Toward Super Temporal Resolution by Controlling Horizontal Motions of Electrons

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Abstract The theoretical temporal resolution limit of silicon (Si) image sensors is 11.1 ps. The super temporal resolution (STR) is defined as a frame interval less than this limit. The temporal resolution of burst image sensors is significantly affected by "mixing" of signal electrons traveling from different starting positions. For example, the penetration depths of photons incident to a surface of a photodiode (PD) disperse exponentially, resulting in a related distribution of the arrival times of photoelectrons to the other end. The temporal resolution is proportional to the standard deviation of the arrival time. This paper proposes measures to suppress various mixing phenomena during the travel of the signal electrons: (1) a Ge PD for visible light to practically eliminate the effect of the vertical mixing caused by the distribution of the penetration depth, (2) an inverted pyramid PD to efficiently suppress the horizontal mixing, and keep a 100% fill factor, (3) a resistive gate to linearize the potential profile to maximize the drift velocity in the diffusion layer, and (4) technologies to squeeze the arrival area of the electrons to minimize the horizontal mixing in the diffusion layer.

Key words: Super temporal resolution, Image sensor, Germanium, Resistive gate

1. Introduction

Theoretically. the highest frame rate of silicon (Si) image sensors for green light of 550 nm is 90.1 Gfps (the temporal resolution, 11.1 ps) [1]. We defined a frame interval shorter than this limit as the super-temporal-resolution (STR) [2]. For the critical field at which the drift velocity reaches 95% of the fully saturated drift velocity, the "mixing" effect on the temporal resolution dominates over the diffusion effect [3]. This paper proposes countermeasures to control various phenomena causing the mixing in backside-illuminated (BSI) burst image sensors (BIS).

In 2013, we proposed a BSI BIS with the structure shown in Fig. 1 [4]. The temporal resolution for the sensor mainly depends on mixing of signal electrons that travel different distances in three different travel elements indicated with arrows and an ellipse in Fig. 1:

(1) vertical mixing in the PD indicated with (↕),
(2) horizontal mixing in the PD (⬭), and
(3) horizontal mixing in the diffusion layer (→ ←).

For example, the vertical mixing is caused by the exponential distribution of the penetration depths of incident photons to the PD. The temporal resolution limit of Si image sensors was derived for this mixing effect with an additional minor diffusion effect [1]. Therefore, to achieve the STR, the PD needs to be made of a material with a higher absorption coefficient than Si, such as Ge, GaAs, and InP as shown in Fig. 2.

We proposed an inverted pyramid to suppress the horizontal mixing in the PD, keeping the 100% fill factor (Fig. 5) [5]. A narrow column-like PD with an on-chip micro-lens can also practically eliminate the horizontal mixing in the PD [6].

The last remaining issue is the horizontal mixing due to electrons horizontally passing through the diameter of the trajectories of the electrons

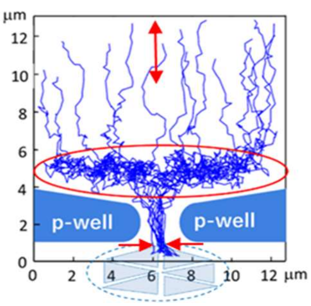


Fig. 1 A backside-illuminated burst image sensor with three elements causing "mixing", (↕, ⬭, and → ←)

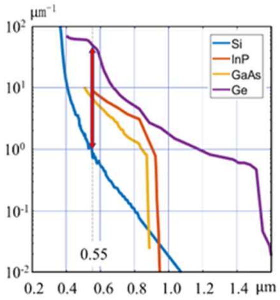


Fig. 2 Absorption coefficients for PD materials for visual and near-infrared light vs. wavelength.

collected to the center, and radially delivered to the in-pixel memory elements in the diffusion layer.

This paper summarizes our previous work to decrease the temporal resolution of the BSI BIS, and further discusses countermeasures to mitigate the horizontal mixing in the central area of the diffusion layer by introducing resistive gates having used in an old CCD technology and technologies to squeeze the diameter of the trajectories of the signal electrons.

2. Suppression of Mixing in PD

2.1 Vertical Mixing in a Ge PD

For intrinsic Si and Ge, Fig. 2 shows the absorption coefficients vs. wavelength. Fig. 3 shows the drift velocities and the diffusion coefficients vs. the E-field [1]. The absorption coefficient of Ge is more than 50 times that of Si. The 95% saturation drift velocities are about 9.1×10^{6} cm/sec for Si, and 5.8×10^{6} cm/sec for Ge. The critical fields, i.e., the E-fields corresponding to the 95%-saturated drift velocities, are about 25 kV/cm for Si and 4 kV/cm for Ge.

