Analysis of temperature and process variation effects on photo sensor circuits using device/circuit mixed-mode simulations

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***Abstract*—Impact of temperature and process variations on the output voltage variations of CMOS photo sensor is discussed. As temperature becomes high, output voltage (Vout) decreases because of the amplifier characteristics. But above 350K, Vout increases in a weak light intensity range. The process variations have an impact when the operation temperature is high and irradiating light intensity is low. We also estimate influence of additional drive-in process, and find the sensitivities of process variation to increase. To consider both process and temperature variations at the same time, we evaluate Vout variation with mixed-mode simulation.**

Keywords-photo sensor; temperature and process variations; mixed-mode simulation

I. INTRODUCTION

CMOS photo sensors are exposed to various operation temperatures. In order to satisfy specifications about operation temperature window, it is important to estimate output voltage variations in wide range temperature. To estimate output voltage variation, circuit simulator is normally used. Photodiodes are usually assumed as current sources which are modeled with simple expressions[1]. But characteristics of photodiodes are determined by photo-voltaic effects and recombination diffusion currents at pn-junctions and both are changed by temperature. Thus it is expected that photodiodes characteristics will fluctuate if junction formation process will change.

In this paper, we evaluate the output voltage variations caused by the temperature and process variations using device-circuit mixed mode simulator.

II. SIMULATION METHOD

Simulated circuit of CMOS photo sensor is shown in fig.1. Two types of silicon photodiodes (PDs), PD1 and PD2 are connected to CMOS logarithmic amplifier (AMP-A). Cross sections of PD1 and PD2 are shown in fig.2, PD1 is p-n-p diode and PD2 is n-p-n diode. The output of the AMP-A is input to the other amplifier (AMP-B) to get final output voltage 0.5-1.4V.

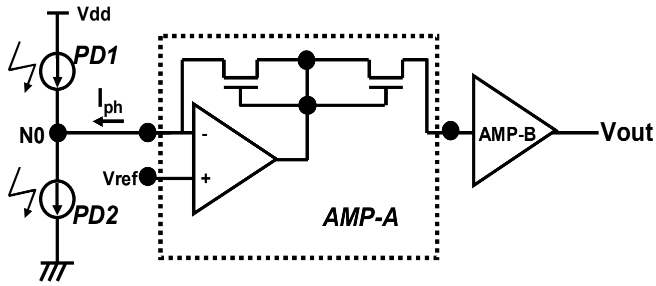

Figure 1. Simulated circuit of the photo sensor. PD1 and PD2 are simulated with process/device simulator.

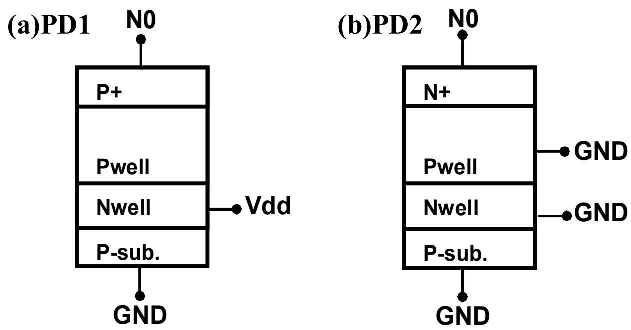

Figure 2. Schematic of photodiodes. (a)PD1 is pnp diode, and (b)PD2 is npn diode.

Simulations are performed using a three-dimensional process/device simulator ENEXSS[2]. Temperature dependencies are considered in mixed-mode simulation, the photodiode effects by device simulation and AMP-A by circuit simulation.

In the following section, the operation temperature dependencies of PDs and AMP-A are discussed. Then, we demonstrate the influence of the process variation to photodiodes by using process simulation.

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III. OPERATION TEMPERATURE DEPENDENCE

The output voltage against light intensity at various operation temperatures is plotted in fig.3. As temperature becomes high, Vout decreases below 350K. Above 350K, Vout extremely increases in weak light intensity range. This dependency comes from both PDs and AMP-A. Fig.4 shows the PDs temperature characteristics. As operation temperature becomes high, dark current becomes high. On the other hand, as temperature becomes high, output of AMP-A becomes low as shown in fig.5.

