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

ELIE COBO<sup>1,\*</sup>, SÉBASTIEN MASSENOT<sup>1</sup>, ALEXANDRE LE ROCH<sup>1</sup>, FRANCK CORBIÈRE<sup>1</sup>, VINCENT GOIFFON<sup>1</sup>, PIERRE MAGNAN<sup>1</sup>, AND JEAN-LUC PELOUARD<sup>2</sup>

<sup>1</sup>Institut Supérieur de l'Aéronautique et de l'Espace, Université de Toulouse, Toulouse, France

<sup>2</sup>Université Paris-Saclay, CNRS, Centre de Nanosciences et de Nanotechnologies (C2N), 91120 Palaiseau, France

\*Corresponding author: [elie.cobo@isae-supaero.fr](mailto:elie.cobo@isae-supaero.fr)

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

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  $\mu\text{m}$  and 5  $\mu\text{m}$  whereas, at a wavelength of 850 nm, the penetration depth after which the light is absorbed by 63% is over 18  $\mu\text{m}$  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 photon-traps to improve the NIR detection of a single photodiode large of 30  $\mu\text{m}$ . More recently, a single micro-hole structure per pixel

has been optically investigated for a silicon based CIS[24] showing a drastic increase on the optical efficiency through simulations and needing a specific etching step.

This work is focused on FrontSide Illuminated (FSI) devices and presents a solution for a NIR enhanced imaging sensor that does not need adding any supplementary steps in the process flow of a standard CIS fabrication. To doing this, the implementation of a poly-silicon nano-grating, designed from the layer of fabrication of the transistors gate, has been studied. In the same way, poly-silicon nano-gratings have already been implemented as reflectors[25–27] or color filters[28], it makes use of the transistor gate layer to design a nano-grating in order to reflect light or to be wavelength selective. In this paper, it is designed to 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 etching steps of the transistors' gate fabrication, resulting in no additional manufacturing costs.

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

## 2. METHODOLOGY

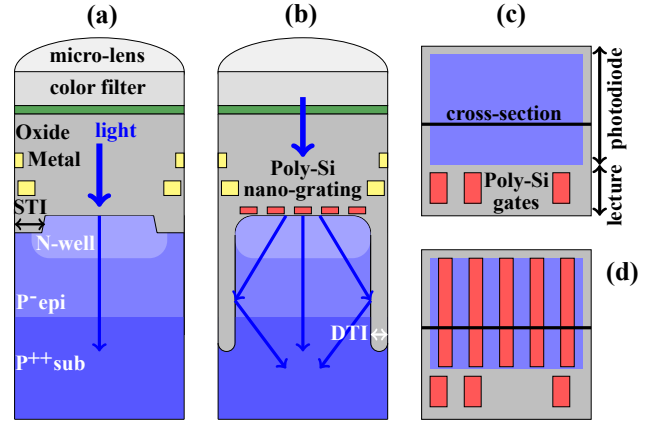
### A. Pixel design

Figure 1.a) is a schematic cross sectional view of an FSI CIS pixel (standard pixel) it is composed of a silicon substrate on which a Si-epitaxial layer is grown. The epitaxial layer is P doped ( $P^-$  epi) two orders of magnitude less than the substrate ( $P^{++}$  sub). An N doped region (N-well) is introduced in the epitaxial layer in order to create the PN junction. At the top of the device are oxide layers and metallizations used to connect pixels and lecture nodes. The color filter is a spectral selective layer used in most cases for color reconstitution (e.g : Red, Green and Blue color filters), the layer between the oxide stack and the color filter is a passivation layer made of silicon nitride and on top of the pixel, the micro-lens is there to concentrate the light on the PN junction area, enhancing the fill factor and it also allows avoiding light scattering by the metallizations[31]. As an image sensor is made up of a matrix of pixels, each pixel needs to be electrically isolated from each other, which is achieved by the use of Shallow Trench Isolation (STI), a trench in silicon filled with oxide in order to prevent electric current leakage between adjacent pixel. Fig. 1.b) is the schematic cross-sectional view of an FSI CIS pixel architecture with integrated Poly-Si nano-grating and Deep Trench Isolation (DTI). As illustrated, the grating diffracts light and DTI replaces standard isolation in order to confine diffracted light inside the photodiode.

