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Design of a CMOS image sensor pixel with embedded poly-silicon nano-grating for near-infrared imaging enhancement

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CMOS (Complementary Metal-Oxide Semiconductor) image sensor sensitivity in the near-infrared spectrum is limited by the absorption length in silicon. To deal with that limitation, we evaluate the implementation of a polysilicon nano-grating inside a pixel, at the transistor gate level of a 90 nm standard CMOS process, through opto-electrical simulations. The studied pixel structure involves a polysilicon nano-grating, designed with the fabrication layer of the transistor gate, which does not require any modifications in the process flow. The diffraction effect of the nano-grating increases the length of the light path in the photosensitive area and thus increases the photoelectric conversion efficiency. The nano-grating is integrated in combination with deep trench isolations in order to reduce crosstalk between pixels. Coupled optical and electrical simulations report 33 % external quantum efficiency improvement and 7 % crosstalk reduction at 850 nm.

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1. INTRODUCTION

Near-Infrared (NIR) spectrum detection has found several appli-2 cations for imaging and machine vision. Multi-spectral camera 3 using together color and NIR detection allow machine vision enhancement for portraying, shadow removal, vein detection 5 and some industrial applications such as fruit and vegetable 6 sorting, food inspection, tiles inspection[1–3]. Facial identification is a typical embedded function in smartphone using NIR 8 detection^[4] and applications as LIDAR based systems^[5], Driver 9 Assistance Systems[6], guidance systems[7] or security camera 10 need the ability to imaging at low light level with a specific 11 illumination sources commonly at 850 nm or 940 nm. NIR de-12 tection can also be useful in other contexts, such as plant tissue 13 analysis^[8] or medical imaging^[9, 10]. Considering the growing 14 15 demand of near-infrared imaging, the sensitivity of CMOS Image Sensor (CIS) for wavelength between 800 and 1100 nm has 16 become a paramount consideration. 17

The CIS market is mainly driven by silicon based CIS for
visible application. However, silicon is poorly absorbent in the
NIR spectrum and represents a limiting parameter for affordable and scalable NIR detection for mass market. Moreover,
CIS foundries use thin optically active layers, obtaining better
performances for visible imaging but resulting with a drastic fall
down of their performances for wavelength above 650 nm[11–

13]. A typical active layer thickness is between 3 μ m and 5 μ m whereas, at a wavelength of 850 nm, the penetration depth after which the light is absorbed by 63% is over 18 μ m in silicon. To be efficient, NIR detection with silicon needs significantly thicker photosensitive layer than what standard CIS fabrication usually allows. Therefore, some studies have investigated a detector with a thicker active layer in silicon[14, 15], making the photosensitive layer going deeper in the silicon with high resistivity epitaxial layer[16, 17] or by applying a negative voltage at the back of the photodiode[12]. Unfortunately, these solutions require processes adaptation differing from more conventional silicon based CIS. Consequently, NIR silicon based CIS require investment in equipment and process variation, impacting the production cost. Another enhancement method is about to extend the effective light path length inside the active layer with diffractive structures.

Backside illuminated CIS with pyramid structures has been extensively studied[18–21]. In addition, the principle of high absorption by a structure combining plasmonic diffraction and the use of metallic trenches has been demonstrated[22]. In the same idea, photodiodes with micro-structured holes have been designed and fabricated[23], the holes structure is used as photontraps to improve the NIR detection of a single photodiode large of 30 μm . More recently, a single micro-hole structure per pixel has been optically investigated for a silicon based CIS[24] show- 110
 ing a drastic increase on the optical efficiency through simula- 111
 tions and needing a specific etching step. 112

This work is focused on FrontSide Illuminated (FSI) devices 113 52 and presents a solution for a NIR enhanced imaging sensor that 114 53 54 does not need adding any supplementary steps in the process 115 55 flow of a standard CIS fabrication. To doing this, the implementation of a poly-silicon nano-grating, designed from the layer of 117 56 fabrication of the transistors gate, has been studied. In the same 118 57 way, poly-silicon nano-gratings have already been implemented 58 as reflectors [25–27] or color filters [28], it makes use of the tran-59 sistor gate layer to design a nano-grating in order to reflect light 60 or to be wavelength selective. In this paper, it is designed to 61 diffract light inside the epitaxial layer and so enlarge the light path inside the photo-active region. The main advantage of this design is that it allows the use of the lithography and the 64 etching steps of the transistors' gate fabrication, resulting in no 65 additional manufacturing costs. 66