IV. SENSITIVITY ANALYSIS OF PROCESS VARIATION

In sensitivity analysis of process variation, we take only ion implantation processes into account, because activation annealing processes do not affect pn-junction formation. The fluctuations of all ion implantation process steps are considered. Fig.6 shows Vout variation when all implant process steps have 10% variations. The horizontal axis of fig.6 means the number indicated on Table 1. When the light intensity is strong, the process variations cause little influence on Vout variation. But under dark condition, though sensitivity of the temperature is still high, the process variations become severe. Fig.7 shows overall Vout variation. The minimum of Vout varies wider than maximum under weak light condition. Because dark current of PDs is sensitive to pn-junction profile, the process variations make large variations of dark current of PDs.

The variations of Vout caused by the process variations are also important at high operation temperature at any light intensity (fig.8). It means that for high temperature application,

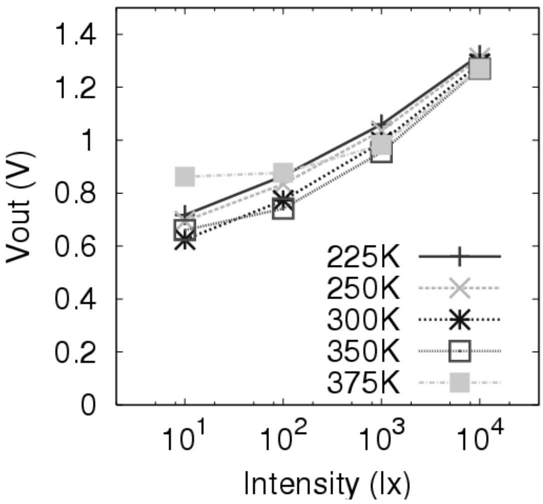

Figure 3. Temperature dependence of output voltage vs. light intensity.

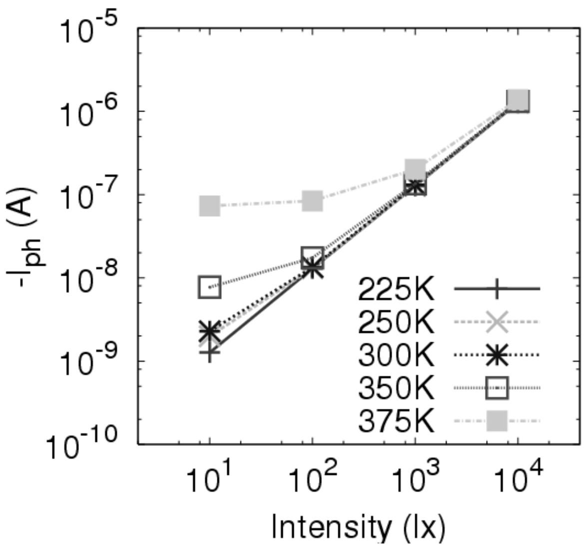

Figure 4. Temperature dependence of PDs (PD1 + PD2).

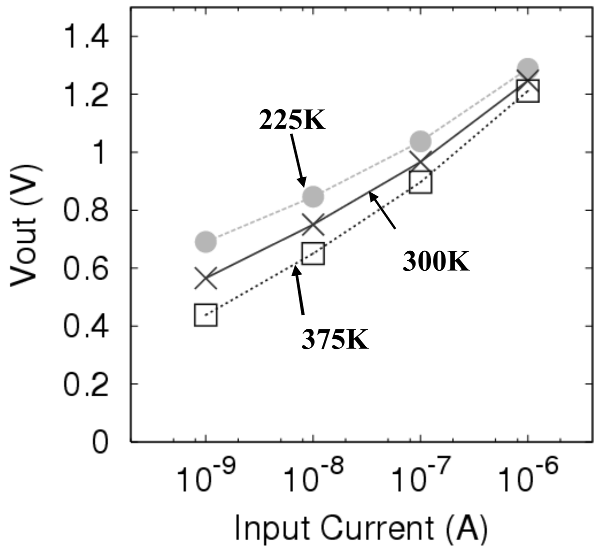

Figure 5. Temperature dependence of AMP-A characteristics.