Fig. 4 shows the theoretical and practical temporal resolution limits for Si and Ge estimated with such data by using the expression of the temporal resolutions derived by us [**Appendix**], and Monte Carlo (MC) simulations [2]. The theoretical and practical temporal resolutions for Si are respectively 11.1 ps and 45.2 ps. Those for Ge are 0.25 ps and 1.45 ps, which are small enough to achieve the STR.

2.2 Horizontal Mixing in a Pyramid PD and a Column PD

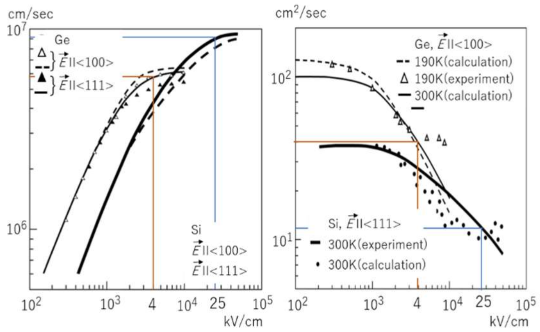
To suppress the horizontal mixing, an inverted pyramid PD was proposed as shown in Fig. 5. The pyramid PD is particularly suitable for ultrafast X-ray imaging, since an X-ray cannot be focused with common optical devices.

For the pyramid PD and the column PD, signal electrons hit the PD walls. Boron is doped to create a negative potential to reduce the collision probability. While the negative potential along the wall reduces the collision probability, it decreases the vertical drift velocity. Fig. 6 shows that there is an optimal concentration of the Boron doping over the wall to balance the collision probability and the temporal resolution [6].

3. Suppression of Horizontal Mixing in a Diffusion Layer

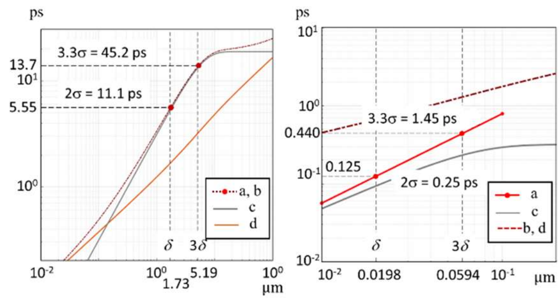
3.1 Mixing around the Pixel Center

Fig. 7 shows a structure of the BSI BIS to increase the frame count, named Hanabi, meaning fireworks in Japanese [6]. Fig. 7c shows a potential profile along a travel route of signal electrons



(a) (b)

Fig. 3 (a) Drift velocities and (b) diffusion coefficients vs. E-field for intrinsic Si and Ge



(a) Si (b) Ge

Fig 4 Standard deviations of arrival times vs. thicknesses of PDs and the theoretical and practical temporal resolutions for incident light of 550 nm (a: MC simulations, b: approximate expressions (1)-(3), c: mixing components, d: diffusion components in **Appendix**)

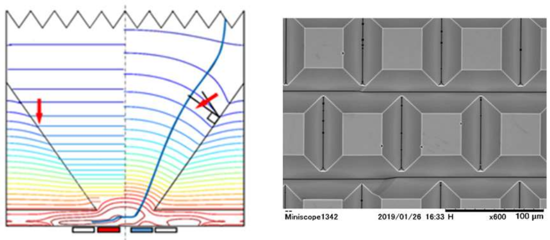
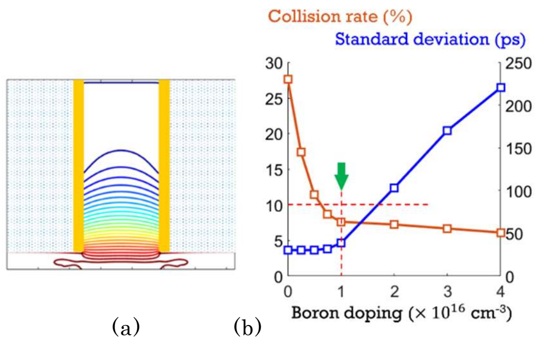
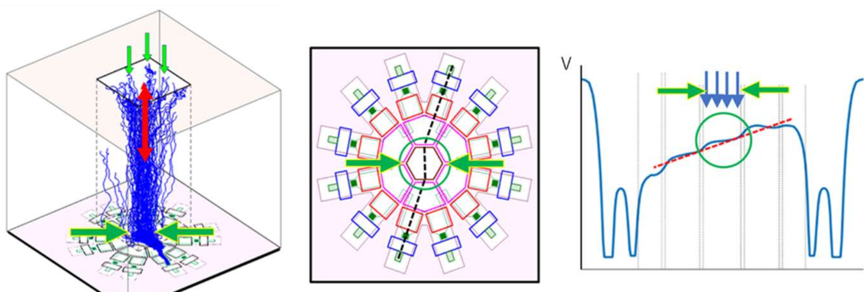