In addition, the use of Deep Trench Isolation[29, 30] (DTI) 67 technology helps the diffracted light to be confined within the 68 pixel avoiding it to spill over to the adjacent pixels, which 69 it is named crosstalk and degrade image quality. FSI silicon 70 based CIS with implemented nano-grating is investigated and 71 designed by optical and electrical simulations, using LUMERI-72 CAL software, to enhance NIR detection at a wavelength of 850 73 nm. FSI CIS are relevant in applications where resolution and 74 pixel size are not significant for primary interest, allowing to 75 achieve high dynamic range and low cost fabrication. Optical 76 and electrical coupling enables to calculate the total number of collected photogenerated carriers by the detector, whereas 78 optical simulations alone calculate only the number of absorbed 79 photons which is less representative of the detector efficiency. 80

81 2. METHODOLOGY

82 A. Pixel design

Figure 1.a) is a schematic cross sectional view of an FSI CIS 122 83 pixel (standard pixel) it is composed of a silicon substrate on ¹²³ 84 which a Si-epitaxial layer is grown. The epitaxial layer is P 124 85 doped (P-epi) two orders of magnitude less than the substrate 125 86 (P⁺⁺sub). An N doped region (N-well) is introduced in the ¹²⁶ 87 epitaxial layer in order to create the PN junction. At the top of 88 127 the device are oxide layers and metallizations used to connect 128 89 pixels and lecture nodes. The color filter is a spectral selective 129 90 layer used in most cases for color reconstitution (e.g : Red, Green 130 91 and Blue color filters), the layer between the oxide stack and 92 the color filter is a passivation layer made of silicon nitride and 132 93 on top of the pixel, the micro-lens is there to concentrate the 133 94 light on the PN junction area, enhancing the fill factor and it also 134 95 allows avoiding light scattering by the metallizations[31]. As an 135 96 97 image sensor is made up of a matrix of pixels, each pixel needs 136 to be electrically isolated from each other, which is achieved 98 137 by the use of Shallow Trench Isolation (STI), a trench in silicon 99 filled with oxide in order to prevent electric current leakage 100 between adjacent pixel. Fig. 1.b) is the schematic cross-sectional 101 view of an FSI CIS pixel architecture with integrated Poly-Si 102 nano-grating and Deep Trench Isolation (DTI). As illustrated, 103 the grating diffracts light and DTI replaces standard isolation in 104 order to confine diffracted light inside the photodiode. 105

Fig. 1.c) and d) show a schematic top view of respectively the standard pixel and the pixel with integrated nano-grating, there is the photodiode dedicated to light absorption and the lecture node allowing to initialize the photodiode, to select the wanted pixel and to read its information. In the lecture node area, one can see the Poly-Si layer used for the fabrication of the gates of transistors. This transistors layer lithography and etching steps are used for the fabrication of the nano-grating on top of the photodiode, which does not involve any additional manufacturing steps compared to the standard pixel. Only the mask for making the transistor gates has to be modified.

In the remainder of this paper results of 2D simulations will be presented allowing conclusion only on a 1D nano-grating.



Fig. 1. A schematic cross-sectional (a) of a standard CMOS Image Sensor pixel and (b) of the new pixel architecture with poly-silicon nano-grating and Deep Trench Isolation. (c) and (d) the top view of respectively the standard and the new architecture pixel.

B. Figures of merit

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The key properties of the pixel are its capability to collect as much of incident light as possible and its capability to avoid collecting light coming from neighbouring pixels. They are quantified by the External Quantum Efficiency (EQE) and the Crosstalk (CTK) that are used here as Figures Of Merit (FOM). The EQE corresponds to the ratio of the number of collected carriers (i.e. the number of electron-hole pairs) to the total amount of incident photons. Eq.1, shows that the EQE can be defined as the Internal Quantum Efficiency (IQE), which is the number of collected carriers over the absorbed photons, times the Optical Efficiency (OE), which is the number of absorbed photons over the number of incident photons. Therefore, the higher the EQE the brighter the image. The crosstalk occurs when a pixel collects carriers that should have not been collected by itself, but rather by the one of those next to it. CTK is, for a given pixel, the ratio of carriers collected which have been photo-created in a neighboring pixel as shown in Eq.2. It follows that the lower the CTK, the sharper the image, suppressing CTK gives better image contrast[32].

collected carriers	collected carriers	absorbed photons
incoming photons =	= absorbed photons ×	incoming photons
EQE	IQE	OE
		imes 100 (1)

$$CTK = \frac{crosstalk collected carriers}{total collected carriers} \times 100$$
 (2)

