Effects of internal angle designs for the breakdown voltages of silicon avalanche photodiode fabricated with 0.6 μm standard CMOS process

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1. Abstract

In recent years, the development of an avalanche photodiode (APD) using a CMOS process is required.^{(1, 2, 3,}

⁴⁾ APD has characteristics of high sensitivity and high-speed response, and it is used for image sensor.⁽⁵⁾ As a process of the image sensor, CMOS process has high versatility and can be manufactured at low cost. Improvement of layout is the best for improving photocurrent multiplication characteristics of APD.

I_p is the current value when light is irradiated, I_{ph} is the photocurrent and I_d is the dark current. At that time, the photocurrent characteristic of APD is obtained by the following equation.

$$I_{ph} = I_p - I_d \quad (1)$$

When voltage is applied in the state of light irradiation, an avalanche multiplication of photocurrent occurs. At that time, an avalanche multiplication of the dark current also occurs.

The avalanche multiplication phenomenon occurs when the electric field value is over $2 \times 10^5 \text{ V/cm}$ on p-n junction.⁽⁶⁾ The avalanche multiplication phenomenon occurs at only part of device when the electric field concentration occurs. So, we have to design p-n junction layout for controlling electrical field concentration. When the avalanche multiplication phenomenon occurs in a place of no exposed areas, the dark current is occurs and the photocurrent is decreased by the dark current.

Three types of APD were designed, for comparing breakdown voltages of photocurrents and dark currents. The layouts are square, triangle and circle (twenty-eight-sided polygon). The dark currents, the photocurrents, and the

multiplication ratios of photocurrent are measured. As a result, the breakdown voltages of these dark current were as follows.

Breakdown voltage: Triangle < Square < Circle (2)

The sharper corners have stronger electric field concentrations and smaller breakdown voltage values. These breakdown voltages are depending on these internal angles. These photocurrent and multiplication ratio characteristics are also depending on it. In this CMOS process, the breakdown voltage can control by internal angles. This result indicated that the circle is best APD layout.

Keywords: CMOS, APD, Electric field concentration,

2. Introduction

In recent years, the development of APD using a CMOS process is proceeding.^(1, 2, 3, 4) APD can amplify photo signal by an avalanche phenomenon at high electric field. The APD can apply to image sensor for weak light sensing.⁽⁵⁾ So that, the image sensors can be used where weak light such as photographing of aurora and fluorescence detection. In order to make the highly sensitive image sensors, it is necessary improve the multiplication characteristics of APD. There are two methods to improve the multiplication characteristics of APD. The first method is an adjusting impurity concentrations in the light receiving area and guard ring area.⁽⁷⁾ The another method is a change layouts of APD for decreasing electric field concentration at outside of light receiving areas. In this research, we use the method of a change the layouts of APD. In particular, we focus on the

interaction of the internal angle of the APD and the breakdown voltage. By making clear these interaction, we put forward a suitable layout for APD.

3. Data and Method

3.1 Problem

First, we will explain about the avalanche multiplication of APD. I_p is the current value when light is irradiated, I_{ph} is the photocurrent and I_d is the dark current. At that time, the photocurrent characteristic of APD is obtained by the following equation.

$$I_{ph} = I_p - I_d \quad (1)$$

When voltage is applied in the state of light irradiation, an avalanche multiplication of photocurrent occurs. At that time, an avalanche multiplication of the dark current also occurs. The dark currents characteristics occurs by electric field concentration without light incident areas. The avalanche phenomenon occurs when a certain standard electric field value is exceeded. For example, avalanche phenomenon in silicon occurs at electric field strength of about $2 \times 10^5 \text{V/cm}$.⁽⁵⁾ The dark current increases as the electric field concentration was increased. And the photocurrent decreases as the dark current was increased. Therefore, an increase in electric field concentration causes a problem of a decrease in photocurrent. To solve this problem, improvement of APD design is optimal. So, we design p-n junction layout for controlling electrical field concentration. Hence, eliminate corners so that electric field concentration does not occur. Three types of APD were designed for comparing electric concentration at their corners. These are triangle, square and circle (twenty-eight-sided polygon).

Fig. 1 shows the electric field distribution diagram of the manufactured APD. The triangle and square layout have the electric field concentrations at their corners. And the triangle corner angle is smaller than square one. In order to evaluate the characteristics due to the difference in the layout, the dark current and the photocurrent characteristics are measured. Then multiplication ratio characteristics of photocurrent and breakdown voltages are calculated from these results.