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

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].

$$\underbrace{\frac{\text{collected carriers}}{\text{incoming photons}}}_{\text{EQE}} = \underbrace{\frac{\text{collected carriers}}{\text{absorbed photons}}}_{\text{IQE}} \times \underbrace{\frac{\text{absorbed photons}}{\text{incoming photons}}}_{\text{OE}} \times 100 \quad (1)$$

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

139 A high EQE leads to a higher sensitivity, and a lower CTK 176  
 140 leads to a higher image quality. These two parameters will be 177  
 141 used to determine the enhancement of the new pixel design over 178  
 142 the standard pixel design. In order to obtain the best image 179  
 143 quality, the pixel design has to maximize the EQE and minimize 180  
 144 the CTK. Most of the time, it will be a compromise between the 181  
 145 two characteristics. 182

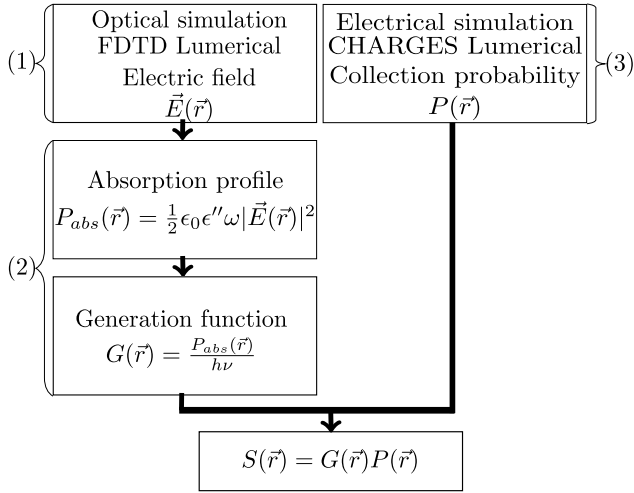
### 146 3. SIMULATIONS METHODOLOGY

#### 147 A. Collected photogenerated-carriers

148 Three steps are needed for the simulation of EQE and CTK, 186  
 149 the first one is the calculation of the optical excitation  $E(\vec{r})$ [33] 187  
 150 (1 in Fig. 2), then comes the calculation of the absorption in 188  
 151 the silicon leading to the photo-carriers generation function 189  
 152  $G(\vec{r})$  (2 in Fig. 2). The last part is the calculation of the photo- 190  
 153 carriers transport in the photodiode leading to the photo-carriers 191  
 154 collection probability  $P(\vec{r})$ [34] (3 in Fig. 2). The first two parts 192  
 155 involve optical simulation and the third part concern electrical 193  
 156 simulation. The total amount of collected photo-carriers,  $S_k(\vec{r})$ , 194  
 157 of the pixel  $k$ , is calculated by Eq.3 where  $\vec{r}$  is the position vector. 195  
 158 The integral is done over the photo-active region.

$$S_k = \int G(\vec{r})P(\vec{r}) d\vec{r} \quad (3)$$

159 The electrical calculation of  $P(\vec{r})$  is done by considering the 196  
 160 response to a generation rate point source located at  $\vec{r}$ . This 197  
 161 impulse source is swept over all  $\vec{r}$  in the simulation domain 198  
 162 in order to achieve a complete map of  $P(\vec{r})$ . Therefore,  $P(\vec{r})$  199  
 163 is calculated once for a specific junction architecture and then 200  
 164 used for arbitrary optical inputs. The Block diagram in Fig. 2 201  
 165 summarizes the different calculation steps to obtain the total 202  
 166 amount of collected photo-carriers for a specific illumination. 203



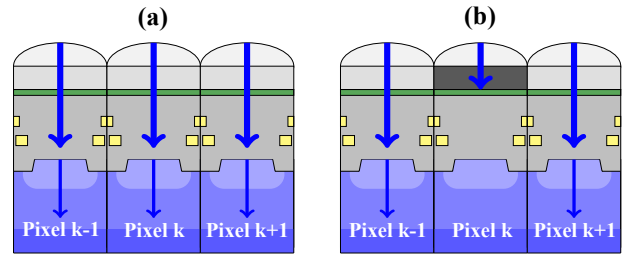
167 **Fig. 2.** Block diagram of the coupling between electrical and 168  
 169 optical simulation 170

