Wide dynamic logarithmic InGaAs sensor suitable for eye-safe active imaging

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ABSTRACT

In this paper, we present a simple method to analyze the injection efficiency of the photodiode interface circuit under fast shuttering conditions. This simple model has been inspired from the companion model for reactive elements largely used in CAD. We have demonstrated that traditional CTIA photodiode interface is not adequate for active imaging where fast and precision shuttering operation is necessary. Then we will present a direct amplification based photodiode interface which can provide an accurate and fast shuttering operation on photodiode. These considerations have been used in NIT's newly developed ROIC and corresponding SWIR sensors both in VGA 15um pitch (NSC1201) and also in QVGA 25um pitch (NSC1401).

1. Introduction

Among the available SWIR solid state detectors such as PbS, InGaAs, MCT, etc, InGaAs remains the most promising because of its high quantum efficiency and its ability to operate at room temperature. Technical progress is constant on this detection material. The dark current at room temperature, one of the most important parameters, has passed from uA/cm^2 to nA/cm^2 [1] and even to sub-nA/cm^2 [2] in a predictable future.

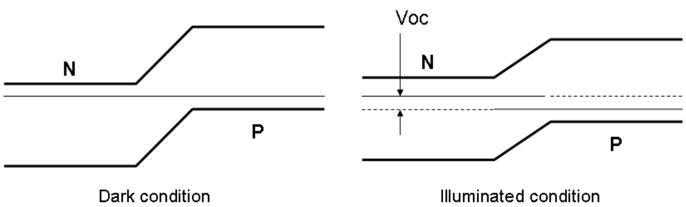

Figure 1. In a illuminated PN junction, the electron and hole Fermi levels are separated in P and N regions. This gives measurable potential difference across the PN junction.

In previous communications [3] [4] [5] [6], we have introduced a new operation mode for junction based photo-detector array by using the junction photodiode as an individual solar cell. With this operation principle, the open-circuit voltage of the junction photodiodes gives an uniform image proportional to the logarithm of the incident optical power. The physical operation principle is illustrated in Fig. 1. The open-circuit voltage on an illuminated junction is generated by the Fermi level splitting in N and P regions. The signal uniformity depends mainly on doping level distribution and minority lifetime in the detection material. With modern fabrication process, these parameters are well controlled and this explains the excellent uniformity that we have observed both in silicon but also in III-V material based photodiode arrays. In solar cell mode sensor, the open-circuit voltage depends on the incident optical power, but not on the incident optic energy like in an integration mode sensor.

This gives a very large operation dynamic range. The instant dynamic range observed on NIT's QVGA and VGA InGaAs sensors is better than 120dB. This huge instant dynamic range makes these sensors excellent candidate for real-time observation applications such UAV, border surveillance, etc. Other interesting behaviour is that for a short light impulse, the solarcell mode photodiode, even operating in logarithmic region, still conserves the capability to integrate this light impulse and gives constant signal amplitude despite of logarithmic compression on the ambient light. This makes our logarithmic InGaAs pixel an excellent candidate for active imaging.

In this paper, we will analyse why a CTIA based pixel design cannot match the need of active imaging by using a new companion model based method. Then we will present also some measured result on the injection efficiency and also shutter efficiency on our logarithmic pixel and also compare them to those of a traditional CTIA based sensor. The NIT SWIR sensors presented in this paper have the reference NSC1201 for VGA 15um pitch and NSC1401 for QVGA 25um pitch, both are available for commercial orders.

2. Fast global shuttering for active imaging and companion model analysis

Active imaging, also called gated imaging, uses a short laser pulse to illuminate the scene. The reflected laser light will be sensed by an image sensor with synchronized global shutter. In order to maximize the laser power, it's preferable to use laser wavelength which is relative safe to human eye, since the operator of the active imaging camera is also quite close. 1.55um SWIR wavelength is considered as an eye-safe wavelength and InGaAs based sensors are the most suited for this wavelength. The active illumination can be of 2 kinds: spot-like and point-like. Spot-like illumination illuminates a limited area of a scene and permits an observation by a SWIR camera and point-like illumination permits to highlight a specific point in the scene often for designation purpose.

