Analysis of temporal resolution in a backside-illuminated multi-collection-gate image sensor employing Monte Carlo method

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Abstract Ultra-high speed image sensors have been developed and applied to various field of science and engineering. Toward the temporal resolution of 1ns, we have proposed a new structure of an image sensor, a backside-illuminated multi-collection-gate image sensor (BSI MCG image sensor). In order to evaluate the performance, it is necessary to simulate the paths of photoelectrons from the generation site to a collecting gate, which is affected by several factors, including randomness in motion of the electrons. In order to address this factor, a Monte Carlo method can be an effective tool. In this paper, the temporal resolution of the sensor is studied for different thickness of the chip by using the Monte Carlo simulator.

Keywords: Ultra-high speed image sensor, backside-illuminated, multi-collection-gate, Monte Carlo simulation

1. Introduction

An ultra-high speed image sensor with in-pixel storage has been developed and its application is expanding in various fields of advanced science and engineering. Since the pioneering work on a CCD image sensor of 1M frames per second [1], Etoh et al. have been updating the highest frame rate of the image sensor and the latest device achieved 16M frames per second (frame interval is 62.5ns) [2]. Toward the frame interval of 1ns, we have recently proposed a new structure of image sensor, a backside-illuminated multi-collection-gate image sensor (BSI MCG image sensor) [3,4].

In order to evaluate the performance of the BSI MCG image sensor, it is necessary to simulate the paths of photoelectrons from the generation site to the collecting gate. This varies according to several factors [4], and randomness in motion of the electrons is considerable in this design of the sensor operating on the sub-nanosecond time scale. It is difficult to address this factor by using a device simulation based on the drift diffusion model. A Monte Carlo method can be an effective tool and some factors affecting the temporal resolution of the sensor have been studied by using this simulation method [6].

In this paper, the traveling time of photoelectrons from the generation site to the collecting gate and its variation are studied for different thickness of the chip by using the Monte Carlo simulation.

2. Structure of BSI MCG image sensor

In the simulation in this paper, we used the pixel design reported in [4], we here describe the brief outline of the structure and operation of the design. In the BSI MCG image sensor, each pixel has multiple collection gates (six in this study) surrounding the center of the pixel, and a storage gate which accumulates a frame's signal electrons is attached to each collection gate. Signal electrons generated from incident photons within the pixel area are guided by the p-well layer which prevents the signal electrons from migrating to the storage and transfer gates, and collected by one assigned collection gate (collecting gate) to which a higher gate voltage is applied (A1 in **Fig.1** left side).

In the operation for image capturing, signal electrons generated on the backside travel toward the front side in accordance with the potential distribution and are collected by the collecting gate. On the back side, a thin p+ layer is formed to eliminate the dark current by recombination with the holes filling the layer. Also a strong negative bias voltage (V_B) is applied to the back side for generating the potential gradient which sends signal electrons toward the front side. The whole area except the channel stop forms a plane buried CCD channel, which is depleted before image capturing. The channel potential at the collecting gate is higher than those of other collection gates, but slightly lower than the channel potential of the storage gates. Electrons collected by the collecting gate are automatically drained to the storage gate and accumulated there. The channel at the collecting gate is always depleted, which keeps the very high travel speed of the signal electrons passing through the collecting gate. The speed suddenly lowers at the storage gate, since charges are accumulating there during the image capturing phase.

3. Monte Carlo simulation

The temporal resolution of the BSI MCG image sensor theoretically depends on a distribution of the traveling time from the generation sites to the collecting gate in front-side of signal photoelectrons. For analyzing the performance of the BSI MCG image sensor which operates on the sub-nanosecond time scale, randomness in motion of the electrons is considerable for estimating the temporal resolution of the sensor. In order to evaluate that, it is necessary to calculate the paths of individual photoelectrons by simulating their motion under the influence of applied electric field and scattering processes, i.e., phonon scatterings, scattering with ionized impurities, and impact ionization at high electric field. The Monte Carlo method can be an effective tool to address these factors. Here, we use the full band Monte Carlo simulation model which is the most accurate model [5] to analyze a photoelectron transport in the proposed

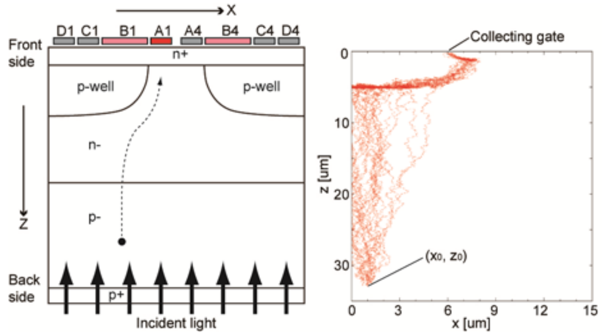

Fig.1 Cross section of the multi-collection-gate image sensor (left), and an example of electron trajectories obtained from the Monte Carlo simulation (right).

image sensor. In the simulation, the potential distribution, which is calculated based on the design described in [4], is provided to the Monte Carlo simulator as a reference table, and the 2-dimensional motion of photoelectrons is calculated.