Fig. 5 A pyramid PD and a test process



(a) (b)

Fig. 6 (a) A column PD with the Boron doping on the wall ( ), (b) collision and standard deviation of the arrival time of electrons vs. the wall Boron concentration



(a) (b) (c)

Fig. 7 A BSI branching-gate image sensor "Hanabi" (a) Electron trajectories (MC) simulation, (b) Gates, (c) Potential profile along the dashed line in (b).

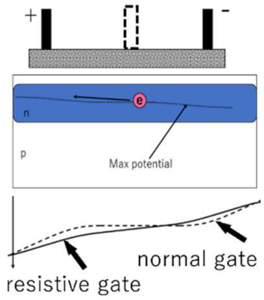


Fig. 8 A resistive gate with two contact, and a normal gate

indicated with a dotted line in Fig. 7b. The profile is linearized, but is wavy.

The bundle of electron trajectories around the center in the diffusion layer also causes the mixing (→ ←). Once an electron goes outside the central area, it is difficult to come back toward the center due to the field in the outside designed to direct outward. Therefore, the basic strategy to minimize the mixing around the pixel center is as follows:

(1) to squeeze the trajectory bundle,
(2) to locally linearize the potential profile, and to increase the field to the critical field, and
(3) to adjust the driving voltage and to suppress the power consumption.

3.2 Resistive Branching Gate

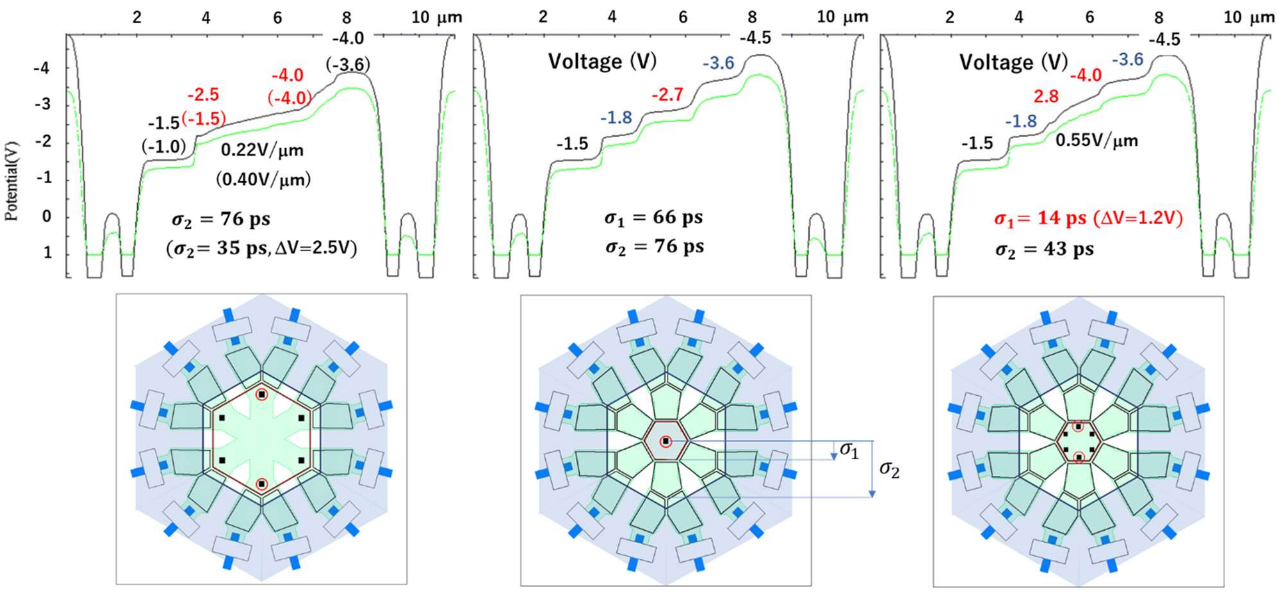
As shown in Fig. 8, a usual CCD gate has one contact ( ) to an electrode, causing a flat or mild potential at the central part of the gate. In an early age of the CCD technology when the process node is large, a resistive gate with double contacts (▮) was employed. When the technology is introduced to Hanabi, the wavy potential profile around the pixel center in Fig. 7c may disappear.