167 FDTD Lumerical software is used to solve the time- 204  
 168 dependent Maxwell differential equations and calculate the 205  
 169 electric field  $\vec{E}(\vec{r})$  inside the photodiode for a specific optical 206  
 170 excitation. From this electric field, the absorbed power  $P_{abs}(\vec{r})$  207  
 171 is calculated, it gives the number of absorbed photons through 208  
 172 Planck relation. The Lumerical software CHARGES is used 209  
 173 to calculate the number of collected photo-carriers through the 210  
 174 calculation of carriers transport equations (drift and diffusion 211  
 175 current) with Finite Element Method (FEM). 212

#### 176 B. External Quantum Efficiency and Crosstalk calculation

177 In order to obtain the EQE and the CTK, two different simula- 178  
 179 tions settings will be considered. Both of them involve three pix- 179  
 180 els to take into account the collection of carriers photo-generated 180  
 181 in neighbouring pixels, named crosstalk. As it is shown in Fig. 181  
 182 1.c) the pixel is not symmetric, so the cross-section chosen for 182  
 183 the 2D simulations (red line in the figure) is in the orientation 183  
 184 that yields the most part of the crosstalk. Indeed, in the other 184  
 185 orientation pixels are more distant from each other due to the 185  
 186 lecture node, limiting the crosstalk.

The first setting is represented in Fig. 3.a) and the second 186  
 187 setting is represented in Fig. 3.b). The two are similar, but one 187  
 188 contains a filter transparent to the wavelength of calculation and 188  
 189 in the other the central filter above the photo-diode of interest 189  
 190 is opaque whereas filters above its adjacent pixels are transparent. 190  
 191 For this filter layer, the real part of the refractive index is set 191  
 192 at 1.5 and the imaginary part is set at 1.2 for the opaque one 192  
 193 (transmitted intensity is more than 150 times lower than the 193  
 194 incident one) and 0 for the transparent ones.



194 **Fig. 3.** Schematic cross-section of (a) the setting used for calcula- 195  
 196 tion of the total amount of collected photo-carrier and (b) the 196  
 197 setting used for calculation of the crosstalked photo-carriers 197

194 Running optical and electrical simulations with settings of 195  
 196 Fig. 3.a) allows the calculation of the total amount of collected 196  
 197 photo-carriers by the pixel  $k$ , running them with the setting of 197  
 198 Fig. 3.b) allows to obtain the number of collected photo-carriers 198  
 199 by crosstalk. EQE is calculated from the setting of Fig. 3.a), 199  
 200 though it contains all the photo-carriers collected by the pix- 200  
 201 els  $k$  including those resulting from crosstalk. The results are 201  
 202 presented as the response of an unpolarized plane wave source 202  
 203 which will be the average response of a parallel and a perpen- 203  
 204 dicular polarized sources, as in Eq.4 where  $|E|^2$  is the modulus 204  
 205 square of the electric field results from an unpolarized source. 205  
 206  $|E_s|^2$  (resp.  $|E_p|^2$ ) is the modulus square of the electric field 206  
 207 resulting from simulation in which the electric field is perpen- 207  
 208 dicular (resp. parallel) to the plane of incidence. 208

$$|E|^2 = \frac{1}{2}|E_s|^2 + \frac{1}{2}|E_p|^2 \quad (4)$$

#### 209 C. Parameters of the model

210 In table 1 are listed the geometric properties and the doping level 210  
 211 of layers presented in Fig.1. The passivation layer is the inter- 211  
 212 mediate layer of  $Si_3N_4$  between the oxide stack and filters. The 212  
 213 simulations are run considering a pixel width of  $6 \mu m$ , which is 213  
 214 a size that allows good dynamic range and with a DTI depth of  $4 \mu m$  214  
 215 and an epitaxial layer thickness of  $3 \mu m$ , typically optimized 215  
 216 for low dark current and good EQE. 216

217 Regarding the optical properties of the different materials 217  
 218 used, the silicon  $Si$  data are taken from Schinke et al.[35] for 218  
 219 extinction coefficient values and from Vogt[36] for refractive 219

