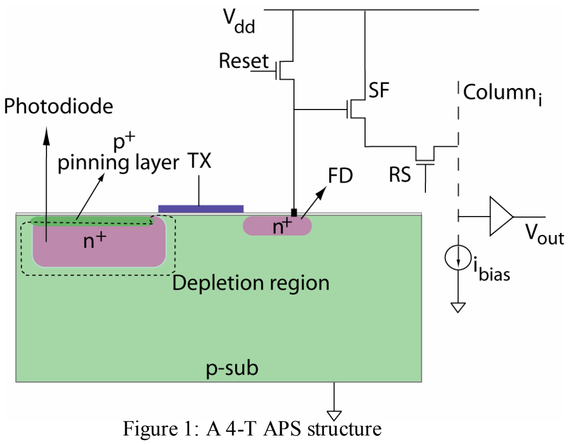

Figure 1: A 4-T APS structure

Where Δn is the excess minority carrier electrons in the p^+ region, F_0 is the photon flux incident on the front surface whose reflection coefficient is zero, α is the absorption coefficient and r is $\frac{x_n}{\sqrt{2}L_A}$, where x_n is the depletion width in to the p^+ region. The minority carriers lost in the front surface interface ($x=0$) is governed by the relationship

$$s\Delta n\big|_{x=0} = D_n \frac{\partial \Delta n}{\partial x}\Big|_{x=0} + \mu_n E \Delta n\big|_{x=0} \tag{2}$$

where s is the front surface recombination velocity. The concentration of excess carriers at the boundary of the depletion region ($x=\omega$) with a reverse bias V_d, can be determined by the diode equation

$$\Delta n\big|_{x=\omega} = \frac{n_i^2}{N_A}\left(e^{\frac{qV_d}{kT}} - 1\right) \tag{3}$$

where n_i is the intrinsic carrier concentration and N_A is the acceptor concentration. An analytic solution based on a power series can be a used to solve (1) – (3) [5]. Recombination in the space charge region is not considered. The contribution from the epitaxial region can be given as [6],

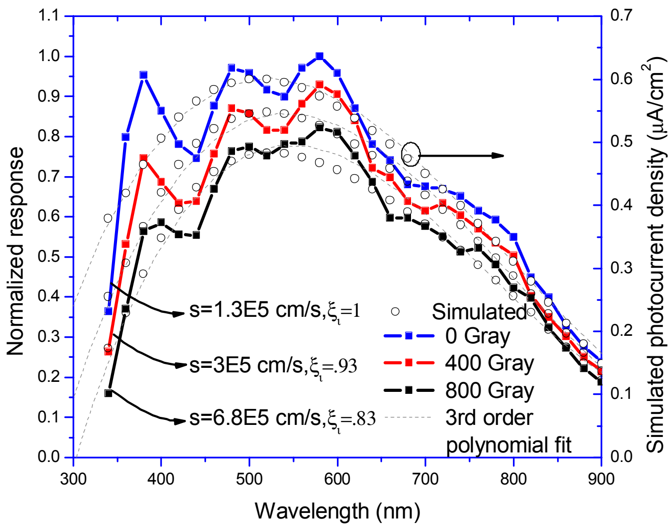

Figure 2: Spectral response of radiated and unradiated sensors and the fit.

$$\frac{qF_0\alpha L_n}{\left(\alpha^2 L_n^2 - 1\right)} e^{-\alpha\left(x_j + W\right)} \times \left(\alpha L_n - \frac{\cosh\left(\frac{H}{L_n}\right) - e^{(-\alpha H)}}{\sinh\left(\frac{H}{L_n}\right)}\right) \tag{4}$$

with the assumption of an infinite recombination rate at the epitaxial/substrate interface. Here x_j is the metallurgical junction depth of the p^+/n diode, W is the depletion width and H is the thickness of the neutral p-region.

Some important research into the degradation of spectral response of image sensors to γ–ray irradiation has been attempted by [7], but has not come to a conclusion for the degradation mechanism. Here we attempt to resolve the mechanisms by fitting the response curve with the variables s (the surface recombination velocity), and an attenuation constant ξ_i (acting through the front layer optical stack).

The radiation characteristics of all the sensors were tested by irradiating them with γ-rays (1.17 MeV-1.33 MeV); dose ranging from 0 to 1000 Gray in steps of 200 Gray with a dose rate of 75.9 Gray/min.