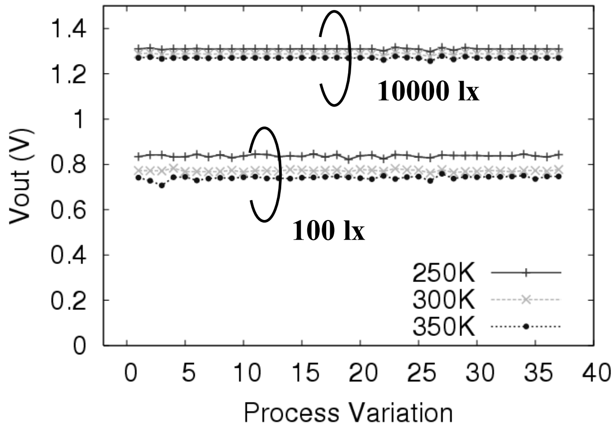

Figure 6. Sensitivity analysis of Vout against process variations. Horizontal axis indicates the number on Table 1.

TABLE I. PROCESS STEPS.

1	Typical		22	PD2 N-well	Dose high
2	PD1 N-well	Dose high	23	↑	Dose low
3	↑	Dose low	24	↑	Energy high
4	↑	Energy high	25	↑	Energy low
5	↑	Energy low	26	PD2 P-well	Dose high
6	PD1 P-well	Dose high	27	↑	Dose low
7	↑	Dose low	28	↑	Energy high
8	↑	Energy high	29	↑	Energy low
9	↑	Energy low	30	PD1 P+	Dose high
10	PD1 P+	Dose high	31	↑	Dose low
11	↑	Dose low	32	↑	Energy high
12	↑	Energy high	33	↑	Energy low
13	↑	Energy low	34	PD1 N+	Dose high
14	PD1 N+ 1	Dose high	35	↑	Dose low
15	↑	Dose low	36	↑	Energy high
16	↑	Energy high	37	↑	Energy low
17	↑	Energy low			
18	PD1 N+ 2	Dose high			
19	↑	Dose low			
20	↑	Energy high			
21	↑	Energy low			

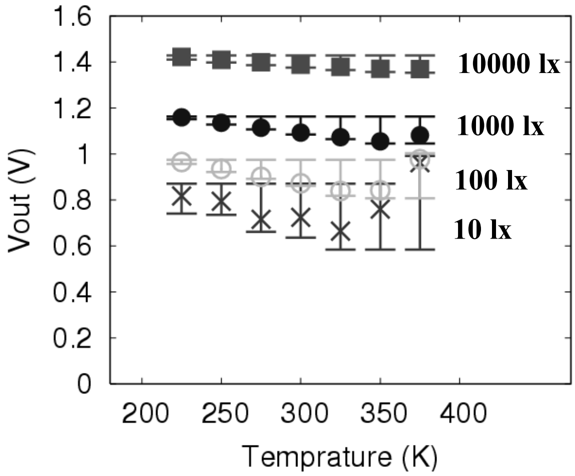

Figure 8. Temperature dependence of Vout variation caused by process variations. The parameter is light intensity. Symbol is typical.

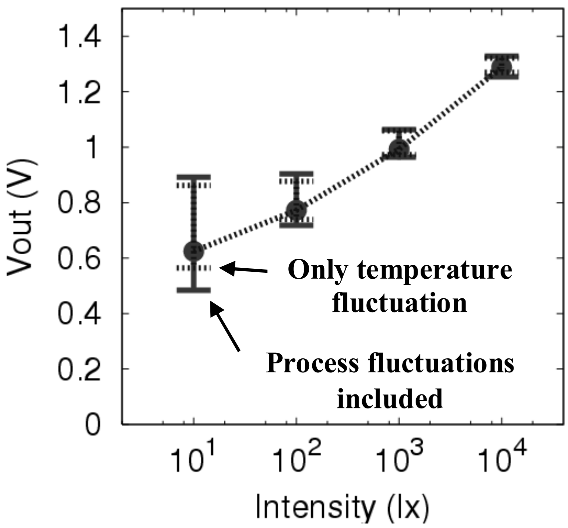

Figure 7. Vout variations vs. light intensity. Dashed bar is the error caused by only operation temperature variations. Solid bar includes the process variations. Symbol is typical.