In this study, the traveling time of photoelectrons from the generation sites to the collecting gate is evaluated for different thickness of the chip. In order to simulate this, the generation sites of the photoelectron in z direction (z_0) is changed. Number of particle is 1000 for each simulation. Fig.1 right-side shows an example of electron paths of randomly selected 20 samples generated at x_0=1.0 μ m. Although each photoelectron generated near the back side shows random motion due to the phonon scatterings, it moves to the collecting gate on the front side in accordance with the potential gradient.

4. Results

Fig.2 shows the histogram of the travel time for different generation sites. The mean traveling time and standard deviation of the traveling time for each condition were calculated based on the simulation results of 1000 samples. Backside voltage (V_B) was -42V. In the case of x_0=7.5 μ m (the center of the pixel), the mean traveling time for z_0=30 μ m, 20 μ m, and 10 μ m were 0.49ns (σ = 0.0428ns), 0.35ns (σ = 0.0434ns), and 0.22ns (σ = 0.0448ns), respectively. In the case of x_0=1.0 μ m (near the pixel boundary), the mean traveling time for z_0=30 μ m, 20 μ m, and 10 μ m were 0.78ns (σ = 0.2064ns), 0.67ns (σ = 0.227ns), and 0.56ns (σ = 0.217ns), respectively. These results are summarized in **Fig. 3**.

5. Conclusion

In this paper, the temporal resolution of the sensor was evaluated for different thickness of the chip by using the Monte Carlo simulator. The results are summarized as follows: (1) The mean traveling time linearly decreased depending on the thickness of the chip. (2) The standard deviation of the traveling time stay much the same if the thickness of the chip is changed. This suggests that the temporal resolution can be reduced by confining the generation sites in planar (x and y) direction rather than by reducing the thickness of the chip.

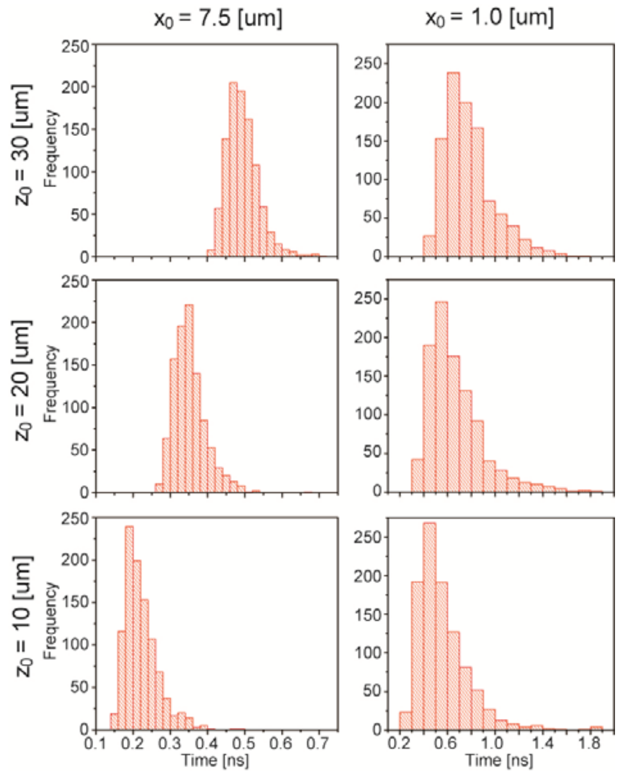

Fig.2 Histogram of the traveling time of the photoelectrons.

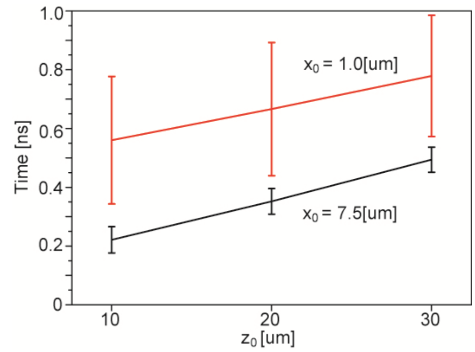

Fig.3 The mean traveling time and standard deviation of the traveling time

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