In both cases, the global shutter on the SWIR sensor should be able to provide: 1) an exposure window as narrow as that of the laser pulse width with high efficiency; 2) well controlled temporal position of the exposure window and 3) zero or negligible sensitivity outside the exposure window. So traditional photodiode interfaces in ROIC design cannot always answer these criterions. Here we propose a companion model based method which can give simple and intuitive analysis of a photodiode interface to evaluate the injection efficient under short exposure time.

In a CMOS photodiode interface, the only reactive element is capacitor. As shown in Fig. 2, a capacitor under differential mode can be replaced simply by a conductance. The value of this conductance depends both on the capacitance and also the differential interval, this conductance is called the companion model of the capacitor. When all the capacitors in the photodiode interface circuit are replaced their companion models, then a simple DC analysis will give the injection efficiency from the photodiode to the output of this interface circuit.

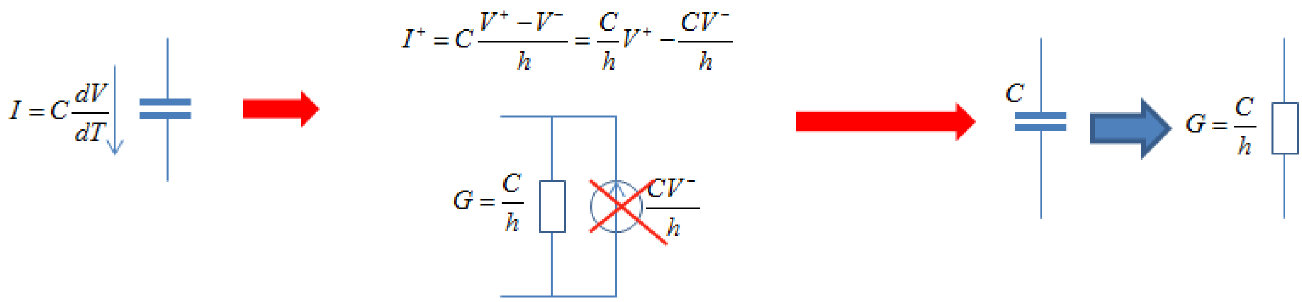

Figure 2. Companion model of a capacitance for a differential analysis.

Fig. 3 gives an example of a classical CTIA based photodiode interface circuit and its equivalent circuit with companion models. We can simply get the injection efficiency using a DC analysis: $\eta = \frac{i1}{i1+i2} = \frac{C1*Co + C1*Gm*h}{(C1+Co)*C2 + C1*Co + C1*Gm*h}$. By using the following parameters which represent those from realistic CMOS design, we can plot the injection efficiency in function of the exposure time in Fig. 4. We can see clearly that a traditional CTIA photodiode interface can only be adequate for an exposure time larger than 10us. For active imaging, this exposure time is normally under 100ns, the CTIA is not a good choice for this purpose. Over-biasing a CTIA pixel can give some improvement, but it's very limited.

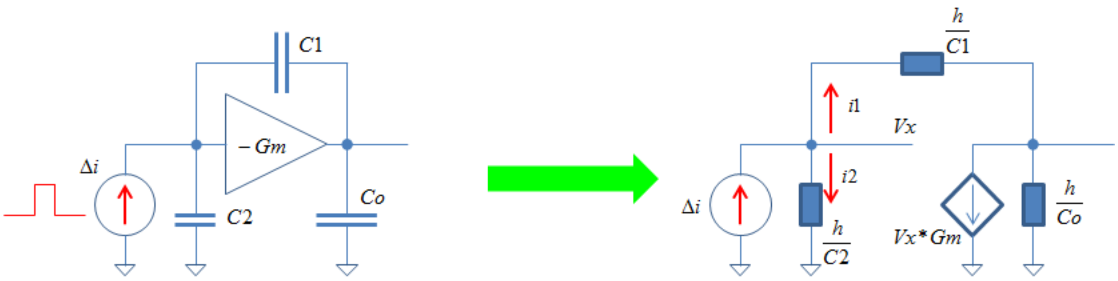

Figure 3. CTIA photodiode interface and its equivalent circuit with companion models.