A high EQE leads to a higher sensitivity, and a lower CTK 176 139 leads to a higher image quality. These two parameters will be 140 used to determine the enhancement of the new pixel design over 141 the standard pixel design. In order to obtain the best image 142 quality, the pixel design has to maximize the EQE and minimize 143 the CTK. Most of the time, it will be a compromise between the 144 181 two characteristics. 145

3. SIMULATIONS METHODOLOGY 146

A. Collected photogenerated-carriers 147

Three steps are needed for the simulation of EQE and CTK, 148 the first one is the calculation of the optical excitation $E(\vec{r})$ [33] 149 (1 in Fig. 2), then comes the calculation of the absorption in 150 the silicon leading to the photo-carriers generation function 151 $G(\vec{r})$ (2 in Fig. 2). The last part is the calculation of the photo-152 carriers transport in the photodiode leading to the photo-carriers 153 collection probability $P(\vec{r})$ [34] (3 in Fig. 2). The first two parts 154 involve optical simulation and the third part concern electrical 155 simulation. The total amount of collected photo-carriers, $S_k(\vec{r})$, 156 of the pixel *k*, is calculated by Eq.3 where \vec{r} is the position vector. 157

$$S_k = \int G(\vec{r}) P(\vec{r}) \,\mathrm{d}\vec{r} \tag{3}$$

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The electrical calculation of $P(\vec{r})$ is done by considering the 159 response to a generation rate point source located at \vec{r} . This 160 impulse source is swept over all \vec{r} in the simulation domain 161 in order to achieve a complete map of $P(\vec{r})$. Therefore, $P(\vec{r})$ 162 is calculated once for a specific junction architecture and then 163 used for arbitrary optical inputs. The Block diagram in Fig. 2 164 165 summarizes the different calculation steps to obtain the total amount of collected photo-carriers for a specific illumination. 166



Fig. 2. Block diagram of the coupling between electrical and optical simulation

FDTD Lumerical software is used to solve the time- 211 167 dependent Maxwell differential equations and calculate the 212 168 electric field $\vec{E}(\vec{r})$ inside the photodiode for a specific optical ²¹³ 169 excitation. From this electric field, the absorbed power $P_{abs}(\vec{r})$ 214 170 is calculated, it gives the number of absorbed photons through 215 171 Planck relation. The Lumerical software CHARGES is used to 216 172 calculate the number of collected photo-carriers through the 217 173 calcultation of carriers transport equations (drift and diffusion 218 174 current) with Finite Element Method (FEM). 219 175

B. External Quantum Efficiency and Crosstalk calculation

In order to obtain the EQE and the CTK, two different simulations settings will be considered. Both of them involve three pixels to take into account the collection of carriers photo-generated in neighbouring pixels, named crosstalk. As it is shown in Fig. 1.c) the pixel is not symmetric, so the cross-section chosen for the 2D simulations (red line in the figure) is in the orientation that yields the most part of the crosstalk. Indeed, in the other orientation pixels are more distant from each other due to the lecture node, limiting the crosstalk.

The first setting is represented in Fig. 3.a) and the second setting is represented in Fig. 3.b). The two are similar, but one contains a filter transparent to the wavelength of calculation and in the other the central filter above the photo-diode of interest is opaque whereas filters above its adjacent pixels are transparent. For this filter layer, the real part of the refractive index is set at 1.5 and the imaginary part is set at 1.2 for the opaque one (transmitted intensity is more than 150 times lower than the incident one) and 0 for the transparent ones.



Fig. 3. Schematic cross-section of (a) the setting used for calculation of the total amount of collected photo-carrier and (b) the setting used for calculation of the crosstalked photo-carriers

Running optical and electrical simulations with settings of Fig. 3.a) allows the calculation of the total amount of collected photo-carriers by the pixel k, running them with the setting of Fig. 3.b) allows to obtain the number of collected photo-carriers by crosstalk. EQE is calculated from the setting of Fig. 3.a), though it contains all the photo-carriers collected by the pixels k including those resulting from crosstalk. The results are presented as the response of an unpolarized plane wave source which will be the average response of a parallel and a perpendicular polarized sources, as in Eq.4 where $|E|^2$ is the modulus square of the electric field results from an unpolarized source. $|E_s|^2$ (resp. $|E_p|^2$) is the modulus square of the electric field resulting from simulation in which the electric field is perpendicular (resp. parallel) to the plane of incidence.

$$|E|^{2} = \frac{1}{2}|E_{s}|^{2} + \frac{1}{2}|E_{p}|^{2}$$
(4)

C. Parameters of the model

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In table 1 are listed the geometric properties and the doping level of layers presented in Fig.1. The passivation layer is the intermediate layer of Si_3N_4 between the oxide stack and filters. The simulations are run considering a pixel width of 6 μ *m*, which is a size that allows good dynamic range and with a DTI depth of 4 μm and an epitaxial layer thickness of 3 μm , typically optimized for low dark current and good EQE.

