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Ultra-sensitive SWIR FPA with enhanced quantum efficiency based on electron multi-injector

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ABSTRACT

By leveraging a three-dimensional device structure to decouple the optical and electronic areas of the detectors, Electron Injector (EI) technology has proven capable of surpassing the current performance of commercial short-wave infrared (SWIR) cameras. The improvement in sensitivity enabled by a nanoscale electronic area, however, comes at the cost of a decrease in quantum efficiency: the diffusion length of the minority carriers limits the area over which a photo-generated carrier can be collected at the small electron injector junction before recombining. This intrinsic limitation hinders the prospect of further improvements of the EI detector performance.

We here present a novel device architecture consisting of multiple nanoscale electron injectors connected to the same contact and constituting one individual pixel: by appropriate spacing of the injectors within the diffusion length of the photogenerated excess carriers, the fill factor of such multi-injector pixel can be considerably improved. The presented design was successfully implemented into an integrated FPA for SWIR imaging, showing excellent pixel yield, and a sensitivity of ~10 photons. While the high sensitivity is enabled by the small size of the 1μm injectors, the multi-injector design allows to achieve an area fill factor or ~20% of the 30x30μm pixel area, which is considerably higher than that of a single-injector design.

In summary, we demonstrate a highly sensitive SWIR FPA based on 1μm electron multi-injector design, which allows for a substantial improvement of the imager's quantum efficiency and sensitivity.

Keywords: Electron Injector detector, Quantum efficiency, SWIR detectors, Infrared imaging, FPA

SENSITIVITY OF ELECTRON INJECTOR PHOTODETECTORS

Optical detectors with internal gain are very attractive for designing compact and highly sensitive optical detection systems, since they allow to amplify the signal from the detectors over the electronics noise floor, effectively eliminating the noise contribution from the read-out circuitry, enabling much higher detection sensitivity.

Mainly two mechanisms have been pursued for generating optical gain in detectors: avalanche multiplication and transistor action. Avalanche-based photodiodes (APDs) are characterized by high operating bias voltage and high dark current, necessary to promote the impact ionization process, thus

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hindering their integration with standard CMOS technology[1]. Conversely, heterojunction phototransistors (HPTs) possess a large optical gain at low bias voltage and are compatible with electronic circuit components in terms of their epitaxial structures and fabrication process.

The HPT electron-injection (EI) detector techonology[2] is a specific detector architecture that combines a large-area absorbing layer with a nano-scale electron injector for internal gain. By leveraging the additional degrees of freedom in its geometry to decrease the junction capacitance, the EI technology has already proven capable of surpassing the performance of state-of-the-art infrared detectors for application in both SWIR cameras[3] and optical coherence tomography (OCT) systems[4].

Unlike conventional photon detectors and imagers, which are based on planar sensing elements made of a stack of semiconductors, EI uses low-dimensional charge confinement in a 3D structure to achieve highly sensitive photon detection, while maintaining a large area layer for optical absorption. The advantage of such architecture is evident when analyzing the sensitivity of a photodetector, typically expressed by its normalized detectivity as[5]:

$$D^* = \frac{\lambda}{hc}\sqrt{\frac{A_o}{A_e}}\,\eta\,\sqrt{\frac{1}{2\,(G+R)t}}$$

where λ is the wavelength, h is Planck's constant, c is the speed of light, A_o and A_e are the optical and electronic areas of the detectors, respectively, η is the quantum efficiency, and G and R are the optical and thermal generation and recombination rates, respectively. Here, it is clear that the ratio A_o/A_e represents an additional degree of freedom that can be leveraged by EI detectors to enhance their sensitivity[6-7].

For this reason, theoretical and experimental work has motivated the push towards further shrinking in size of the electronic area in order to achieve yet higher sensitivity[8-9]. However, this improvement in sensitivity comes at the cost of a decrease in quantum efficiency, as the actual device sensitivity deviates from the above expression, when some of the excess carriers generated over the large-area absorber, A_o, cannot effectively transport to the small electronic area, A_e, before recombining.

A schematic of the EI gain mechanism and quantum efficiency is offered in Figure 1 for the case of a small sub-micron electronic area injector, coupled to a 30 μm absorbing layer: is it evident that the chance of photogenerated electron-hole pair to transport to the electron injector pillar is not uniform for absorption events across the large absorber, leading to a sub-unity quantum efficiency[10-12]. This lateral transport is partly aided by the electric field distribution imposed by the bias, as shown in Figure 1b, and it is contrasted by defect trap states at the surface of the absorber.