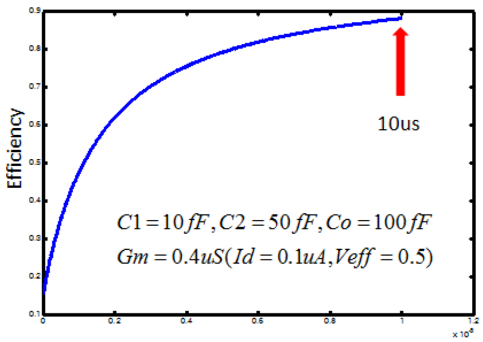

Figure 4. Injection efficiency of CTIA photodiode circuit in function of exposure time.

3. Efficient global shuttering for active imaging

Another requirement in active imaging is global shutter efficiency that means the pixel should be respond to incident light outside the exposure window. In a traditional CTIA based photodiode interface, the shutter efficiency cannot be 100% at the vicinity of the exposure window. This parasite sensitivity outside the exposure window can affect the active imaging performance. For observation oriented active imaging, it will increase the efficiency of distance gating effect and for designation oriented active imaging, this can give erroneous results. The reason is that the reset operation in CTIA photodiode interface is made by closing a MOS switch transistor across the integration capacitor (C1 in Fig. 3). When a laser pulse is received by photodiode, the photodiode potential cannot be maintained especially when the bias current of the operational amplifier is low. We can test the shutter efficiency by using a short pulse laser shining on the sensor and monitoring the sensor output and laser pulse phase shift. An example is shown in Fig. 5 where a 4ns pulse width laser at 1550nm shines on NIT SWIR sensor and a CTIA traditional SWIR sensor. We can see that the shutter efficiency is bad before the exposure window and NIT SWIR gives an almost perfect exposure window with high shutter efficiency.

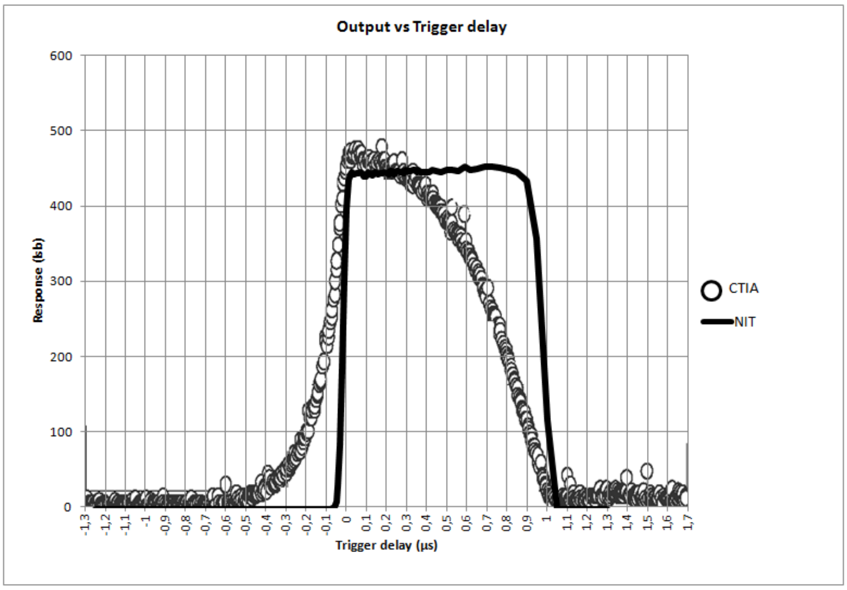

Figure 5. Shutter efficiency comparison between NIT SWIR sensor and a CTIA based SWIR sensor.