Regarding the optical properties of the different materials used, the silicon Si data are taken from Schinke et al.[35] for extinction coefficient values and from Vogt[36] for refractive

Table 1. Simulations parameters

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layer	material	thickness	other	
$P^{++}sub$	Si	27 µm	doping : $10^{18} cm^{-3}$	
P^-epi	Si	3 µm	doping : $10^{15} cm^{-3}$	
N-well	Si	800 nm	doping : $10^{18} cm^{-3}$	
Oxyde stack	SiO_2	3 µm		
STI / DTI	SiO_2	0.4 / 4 µm	width : 1 / 0.15 μm	
passivation	Si_3N_4	200 nm		
filter	custom	1.05 µm		
micro-lens SiO ₂		1.5 µm	radius : 3 µm	

index values. Fused silica SiO_2 and silicon nitrides Si_3N_4 data are taken from Phillip[37, 38]. Poly-silicon is considered to have the same optical properties as crystalline silicon[39] and metals are set as perfect electrical conductors.

224 4. NANO-GRATING OPTIMIZATION AND RESULTS

A complete optimization of the grating parameters is performed 225 in order to find the best period and width of the grating at a 850 226 nm wavelength, used in typical NIR detection applications. First 227 simulations are performed in order to calculate the references 228 EQE and CTK so Fig. 4 and Fig. 5 are the simulations done for a 229 pixel with standard oxide isolation and without nano-grating, 230 cf. Fig. 1.a). The generation functions Fig. 4.a) and Fig. 5.a) 231 multiplied by the collection probabilities Fig. 4.b) and Fig. 5.b) 232 give the collected photo-carriers densities Fig. 4.c) and Fig. 5.c).



Fig. 4. Simulations for the EQE calculation (a) the generation256function (carriers.m $^{-2}$.s $^{-1}$), (b) the probability of collection of257the central pixel and (c) the density of photo-carriers collected258by the central pixel (carriers.m $^{-2}$.s $^{-1}$).259200200



Fig. 5. Simulations for the CTK calculation (a) the generation function (carriers.m⁻².s⁻¹), (b) the probability of collection of the central pixel and (c) the density of photo-carriers collected by the central pixel (carriers.m⁻².s⁻¹).

The EQE calculated from Fig. 4 is equal to 26.6 %. The CTK is found equal to 20.4 % which is calculated from simulations of the setting Fig. 5, normalized by the amount of collected carriers calculated from Fig. 4.

A. Nano-grating parameters

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In a 90 nm standard bulk CMOS process[40], the thickness of poly-silicium layer is 100 nm, the minimum structure width is 90 nm and the minimum spacing is 140 nm. This technology node allows fabrication of DTI[13] which are needed to reduce the cross-talking induced by the diffraction on the grating. The 1D grating parameters shown in Fig.6.a) are : the width (w), the spacing (s), the thickness (t) and the period (p). A thin layer of silicon nitride (Si_3N_4) is usually deposited during the fabrication process. There is an oxide layer of few nanometers under the Poly-Si gate, but it is not taken into account in the simulations due to its low impact and limited access to computing resources.



Fig. 6. a) A schematic poly-silicon nano-grating with indicated parameters : width (w), spacing (s), thickness (t) and period (p). b) The illustration of diffraction and total reflection.

Considering an incoming light at normal incidence θ_i , it is diffracted at the angles θ_m given by the Eq.5 where *m* is the diffraction order and *p* the period of the grating, Fig. 6.a) and Fig. 6.b).

$$\theta_m = \arcsin(\frac{m \times \lambda}{n_{Si} \times p})$$
(5)

To stay in the conditions of the total internal reflection on the DTI-silicon interface, the diffracted angle θ_m must be smaller than the upper limit defined in Eq.6 so the angle θ_c in Fig. 6.b) is small enough to yield total reflection. Indeed, when the angle of reflection θ_m is too small, the total reflection condition is not satisfied, the light is not totally reflected so goes partially to the adjacent pixel and the image quality is degraded. In another hand, in order to be reflected by the DTI and because the depth of the DTI is finite, the diffracted angle must be greater than the lower limit defined in Eq.7, where l_{pixel} the size of the pixel and D_{DTI} the depth of the DTI. If not satisfied, the light goes beneath the DTI and illuminates the adjacent pixel.