For example, Fig. 9a and Fig.9c shows two structures of the Si BSI BIS, each with a resistive gate at the center. We named the sensor structure, a brunching-resistive-gate (BRG) image sensor.

Once an electron goes outside the resistive gate, it is difficult to come back toward the center. Therefore, the temporal resolution is evaluated for the mixing in the resistive gate.

Fig. 9a has a middle-size resistive gate. When the voltage amplitude of the resistive gate is 2.5V (=-1.5+4.0), the practical temporal resolution Δt_P is 115.5 ps (=35x3.3). However, as explained **4.**, the voltage swing of 2.5 V is too high for highspeed digital circuits.

Comparison of Fig. 9b and Fig. 9c prove that the



(a) With a middle-size resistive gate (b) All normal gates (c) With a small resistive gate at the center

Fig. 9 Example designs of the diffusion layers of the branching resistive gate (BRG) image sensors with a hexagonal PD shown with dark blue lines (lower figures), and the potential profiles along the vertical lines (upper figures).

The diameter of the electron trajectory bundle is almost the same as the size of the small center resistive gate. The standard deviation due to the mixing is evaluated for the diameters of the resistive gates, excluding the delay in the PD.

resistive gate reduces the temporal resolution by 4.7 times (66 ps/14 ps). Then, Δt_P = 46.2 ps (= 14x3.3) for ΔV=1.2V.

4. Ring Oscillators for the Driver

For the ultrafast operation, we proposed an in-situ ring-shaped driver (Fig. 10), in which a soliton propagates to open switches along the ring to send a driving voltage pulse train to the collection gates around the pixel center in turn [7]. The ring can be an optical fiber or a metal wire. However, it is difficult to adjust the travel speed of the soliton.

We invented a ROXNOR circuit, which includes a ring oscillator (RO) and XNOR circuits attached to each invertor of the RO (Fig. 11) [8]. The frequency of a set of the ROs can be synchronized with a model RO controlled by a digital pulse generator.

The test ROXNOR can drive a capacitive load for 6x8 pixels of the BSI BIS shown in Fig. 1 at 1 ns for the voltage swing of 3.5 V. The circuit contains a voltage level shifter from 1.2 V to 3.5V. Without the level shifter, it can drive the sensor at about 100 ps for the voltage swing of 1.2 V.

Fig. 10 A soliton for driver for BSI MCG Image sensor[7)]

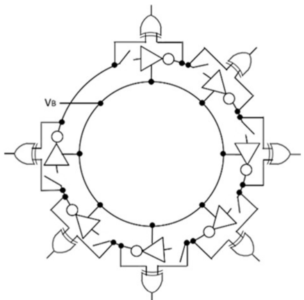


Fig. 11 ROXNOR driver[7)8)]

5. Conclusion

There are three major causes of mixing that elongates the temporal resolution. The countermeasures are presented. With a proper in-situ driver circuit, such as a ROXNOR circuit, in addition to the countermeasures, the temporal resolution will reach 100 ps.

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Appendix: Definitions of Theoretical and Practical Temporal Resolutions [1]

Assuming that the arrival time distribution is approximated by Gaussian distribution, we derived an expression of the standard deviation of the distribution in terms of drift velocity v, diffusion coefficient D, the average penetration depth of light to the PD material δ, and the thickness of the PD, W [1,2].

$$\sigma = \sqrt{\sigma_m^2 + \sigma_d^2} \qquad (1)$$

where,

$\sigma_m^2 = \{1 - W'^2(1-p)p^2\}t'^2$,

$\sigma_d^2 = D't'(W' - p)/p)$,

$p = 1 - \exp(-W')$, $W' = W/\delta$, $t' = \delta/v$, $D' = 2D/v^2$.

Assume that two instantaneous pulses of light with a time difference of Δt enter the backside of the sensor. The light pulses generate two signal electron packets that are perfectly separated at the incident surface, and partly mix at the detection surface on the front side. For the condition,

$$\Delta t_T = \mu_2 - \mu_1 = 2\sigma, \qquad (2)$$

the crests of the two distributions coalesce and the sum of the distribution cannot be separately recognized anymore. The no-dip condition is employed as the definition of the temporal resolution limit together with W'=1, i.e., the width of the PD is equal to the average penetration depth.

However, in this case, an overlap of two distributions or crosstalk of two detected signal packets is significant, and the portion of incident electrons passing through the PD results in a photon loss of 36.8%. Therefore, we also proposed the practical temporal resolution Δt_P as:

$$\Delta t_P = \mu_2 - \mu_1 = 3.3\sigma \text{ and } W' = 3. \qquad (3)$$

Then, both the crosstalk and the loss of light are 5%.

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