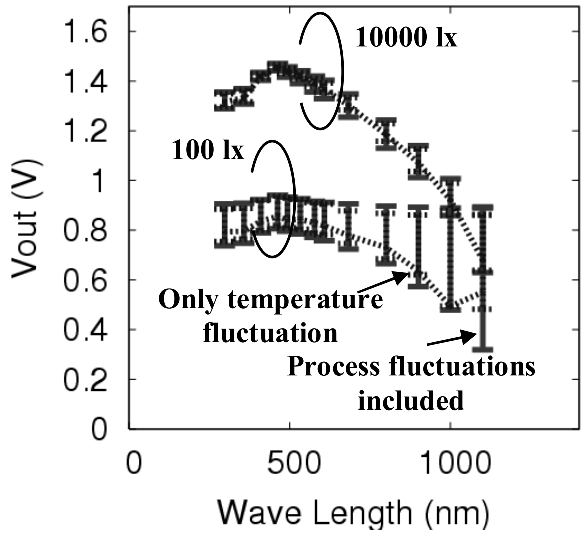

Figure 9. Vout variations vs. wave length. Dashed bar is the error caused by only operation temperature variations. Solid bar includes the process variations.

devices need much margin.

The variation sensitivities vary with wavelength (fig.9). Although levels of Vout are the same, Vout variation is greater at longer wave length.

We also estimate the influence of process variations in another process (fig.10). Because a drive-in process is added to this process, concentration of the dopant at the pn junctions decreases. The depletion layers widen and recombination current increase (fig.10). Then sensitivity of the process becomes large, so that the drive-in temperature dependence becomes stronger. It is revealed that original process is much better than this process.

V. CONCLUSION

We evaluate the output variation of a photo sensor caused by the operation temperature and process variation using mixed-mode simulation. As temperature becomes high, Vout decreases because of the amplifier characteristics. But above 350K, Vout extremely increases in weak light intensity range, because the PDs dark current increases. The process variations have an impact when the operation temperature is high and irradiating light intensity is low. We also estimate influence of additional drive-in process, and then, sensitivities of process variation increase. Mixed-mode method is very effective when PDs characteristics are changed by the same parameters as external circuit, such as temperature, and their sensitivities are changed by processes.

REFERENCES

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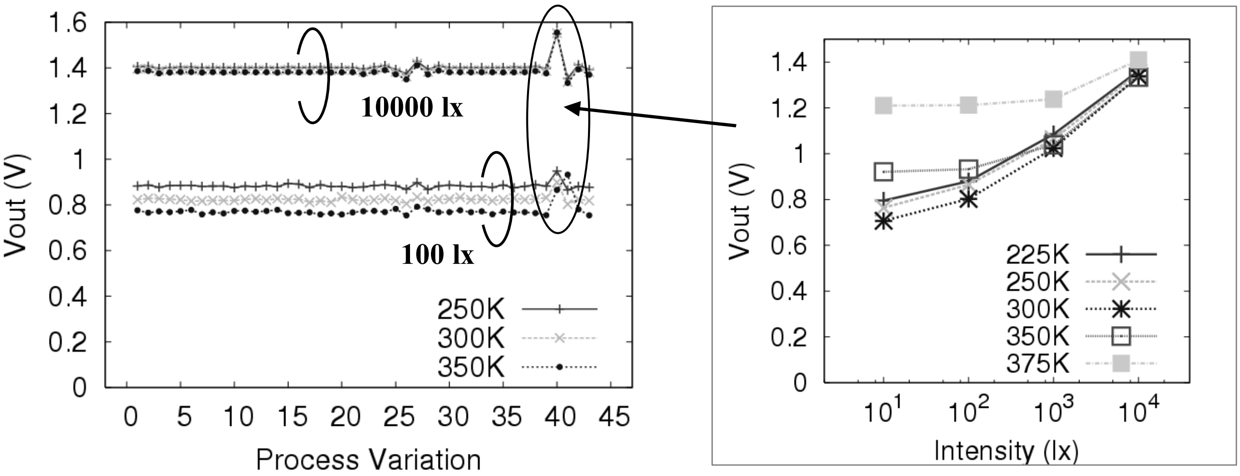

(a) (b)

Figure 10. (a) Sensitivity analysis of Vout against process variations of a process including drive-in step. Horizontal axis indicates the number on Table 1. (b) Temperature dependence of output voltage vs. light intensity of a sample which drive-in temperature is high.