$$\theta_m < \frac{\pi}{2} - \arcsin(\frac{n_{SiO_2}}{n_{Si}})$$
(6)

$$\theta_m > \arctan(\frac{l_{pixel}}{2 \times D_{DTI}})$$
(7)

Applying this to a wavelength of 850 nm, a DTI depth of 4 μm and a pixel size of 6 μm , results in an optimal period range between 255 and 389 nm, with $n_{SiO2} = 1.45$ and $n_{Si} = 3.64$. Here, we consider periods allowing only the diffraction of orders 0 and

+/- 1, because there are no configurations where the diffraction 300
 angles of orders +/-1 and +/-2 are both between the limit angles 301
 defined above. 302

B. Influence of the DTI width

The DTI width is dead space for imaging, the larger DTI width 305 275 the smaller the photo-sensitive area. However, the DTI width 306 276 must not be too small in order to efficiently reflect the diffracted 307 277 light. Indeed, the reflected light could be coupled to the neigh- 308 278 boring pixel by frustrated total internal reflection leading to loss 309 279 a of energy reflected on the DTI. As illustrated Fig. 7.a), a part ³¹⁰ 280 of the light goes through the trench by optical tunneling effect. ³¹¹ 281 In order to optimize the DTI width, a simulation has been 312 282

²⁸³ carried out considering the DTI depth infinite. The calculated

²⁸⁴ CTK is presented in Fig. 7.b), the period of the nano-grating is

285 set to 350 nm to obtain the first order of diffraction. The CTK is less than 1% for DTI widths greater than 250 nm.



Fig. 7. (a) Illustration of frustrated total internal reflection inside a pixel (b) CTK as a function of DTI width considering the DTI depth infinite.

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In the remainder of this paper, a DTI width of 150 nm will be considered[13], it represents a CTK of 1.6 % and corresponds to a trade-off between the size of the photo-sensitive area and the crosstalk.

291 C. Grating parametrization

The simulation methodology was applied for the proposed pixel
structure (with a nano-grating) and with a DTI depth of 4 µm
as illustrated by the Fig. 1.c). The simulations are conducted by
stepping the period and the width of the nano-grating, looking
for the optimization of the EQE without damaging the CTK
compared to the standard structure. Fig. 8 shows the EQE and
the CTK enhancement as a function of the period and the width of the nano-grating.



Fig. 8. a) EQE and b) CTK as function of the period and width parameters of the nano-grating, the limit p > w + 140 nm of the calculated values is due to the fabrication process.

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period (nm)

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period (nm)

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The analytical result for the optimal period range (Eq. 5, 6, and 7), calculated previously, is also plotted in Fig. 8.b) (vertical dashed lines) and it shows that it is relatively well fitted to that of simulations. The analytical results are obtained considering an incident plane wave on the grating whereas in the simulations the plane wave is focused by the micro-lens before the grating, hence the slight differences observed between both models. The maximum EQE is reached for p = 360 nm and w = 195 nm, it is equal to 35.5 % which is an improvement of 33.5 % relatively to the standard pixel. It corresponds to a CTK of 19 % which is an enhancement of 6.9 % relatively to the standard pixel.

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Fig. 9 shows the collection function of the photo-carriers $S(\vec{r})$ for the pixel k. It can be seen the diffraction induced by the grating and the reflection on the pixel side caused by the DTI.



Fig. 9. The density of collected photo-carriers by the pixel k with a nano-grating (w = 195 nm; p = 360 nm).

The new design proposal includes two modifications from the standard pixel architecture, the DTI that replaces the STI and the implemented grating on top of the photodiode. In order to highlight which of these modifications affect the EQE and the CTK, figure 10 shows results of four different designs: (1) the standard design that was calculated previously, (2) a pixel architecture with DTI alone, (3) a pixel with a grating but without DTI and (4) the architecture with both grating and DTI. The grating parameters are set to the optimal period and width values calculated earlier in this section.



Fig. 10. EQE and CTK of a standard pixel, pixel with DTI alone, pixel with grating alone and pixel with both grating and DTI.