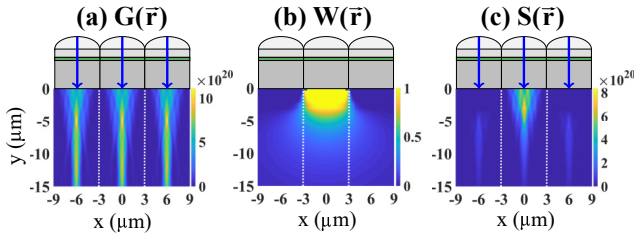
**Table 1.** Simulations parameters

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

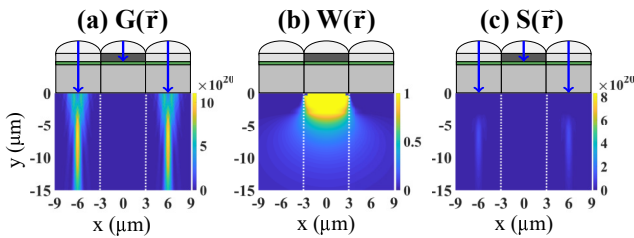
index values. Fused silica  $SiO_2$  and silicon nitrides  $Si_3N_4$  data are taken from Phillip[37, 38]. Poly-silicon is considered to have the same optical properties as crystalline silicon[39] and metals are set as perfect electrical conductors.

#### 4. NANO-GRATING OPTIMIZATION AND RESULTS

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



**Fig. 4.** Simulations for the EQE 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. $m^{-2}.s^{-1}$ ).

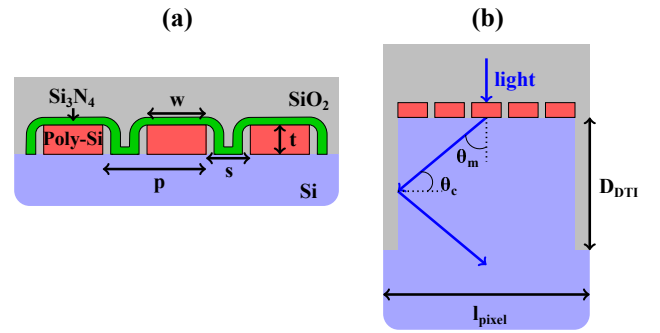


**Fig. 5.** Simulations for the CTK calculation (a) the generation function (carriers. $m^{-2}.s^{-1}$ ), (b) the probability of collection of the central pixel and (c) the density of photo-carriers collected by the central pixel (carriers. $m^{-2}.s^{-1}$ ).

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

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  $\theta_i$ , it is diffracted at the angles  $\theta_m$  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).

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

To stay in the conditions of the total internal reflection on the DTI-silicon interface, the diffracted angle  $\theta_m$  must be smaller than the upper limit defined in Eq.6 so the angle  $\theta_c$  in Fig. 6.b) is small enough to yield total reflection. Indeed, when the angle of reflection  $\theta_m$  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.

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

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

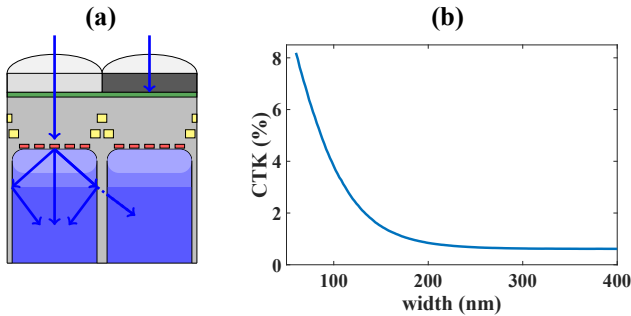
Applying this to a wavelength of 850 nm, a DTI depth of 4  $\mu m$  and a pixel size of 6  $\mu m$ , results in an optimal period range between 255 and 389 nm, with  $n_{SiO_2} = 1.45$  and  $n_{Si} = 3.64$ . Here, we consider periods allowing only the diffraction of orders 0 and

271 +/- 1, because there are no configurations where the diffraction 300  
 272 angles of orders +/-1 and +/-2 are both between the limit angles 301  
 273 defined above. 302

### 274 B. Influence of the DTI width

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

282 In order to optimize the DTI width, a simulation has been 312  
 283 carried out considering the DTI depth infinite. The calculated 313  
 284 CTK is presented in Fig. 7.b), the period of the nano-grating is 314  
 285 set to 350 nm to obtain the first order of diffraction. The CTK is 315  
 less than 1% for DTI widths greater than 250 nm.