MULTI-INJECTOR ARCHITECTURE DESIGN AND FABRICATION

We demonstrate an EI detector architecture that allows to alleviate the detrimental effect on quantum efficiency of small electron injectors, significantly increasing the area fill factor of the detectors while maintaining a small device capacitance. The proposed architecture, shown in Figure 1, encompasses the use of multiple small electron injectors to form a single pixel of the FPA: such injectors are separated in space so as to span a larger portion of the optical area of the absorber, without the need for large electronic area.

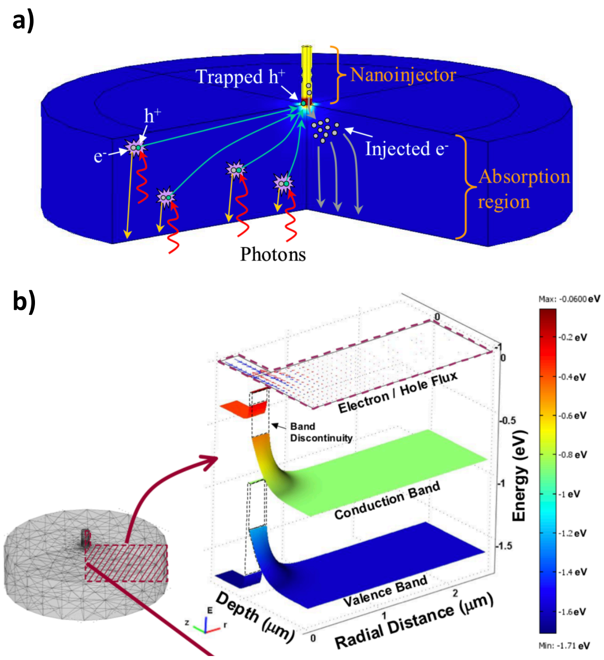

Figure 1. a) Schematic of the geometric design of the EI detector, combining a large-area absorption region with a small-volume hole- trapping multiplication region (nanoinjector); b) Cross-sectional 3D band structure showing lateral band bending for charge compression and confinement

An FPA based on EI multi-injectors was fabricated starting from a planar epitaxial structure entirely based on the InP/InGaAs materials system, and consisting of 200 nm of n^+ (10^{16} cm^{-3}) InP injector, 25 nm of $In_xGa_{1-x}As_yP_{1-y}$ transitional quaternary layer, 100 nm of p^+ (2.0×10^{17} cm^{-3}) $In_{0.53}Ga_{0.47}As$ trapping layer, 1500 nm of n^- ($< 1 \times 10^{15}$ cm^{-3}) $In_{0.53}Ga_{0.47}As$ absorber[13]. The epi-layers are grown on InP substrate using metal organic chemical vapor deposition (MOCVD).

The multi-injectors were defined lithographically and etched, following a standard EI fabrication procedure. An SEM image of the lithographically defined 2-by-2 multi-injector is shown in Figure 2b. Subsequently, BCB spin coating and curing (250 °C) was implemented for passivation and planarization, followed by the etch-back of BCB in order to expose the emitter contact metal. Finally, the top contact was evaporated so that the emitters of the four injectors can be connected to each other. A schematic of the multi-injector EI photodetector, hybridized under a single pixel contact, by means of embedding in a BCB polymer matrix is shown in Figure 2a. A microscope image of a series of 2-by-2 multi-injector pixels including the common top contact is shown in Figure 2c.