4. Pixel Structure & Operation

The electrical schematic of NIT SWIR sensor pixel is shown on Fig. 6. The photodiode front-end circuit, in pure voltage mode, is made with non-inverting amplifier with a fixed gain. The in-pixel amplifier's output can then be connected to one of the 3 pixel's capacitances to store the amplifier's output signal. Finally, each one of the pixel's storage capacitance is connected to a dedicated column bus with a simple source follower. The 3 in-pixel storage capacitances access is fully programmable by the user using external control signals. This means that the user can choose any one of the memory to store the reset or exposed signal levels during exposition. The ROIC flexible controls allows the user to implement the conventional Integration While Reading (IWR) with CDS mode and Integration Then Reading (ITR) with CDS readout mode as well as a differential imaging mode that can be used for active imaging to suppress background illumination. Special cares have been applied in order to keep these control signals as isochrones as possible for a better gating precision over the pixel array.

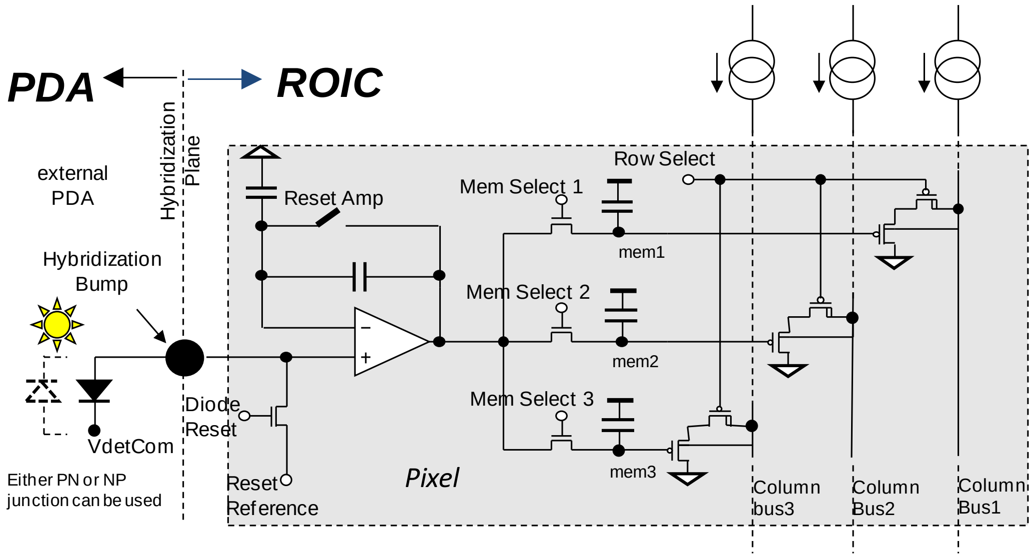

Figure 6. NSC1201 Pixel schematic.

5. Applications

The military, the special agencies and law enforcement personnel need now new equipments for making clear identification of individuals through field operations or covert surveillance . Eye safe SWIR active imaging solutions is one of the most promising available technologies that can tackle these challenges. Use of a continuous semiconductor laser à 1.5µm (eye-safe) with narrow field of view coupled with a QVGA Widy SWIR cameras from NIT had first been used by ISL for making a demonstrator in 2014 (Figure. 7). More recently this French-German institute has carried comparative tests with several InGaAs camera makers and finally selected NIT WiDy SWIR 640U-S for its performances as well as size, weight and power efficiency. The capacity to offer Wide Dynamic Range enhances the image performance both by active imaging at night to cope with high reflective materials and by daytime to deal with high and rapidly changing contrast conditions.

Fig 7. Pelis Demonstrator *(Courtesy of ISL)*

Fig 8; Scene @800meters shot with WiDy SWIR 640U-S with 200ns exposure *(Courtesy ISL)*

6. Conclusion

In this paper, we have introduced a new analyse method based on companion model to analyse photodiode interface circuit under fast shuttering operation for InGaAs sensors. We have shown that traditional CTIA based photodiode interface is not adequate for active imaging applications. We presented also measured results from newly developed NIT VGA and QVGA SWIR sensors under fast shuttering operation conditions and shown a considerable improvement compared to CTIA based pixel design. These newly developed SWIT InGaAs sensors (NSC1201 and NSC1401) are actually available for commercial orders.

7. References

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