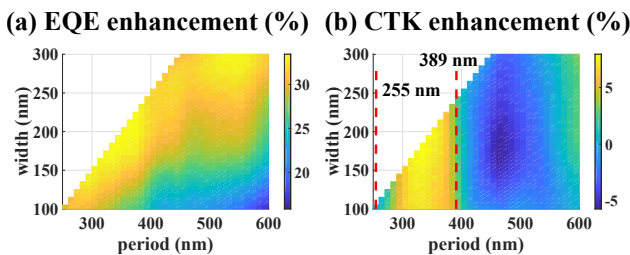


286 **Fig. 7.** (a) Illustration of frustrated total internal reflection  
 287 inside a pixel (b) CTK as a function of DTI width considering  
 288 the DTI depth infinite. 289

286 In the remainder of this paper, a DTI width of 150 nm will be  
 287 considered[13], it represents a CTK of 1.6 % and corresponds to  
 288 a trade-off between the size of the photo-sensitive area and the  
 289 crosstalk. 290

### 291 C. Grating parametrization

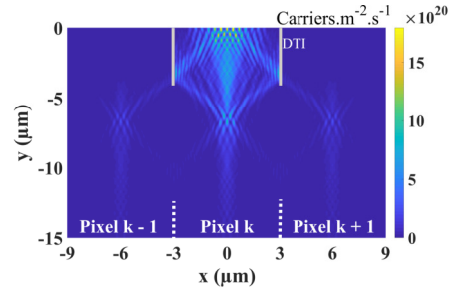
292 The simulation methodology was applied for the proposed pixel  
 293 structure (with a nano-grating) and with a DTI depth of 4 μm  
 294 as illustrated by the Fig. 1.c). The simulations are conducted by  
 295 stepping the period and the width of the nano-grating, looking  
 296 for the optimization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



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

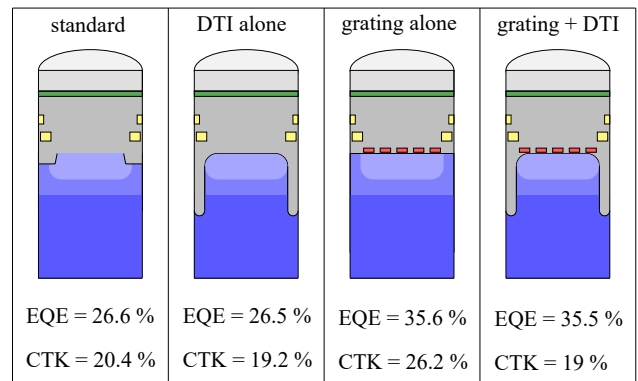
300 The analytical result for the optimal period range (Eq. 5, 6,  
 301 and 7), calculated previously, is also plotted in Fig. 8.b) (vertical  
 302 dashed lines) and it shows that it is relatively well fitted to that of  
 303 simulations. The analytical results are obtained considering an  
 304 incident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

311 Fig. 9 shows the collection function of the photo-carriers  $S(\vec{r})$   
 312 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.



313 **Fig. 9.** The density of collected photo-carriers by the pixel  $k$   
 314 with a nano-grating ( $w = 195 \text{ nm}$  ;  $p = 360 \text{ nm}$ ). 315

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



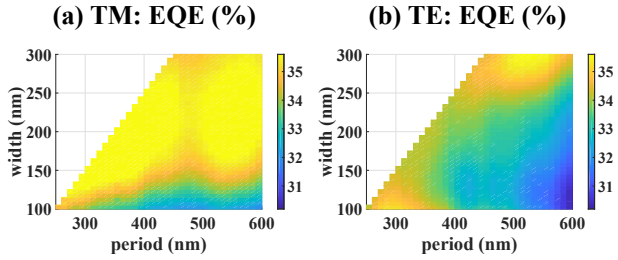
323 **Fig. 10.** EQE and CTK of a standard pixel, pixel with DTI  
 324 alone, pixel with grating alone and pixel with both grating  
 325 and DTI. 326