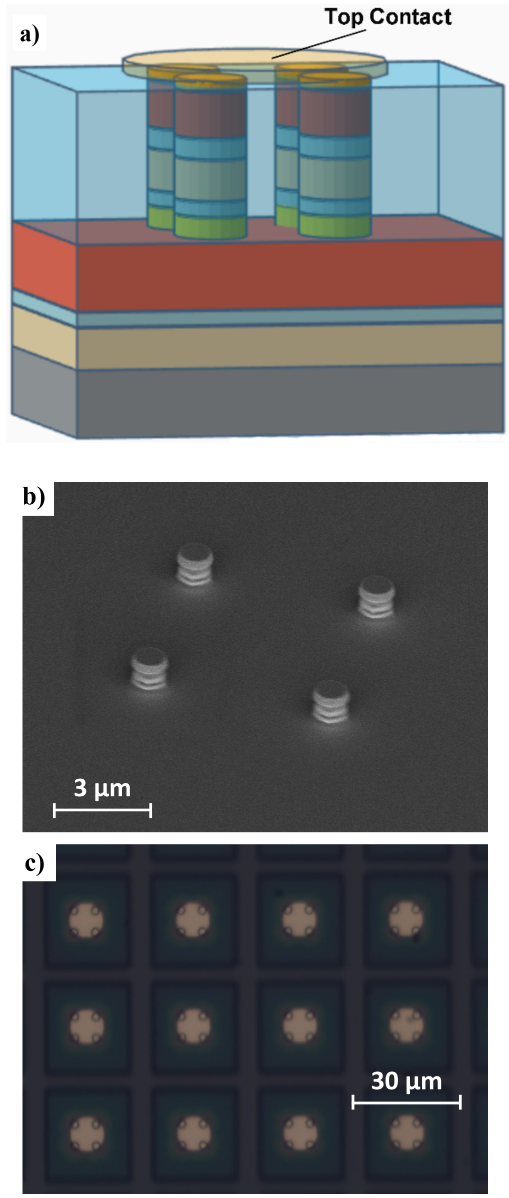

Figure 2. a) Schematic of the fabricated multi-injector EI detectors, displaying the connection of 4 injectors to a single pixel contact; b) SEM image of the 4 mesas after the etching process; c) Microscope image of a few multi-injector isolated pixels, with a common contact for each pixel, including 4 injectors.

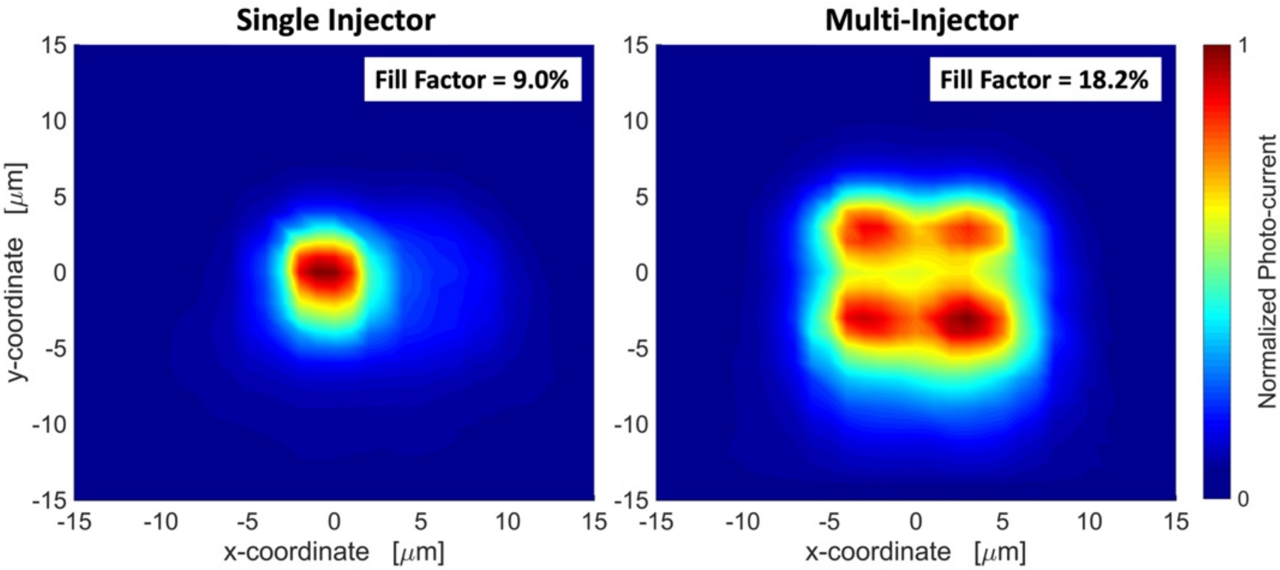

Figure 3. Area fill factor of a single-injector and a multi-injector EI detector pixels compared.