While the standard pixel and the pixel with DTI show the same EQE, the two designs that integrate grating show the same improvement in EQE. The grating implementation dominates the EQE increase. Besides, the grating architecture without DTI shows a drastic deterioration of the CTK, it is increased by

approximately 36.5 % whereas designs that contain DTI show 329 a decrease in CTK from 20.4 % to 19.2 % and 19 %. The DTI 330

implementation dominates the CTK decrease. 331

D. Polarimetric dependency 332

As the poly-silicon nano-grating is a 1D line, it generates a po-333 larization dependent optical response. The EQE and the CTK 334 diagrams for Transverse Magnetic (TM) and Transverse Electric 335 (TE) polarizations are given in Fig. 11.a), b) and Fig. 12.a, b) 336 respectively. The TE polarization (resp. TM) corresponds to an 337 excitation with an electrical field perpendicular (resp. parallel) 338 to the plane of incidence E_s (resp. E_v). 339



Fig. 11. EQE calculated with a source of (a) TM and (b) TE polarization.



Fig. 12. CTK calculated with a source of (a) TM and (b) TE polarization.

For the optimal values of the period and the width obtained 340 for a non-polarized light (p = 360 nm and w = 195 nm), EQE 341 (resp. CTK) is equal to 34.1 % (resp. 19.1 %) in polarization 342 TM and 36.9 % (resp. 18.8 %) in TE polarization. This weak 343 dependence on polarization is attributed to the thin thickness of 344 the grating (t = 100 nm) and could be made negligible by using 345 a 2D symmetrical grating, which is intrinsically independent of 346 polarization. 347

E. Spectral responses 348

The spectral response of a standard pixel and that of a pixel 349 382 with nano-grating was calculated. The grating parameters come 383 350 from the optimization at wavelength of 850 nm, presented in the 384 351 previous section (p = 360 nm; w = 195 nm). EQE and CTK are 385 352 plotted Fig. 13.a) and b), as a function of wavelength, the dotted 353 386 curve is for the standard pixel and the solid line is for the pixel 354 387 with embedded grating 355 388

The EQE is enhanced for wavelengths greater than 600 nm, 389 356 and it can be noticed a drop at wavelengths smaller than 500 nm. 390 357 This decrease is attributed to the optical losses due to absorption 391 358 in the Poly-Si grating that become more significant in this wave- 392 359 length range[39]. The CTK curves are globally similar, but the 393 360



Fig. 13. a) EQE and b) CTK as function of the wavelength, dotted line is the reference standard pixel, solid line is the pixel with implemented nano-grating.

CTK for the pixel with embedded grating is significantly lower than the CTK of the reference between 800 nm and 1000 nm.

In summary, the proposed design allows for a combined improvement in EQE (increase) and CTK (decrease) for the wavelengths of application, meaning a higher image quality with better sensitivity and better contrast than standard pixels for wavelengths between 800 and 1000 nm.

F. Angular responses 368

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The previous results are obtained with pixels illuminated by a plane wave source at normal incidence. These results already take into account the entire angular range provided by the microlens of the pixel. But in an imaging device, an upstream optical system focuses the light on the image sensor, meaning that the light comes with an angle of incidence on the pixel, even before the micro-lens. The angle seen by one pixel depends on its location in the pixel matrix and on the characteristics of the optical system. The pixels located on the edges of the matrix see a larger angle of incidence than the pixels in the center. So, for an imaging device to have homogeneous spatial image quality, it is important to minimize the EQE and CTK variations with the angle of incidence, shown in fig. 14.a) and b) respectively.



Fig. 14. a) EQE and b) CTK as function of the angle of incidence, dotted line is the reference standard pixel, solid line is the pixel with implemented nano-grating.

For all the angles of incidence studied here, the EQE and the CTK of the new architecture are improved compared to those of the standard pixel. The CTK variation trend of the grating pixel and the standard pixel is roughly the same for the two pixels. However, the EQE of the pixel with grating, drops from 35.5 % at normal incidence to 30.3 % at 30° , which is a larger variation than that of the standard pixel that stays in values of EQE between 26.6 % and 29 % for the same angular range. As it can be seen in figure 15.a), the transmission calculated at the interface SiO₂/Si just below the polysilicon nano-grating has the same trend than the EQE, meaning that the shape of the angular response depends is mainly defined by the transmission

of this interface. The introduction of a grating at the SiO2 / Si 440 394 interface changes its optical response by two additional effects: 441 395 more light penetrates into the silicon (anti-reflection effect) and 442 396 the optical path in the silicon is increased (diffracted orders). 397

Even if the grating cannot be considered as a homogeneous 444 398 medium (it diffracts in first orders), its optical behaviour gets 445 399 400 close to that of an antireflective layer. For example, for a true antireflective layer between SiO_2 and Si, its ideal thickness would 40 be $\lambda / (4\sqrt{n_{Si}n_{SiO2}}) \approx 92 \ nm$ for $\lambda = 850 \ nm$, a value very 402 closed to the thickness of 100 nm of the polysilicon layer. As an 403 illustration, Fig. 15.b) shows the EQE of the pixel as a function 404 of the thickness of the poly-silicon grating. The maximum EQE 405 is obtained for a thickness of 158 nm. This maximun depends 406 of the nano-grating reflection and how this reflection influences 407 the optical transmission of the all optical stack.