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

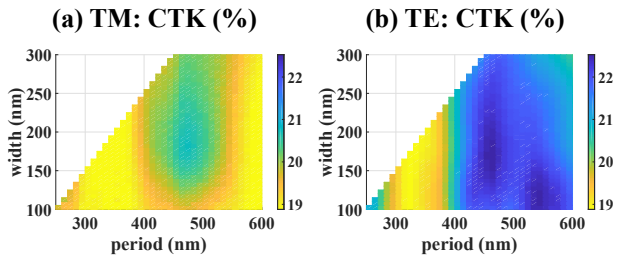
329 approximately 36.5 % whereas designs that contain DTI show  
 330 a decrease in CTK from 20.4 % to 19.2 % and 19 %. The DTI  
 331 implementation dominates the CTK decrease.

#### 332 D. Polarimetric dependency

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



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



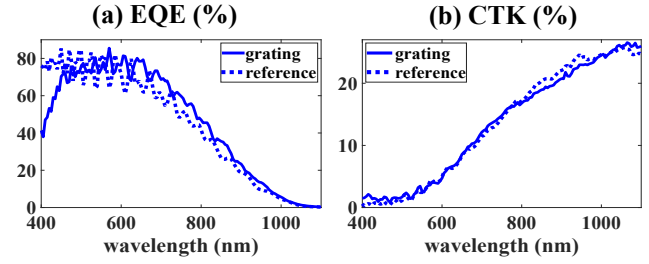
342 Fig. 12. CTK calculated with a source of (a) TM and (b) TE  
 343 polarization.

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

#### 348 E. Spectral responses

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

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



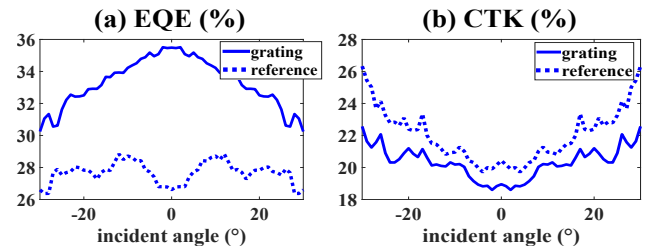
361 Fig. 13. a) EQE and b) CTK as function of the wavelength,  
 362 dotted line is the reference standard pixel, solid line is the  
 363 pixel with implemented nano-grating.

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

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

#### 368 F. Angular responses

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

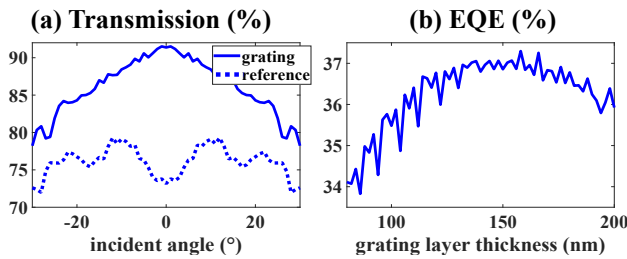


381 Fig. 14. a) EQE and b) CTK as function of the angle of inci-  
 382 dence, dotted line is the reference standard pixel, solid line is  
 383 the pixel with implemented nano-grating.

384 For all the angles of incidence studied here, the EQE and the  
 385 CTK of the new architecture are improved compared to those  
 386 of the standard pixel. The CTK variation trend of the grating  
 387 pixel and the standard pixel is roughly the same for the two  
 388 pixels. However, the EQE of the pixel with grating, drops from  
 389 35.5 % at normal incidence to 30.3 % at 30°, which is a larger  
 390 variation than that of the standard pixel that stays in values of  
 391 EQE between 26.6 % and 29 % for the same angular range. As  
 392 it can be seen in figure 15.a), the transmission calculated at the  
 393 interface  $SiO_2/Si$  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

394 of this interface. The introduction of a grating at the SiO<sub>2</sub> / Si 440  
 395 interface changes its optical response by two additional effects: 441  
 396 more light penetrates into the silicon (anti-reflection effect) and 442  
 397 the optical path in the silicon is increased (diffracted orders). 443