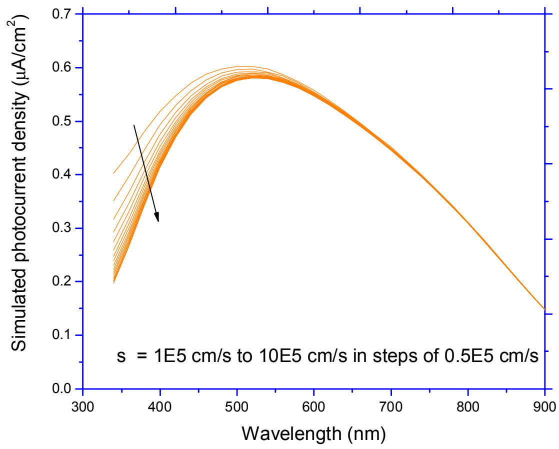

Figure 3: Simulated variation of spectral response as a function of s.

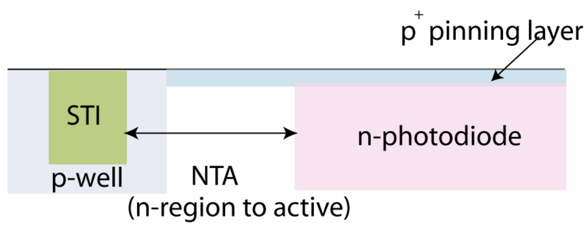

Figure 4: Layout schematic of the pixels.

All the structures were fabricated in Philips' 0.18-μm CMOS technology (Table. 1).

Fig. 2 shows the normalized spectral response (sensors output (DNs)/calibrated sensor output (A)) of radiated as well as unradiated devices. The equivalent reverse voltage V_d for the model was found to be 1.2 V resulting in a total depletion width of ~ 1.6 μm.

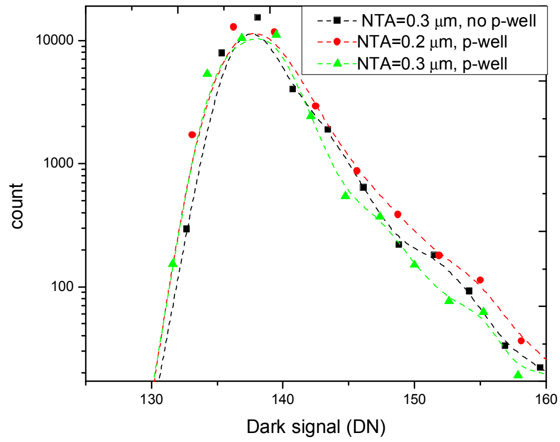

Figure 5: Histogram of the dark signal for the unradiated sensors.

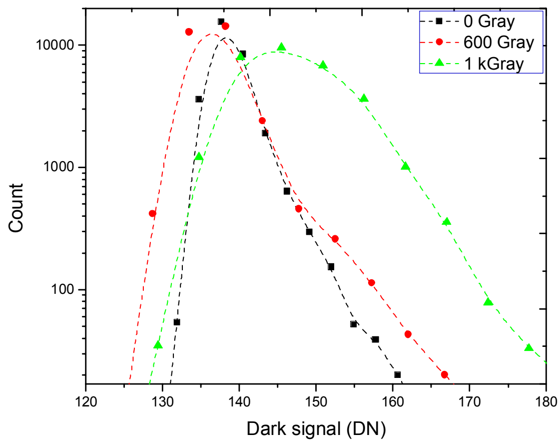

Figure 6: Histogram of the dark signal for sensor with NTA=0.3 µm, p-well protected.

The apparent p-region epi-depth was obtained at 10 µm. The deviation of this value from the physical epi-layer thickness of ~ 4 µm can be explained by the contribution of photo-generated electrons from deep within the substrate which was neglected in the model. A very good fit for all the curves is obtained by using an attenuation factor ξ_i as well as the term for surface recombination velocity, *s*.

The extracted parameters indicate monotonic optical stack degradation as well as a change in the Si/SiO_2 interface effects. High energy rays such γ-rays change the material properties of the materials they penetrate and mainly interact through electronic excitation, electronic ionization and atomic displacements. As a result, color centers are introduced in the material [8]. The change in the absorption by the top layer material layers can explain the attenuation observed. From Fig. 2, a smoothening of the sharp peaks found in the un-irradiated devices can be seen on radiated devices which can also be explained by this hypothesis. The variation of the lifetime in the epi-layer does not have much effect in the present sensor, with a thickness of ~ 4 µm.