Fig. 15. a) Transmission at the interface $Si0_2/Si$ for the pixel with the integrated grating and the standard one b) EQE of the pixel with grating depending on the grating layer thickness.

408 As a conclusion for this section, the angular response of the 409 pixel with the implemented grating shows that it over performes 446 410 the standard pixel for a large angular range, making it relevant 447 411 for imaging with large angle optics. However, the difference in 448 412 quality between the edge and center pixels could be higher than ⁴⁴⁹ 413 that of imaging with a standard pixel. 414

5. INFLUENCE OF THE EPITAXIAL LAYER THICKNESS 415 AND THE DEEP TRENCH ISOLATION DEPTH 416

A. Spectral study for a fixed deep trench isolation depth 417

A common and easiest way to enhance the NIR detection of a 455 418 standard CIS is to thicken the epitaxial layer, allowing the car- $^{\scriptscriptstyle 456}$ 419 riers to be collected deeper in the silicon (life-time of carriers is 457 420 longer in the epitaxy than in the substract). So far, in this paper, 458 421 an epilayer thickness of 3 μ m has been considered, designs with 459 422 a 10 μ m epitaxial layer will now be considered. All configura-460 423 tions studied in this part are shown in Fig 16.a). Standard E3 461 424 and grating E3 are the names of the designs previously studied. 462 425 Standard E10 is for the standard pixel with an enlarged epitaxial 463 426 42 layer of 10 μ m and Grating E10 is a pixel with implemented 464 nano-grating on an epitaxial layer of 10 μ m. The DTI depth is 465 428 kept at its previous value of 4 μ m. Fig. 16.b) and Fig. 16.c) show 466 429 results for the EQE and CTK for the four different pixels designs. 467 430 All results are standardized by those of the standard E3 for ease 468 431 of comparison. 432 469

It can be seen that the thickening of the epitaxial layer leads 470 433 to an EQE enhancement, but also leads to a large deterioration 434 471 of the CTK. If averaged values between 700 nm and 1100 nm are 472 435 considered, the EQE of grating E3 is 20,4 % higher than the EQE 473 436 of standard E3 whereas the EQE of standard E10 is 39.9 % higher 474 437 than the one of standard E3. Then, the best EQE enhancement is 475 438 for grating E10 (68.3 %). Considering the crosstalk, it can be seen 476 439

that the CTK for grating E3 is better than the reference standard E3 (between 800 and 1000 nm). Grating E10 configuration is better than the standard E10. The 10 µm epitaxial layer degrades the CTK since the DTI depth of 4 μ m considered here is not deep enough to be sufficiently efficient. A deeper DTI might give better results. This parameter will be theoretically investigated in the next part of this paper.

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Fig. 16. a) schematic pixel design respectively for standard E3, grating E3, standard E10, grating E10. b) EQE and c) CTK as function of the wavelength.

At the wavelength of interest (850 nm), the EQE enhancement of "grating E3" structure is almost equivalent to that of "standard E10" its CTK is 60 % lower than that of "standard E10". So at 850 nm, the EQE of the design presented in this paper is equivalent to that of a pixel having an active layer more than three times thicker. While improving EQE by thickening the active layer leads to drastic deterioration of CTK, the design presented here improves both EQE and CTK.

B. Results for a variation of the epitaxial layer thickness and deep trench isolation depth at 850 nm

So far in this article, the depth of the DTI was fixed at a value of 4 μ m, in this part, the influence of the DTI depth on EQE and CTK is studied for several epitaxial layers. Corresponding results are shown in Tab.2. For each combination of epitaxial thickness and DTI depth, the EQE and CTK are reported. These results are obtained for a wavelength of 850 nm and the grating parameters are set to p = 360 nm and w = 195 nm for all configurations. DTI depth of 6 μ m and 8 μ m will be studied, but as it is complicated to fabricate DTI deeper than 4 μ m, the results are shown for theoretical knowledge, as a process development anticipation.