398 Even if the grating cannot be considered as a homogeneous 444  
 399 medium (it diffracts in first orders), its optical behaviour gets 445  
 400 close to that of an antireflective layer. For example, for a true an-  
 401 tireflective layer between SiO<sub>2</sub> and Si, its ideal thickness would  
 402 be  $\lambda / (4\sqrt{n_{Si}n_{SiO_2}}) \approx 92 \text{ nm}$  for  $\lambda = 850 \text{ nm}$ , a value very  
 403 closed to the thickness of 100 nm of the polysilicon layer. As an  
 404 illustration, Fig. 15.b) shows the EQE of the pixel as a function  
 405 of the thickness of the poly-silicon grating. The maximum EQE  
 406 is obtained for a thickness of 158 nm. This maximum depends  
 407 of the nano-grating reflection and how this reflection influences  
 the optical transmission of the all optical stack.



**Fig. 15.** a) Transmission at the interface SiO<sub>2</sub>/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 performs 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. 450  
 414

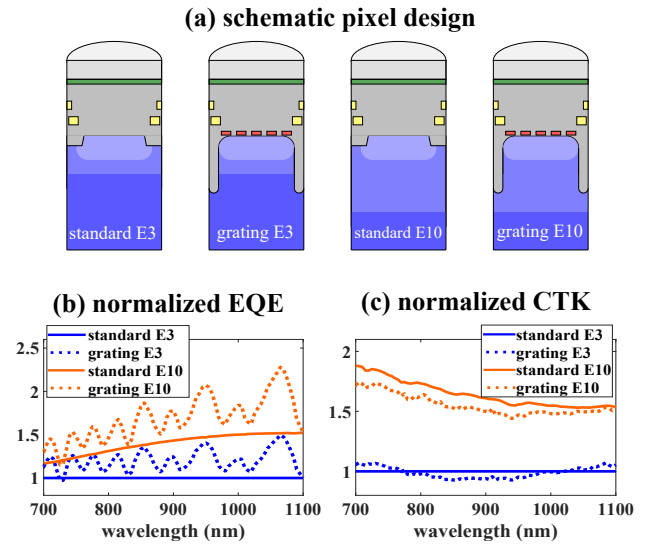
## 415 5. INFLUENCE OF THE EPITAXIAL LAYER THICKNESS 416 AND THE DEEP TRENCH ISOLATION DEPTH

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

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

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

that the CTK for grating E3 is better than the reference standard 440  
 E3 (between 800 and 1000 nm). Grating E10 configuration is 441  
 better than the standard E10. The 10  $\mu\text{m}$  epitaxial layer degrades 442  
 the CTK since the DTI depth of 4  $\mu\text{m}$  considered here is not deep 443  
 enough to be sufficiently efficient. A deeper DTI might give 444  
 better results. This parameter will be theoretically investigated 445  
 in the next part of this paper.



**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.

446 At the wavelength of interest (850 nm), the EQE enhancement 447  
 448 of "grating E3" structure is almost equivalent to that of "standard 449  
 450 E10" its CTK is 60 % lower than that of "standard E10". So at 850 451  
 452 nm, the EQE of the design presented in this paper is equivalent 453  
 454 to that of a pixel having an active layer more than three times 455  
 thicker. While improving EQE by thickening the active layer 456  
 leads to drastic deterioration of CTK, the design presented here 457  
 improves both EQE and CTK. 458

### 459 B. Results for a variation of the epitaxial layer thickness and 460 461 deep trench isolation depth at 850 nm

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

472 A first observation is that the CTK is deteriorated compar-  
 473 atively to the reference for DTI depths of 0 and 2  $\mu\text{m}$  and is  
 474 enhanced for values higher than 4  $\mu\text{m}$ , whatever the thickness  
 475 of the epitaxial layer. This corresponds to the minimum depth  
 476 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

**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

DTI	FOM	Epitaxial thickness ( $\mu\text{m}$ )							
		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 $\mu\text{m}$	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 $\mu\text{m}$	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 $\mu\text{m}$	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 $\mu\text{m}$	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 $\mu\text{m}$	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%

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

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

## 491 6. CONCLUSION

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

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## 516 DICLOSURES

517 The authors declare no conflicts of interest.

## 518 DATA AVAILABILITY

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

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