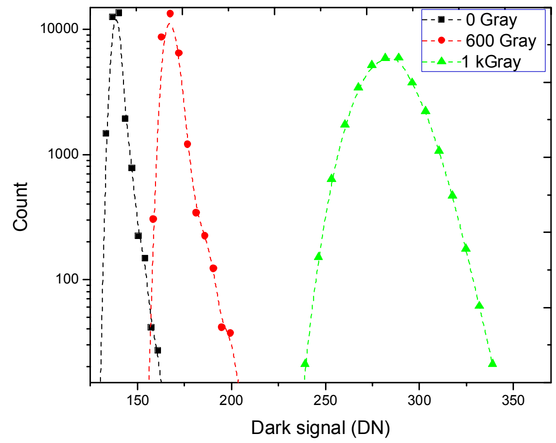

Figure 7: Histogram of the dark signal for sensor with NTA=0.2 µm, p-well protected.

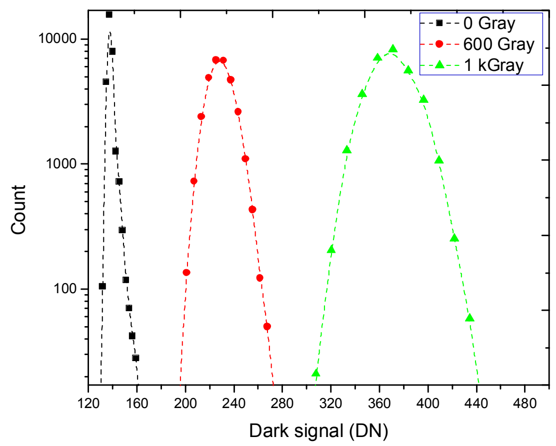

Figure 8: Histogram of the dark signal for sensor with NTA=0.3 µm, no p-well protection.

Parameter	**Value**
Pixel pitch	3.5 µm
Conversion gain (*g*) (photon shot-noise method)	39.7 $\mu V/e^-$
Transfer gate length	0.6 µm
Operating voltage	3.3 V
Integration time	6.4 ms

Table 1: Sensor details.

Since γ-ray irradiation do not produce significant displacement damages, the change in τ_n as a function of radiation dose can be safely neglected.

The variation of the spectral response as a function of *s* obtained through the model is shown in Fig. 3. The value of *s* is seen to significantly affect the response of the sensor towards higher frequencies since electrons are generated very close to the interface. The response is also seen to saturate at higher values of *s*.

B. Dark current

For sub-0.25 μm processes, STI is the only viable scheme of achieving high packing densities [9]. The STI is considered to be the prominent mechanism of leakage current in pinned photodiodes [1]. The generation rate can be characterized through the surface recombination/generation velocity at the interface and also by the generation lifetime in the bulk of the STI, the interface effects being prominent [2]. Protecting the STIs by p-well structures has proved useful against STI induced leakage mechanisms. But not much work has been done to characterize the effect of such structures in radiative environments especially on image sensors. Test structures (Fig. 4) with and without p-well protection were fabricated for two different p-well to active region distances (NTA) to estimate the degradation due to these configurations.

The histograms of the dark signal of the sensors (Fig. 5 - 8; all different horizontal scales) reveal that the radiation-induced degradation mechanism is sensitive to the nature and the location of the STI. The largest degradation is seen in structures that have unprotected STIs. Further, structures that have the STI closer (NTA = 0.2 μm) to the photodiode is seen to degrade faster than the structures that have the STI further apart (NTA = 0.3 μm). A larger value of NTA results in higher immunity to radiation damage, but this value should be optimized so the sensitivity and saturation level of the sensor is not overly sacrificed. Since the doping density of the p-well region is relatively higher than that of n-type region of the photodiode, the STI is isolated from the depletion region during integration for structures with p-well protection [11]. This explains the lower dark current from these structures, and the also the slower degradation of these structures to irradiation.

III. CONCLUSIONS

1. γ-ray irradiation affects the spectral response of 4-T image sensors by altering the top layer material properties and changing the surface interface properties. For the dose rates considered in this work, both these phenomenon were found to vary monotonically with the dose as can be explained from the model that was developed. Further work needs to be done to characterize the top-layer material properties as a function of radiation dose for high quality imaging in future technologies.

2. The results indicate that p-well protected STI structures are inevitable for radiation-hard designs. A larger value of NTA results in higher immunity to radiation damage, but should be optimized to avoid loss of sensitivity and saturation levels of the sensor. With the shrinking of pixel size, the STI as well as the p-well fabrication processes would become the focus of attention for optimizing the process for high quality imaging especially for applications related to harsh environments.

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