A first observation is that the CTK is deteriorated comparatively to the reference for DTI depths of 0 and 2 μm and is enhanced for values higher than 4 μm , whatever the thickness of the epitaxial layer. This corresponds to the minimum depth needed to have the first diffracted order of the nano-grating reflected by the DTI.

In addition, it can be seen that the EQE is almost independent of the DTI depth. Indeed, diffraction by nano-grating extends the light path in the silicon layer in a same proportion with and without DTI. When the DTI is not deep enough, light diffracted

DTI	FOM	Epitaxial thickness (μm)							
		3	4	5	6	7	8	9	10
reference	EQE	26.6%	29%	31%	32.7%	34.1%	35.1%	35.9%	36.6%
	CTK	20.4%	21%	23.8%	26.7%	29.2%	31%	32.4%	33.6%
0 µm	EQE	35.5%	38.6%	41.3%	43.4%	45%	46.5%	47.5%	48.4%
	CTK	26.6%	28%	30%	31.7%	32.9%	33.9%	34.6%	35.3%
2 µm	EQE	35.5%	38.6%	41.3%	43.5%	45.1%	46.4%	47.5%	48.4%
	CTK	25.6%	27%	29.1%	30.9%	32.2%	33.2%	34%	34.7%
4 µm	EQE	35.5%	38.7%	41.4%	43.6%	45.3%	46.6%	47.7%	48.5%
	CTK	19%	16.7%	21.3%	24.5%	27%	28.9%	30.2%	31.2%
6 µm	EQE	35.7%	38.7%	41.7%	44.5%	46.2%	47.5%	48.5%	49.3%
	CTK	15.8%	15%	14.1%	13.1%	21.7%	24.7%	26.7%	27.9%
8 µm	EQE	36%	39%	41.8%	44.5%	47.1%	49.6%	50.1%	50.7%
	CTK	12.7%	12.5%	12.3%	12.1%	11.8%	11.4%	22%	24.4%

Table 2. EQE and CTK calculation for different DTI and epitaxial layer thicknesses, results are presented for the grating parameters that optimize the EQE for a wavelength of 850 nm

by a nanograting propagates toward neighbour pixels and the
 number of photons collected by a pixel remains roughly the
 same because of the periodicity of the pixels.

DTI are efficient when their depth is greater than or equal to 480 that of the epitaxial layer. For example, at DTI depth of 6 μ m the 516 481 CTK is 15.8 %, 15 %, 14.1 % and 13.1 % respectively for epitaxial 482 517 thicknesses of 3 μ m, 4 μ m, 5 μ m and 6 μ m. Then the CTK jumps 483 to 21.7 % for an epitaxial thickness of 7 μ m and is growing higher 484 with thicker epi-layer. An optimum is generally observed when 485 518 the DTI depth equals the thickness of the epitaxial layer. Since 486 the carrier life-time in the epitaxial layer is higher than that in the 519 487 substrate (its doping level is much higher), most of the electrical 520 488 cross-talk occurs in the epitaxial layer where the carriers likely 489 to diffuse in neighboring pixels will be blocked by the DTI. 490 521

491 6. CONCLUSION

The near-infrared enhancement of the sensitivity of a standard 492 525 frontside pixel of a CMOS image sensor with an integrated poly-493 526 silicon nano-grating has been demonstrated through electro-527 494 528 optical numerical simulations. The pixel is designed so that 495 529 it does not require any additional process steps compared to 496 530 manufacturing a standard CMOS. It has been shown that the 497 531 diffractive effect of a nano-grating combined together with deep 498 532 trench isolation can lead to improved near-infrared detection 499 533 without deteriorating the crosstalk compared to a standard pixel. 500 534 The angular dependency of the pixel is slightly deteriorated by 501 535 the nano-grating but is always more efficient for angles of inci-536 502 dence between 0 and 30°. At a wavelength of 850 nm, it has been 537 503 shown that the near-infrared detection enhancement is about 538 504 33.5 % and the crosstalk is reduced by 6.9 %. The implementation 505 540 of the nano-grating could lead to imaging in the near-infrared 506 541 with better sensitivity and image contrast. The improvement 507 in EQE provided by the nano-grating is equivalent to that of 508 an active layer 3 times thicker but without the deterioration of 509 544 CTK associated with this thickening. The best configurations 510 545 are obtained with an epitaxial layer thickness equals to the DTI 511 depth. For multi-spectral applications, each pixel could have its 512 547 own grating parameters optimized for its operating wavelength. 548 513

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The authors declare no conflicts of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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