QUANTUM EFFICIENCY ENHANCEMENT

First, the area fill factor of the multi-injector EI architecture was characterized in comparison to the single injector, by scanning a 1550 nm beam, focused to a FWHM of 3 μm, across the pixel pitch. The comparison of the scanned 2D mapping of the pixel response as a function of the position of the illumination spot is reported in Figure 3. The two pixels compared consist in a single injector of 2 μm diameter and a 2-by-2 multi-injector of 1 μm diameters, corresponding to the same total electronic area, hence same device junction capacitance, C_{TOT}. Interestingly, the fill factor is more than doubled when the multi-injector design is implemented, from 9% to 18% of the pixel area.

The main advantage of the multi-injector strategy is that it allows to increase the area fill factor without the need for a large injector which would imply large device capacitance. This is confirmed through measurement of the device rise time as a function of incident optical power, which is known to follow:

$$\tau_{RISE} = 2.2\,\beta\,(\tau_{\mathrm{TR}} + r_d C_{TOT})$$

where β is the device gain, τ_{TR} is the base transit time, r_d is the dynamic resistance, and C_{TOT} is the total junction capacitance. The measured rise time as a function of the optical illumination power for the same two devices reported above is shown in Figure 4. In particular, the dependency on both terms of the above equation (i.e. the constant base transit time, and the $r_d C_{TOT}$ product, which is power-dependent as $r_d = \frac{k_B T/q}{I_d + I_{ph}}$), are exhibited by the devices, as represented by the dashed lines in the figure.

The behavior of the detector rise time as a function of optical power for a 2 μm single injector and a 1 μm multi-injector EI is indeed confirmed to be identical, due to the two architectures having the same junction area, hence the same capacitance, as discussed above.

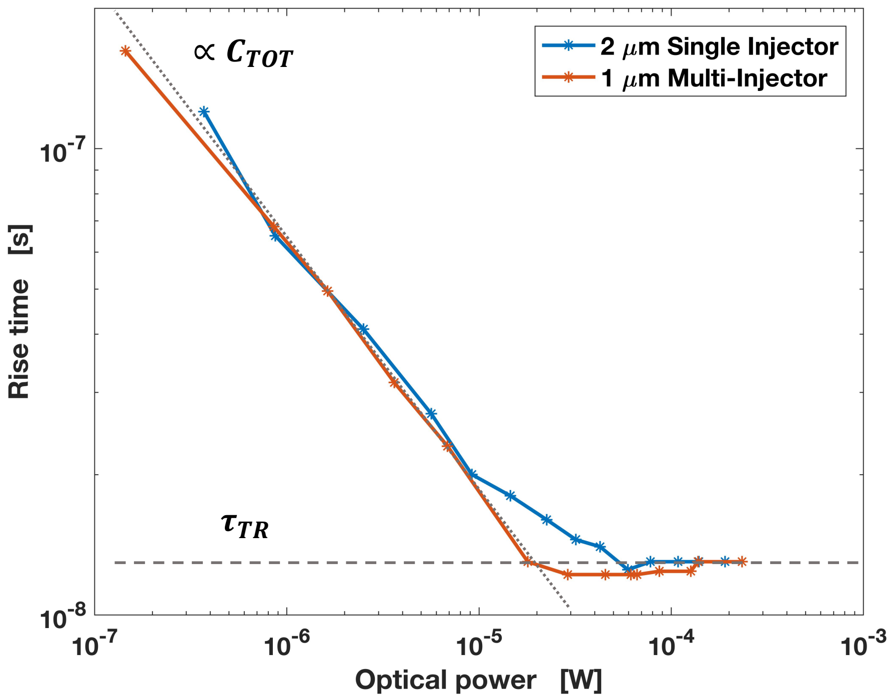

Figure 4. Rise time of single and multi-injector EI detectors as a function of optical power. The two terms of the above equation are highlighted by the dashed and dotted lines.

CONCLUSION

We demonstrated an EI detector architecture that allows to alleviate the detrimental effect on quantum efficiency of small electron injectors, significantly increasing the area fill factor of the detectors while maintaining a small device capacitance. These devices exhibit a more than 2-fold increase in fill factor at no apparent costs for the responsivity and speed of the devices, thanks to the modest increase in electronic area.

The presented strategy is fully compatible with the hybrid integration of the FPA with a Si ROIC, and can be further developed to optimize the number, spacing and geometry of the injectors, in order to reach the ideal tradeoff point between increase in fill factor and decrease in detector speed and sensitivity.

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