(a) Square type of APD

(b) Triangle type of APD

(c) Circle type of APD

Fig. 1. The electric field distribution diagram

3.2 CMOS-APD

Figure 2(a) shows the IC layout with square and circle type CMOS-APDs. The IC size is $1.8\text{mm} \times 1.8\text{mm}$. There are 4 square type APDs and 4 circle type APDs. Figure 2(b) shows the IC layout with triangle and circle type CMOS-APDs. The IC size is also $1.8\text{mm} \times 1.8\text{mm}$. There

are 2 triangle type APDs and 3 circle type APDs. Figure 2(c), (d) and (e) are enlarge view of square, triangle and circle, respectively. The edge of triangle layout modify small squares and the circle layout was used twenty-eight-sided polygon for removing DRC error.

These APDs have 3 terminals, these are connected N-diff, P-Well and N-well. These light receiving areas of square, circle and triangle are $1.0 \times 10^{-8}m^2$, $7.85 \times 10^{-9}m^2$ and $7.70 \times 10^{-9}m^2$, respectively.

(a) IC layout with square and circle type

(b) IC layout with triangle and circle type

(c) Square type of APD layout

(d) Triangle type of APD layout

(e) Circle type of APD layout

Fig. 2. CMOS-APD Layout

Figure 3 shows the cross-section image of CMOS-APD design. Wiring parts consist of the first metal layer, the second metal layer, and the third metal layer. These metal layers were also used by light shield to without light receiving areas. The via and the contact hole serve to connect the respective metal layers. We apply voltage to the terminals (VDD, GND) and measure the dark current and photocurrent at the p-n junction (P-Well and N-Diff).

Fig. 3. The cross-section image of CMOS-APD design

Figure 4(a) and (b) shows the photograph of IC with square and triangle and circle type CMOS-APDs. These metal layers and bonding wire are not covered light receiving areas. Figure 4(c), (d) and (e) are enlarge view of square, triangle and circle, respectively. The edge of triangle and square was formed smooth and rounded by etching process. The twenty-eight-sided polygon layout also formed smooth and rounded by etching process. It likes almost circle.

(a) photograph of IC with square and circle

(b) photograph of IC with triangle and circle

(c) Square type of APD photograph

(d) Triangle type of APD photograph

(e) Circle type of APD photograph

Fig. 4. Photograph of CMOS-APD

3.3 Dark Current Characteristics

At first, APD is put in the dark place for measuring dark current characteristics. Next, reverse bias voltage was applied to the APD. Then these devices were measured dark current. Figure 5 shows a dark current measurement circuit diagram.

Fig. 5. Dark current measurement circuit diagram

3.4 Photocurrent Characteristics

First, light (laser diode) was applied to the APD. The wavelength of was 650nm and the power was 0.612mW. Next, reverse bias voltage was applied to the APD with light. Then these devices were measured photocurrent. Figure 6 shows a photocurrent measurement circuit diagram. I_p is the current value when light is irradiated, I_{ph} is the photocurrent and I_d is the dark current. The photocurrent characteristics are obtained by the following equation.

$$I_{ph} = I_p - I_d \quad (1)$$

Fig. 6. Photocurrent measurement circuit diagram

4. Results

4.1 Dark Current Characteristics

Figure 7 shows the result of dark current characteristics. We decide to breakdown voltage that dark current reach to 100 nA. These breakdown voltages of square, triangle and circle type were 13.0 V, 12.9 V and 13.5 V, respectively. As a result, the breakdown voltages of dark current characteristics were as follows.

Breakdown voltage: Triangle < Square < Circle (2)

Fig. 7. Dark current characteristics

4.2 Photocurrent Characteristics

Figure 8 shows the result of photocurrent characteristics. These photocurrents are not decreased by dark currents. And these avalanche phenomena start lower voltage compare with dark currents.

Fig. 8. Photocurrent characteristics

4.3 Photocurrent multiplication ratio

Figure 9 shows the photocurrent multiplication ratio characteristics. The multiplication ratio when the current value at 1 V was set to magnification 1. M is the photocurrent multiplication ratio, I_{ph} is the photocurrent and I_{ph0} is the photocurrent at 1 V. The calculation method is obtained from the following equation.

$$M = \frac{I_{ph}}{I_{ph0}} \quad (3)$$

Fig.9. Multiplication ratio of photocurrent

5. Discussion

These breakdown voltages are depending on these internal angles. These internal angles of triangle, square and twenty-eight-sided polygon are 60 degree, 90 degree and 167.14 degree, respectively. Figure 10 shows breakdown voltages dependence on the internal angles. In this CMOS process, the breakdown voltage can control internal angles. These photocurrent and multiplication ratio characteristics are also depending on internal angles. This result indicated that the circle is best APD layout. And it seems that the breakdown is start from circumference of a circle.

Fig.10 Dependence of breakdown voltage

Conclusions

To improve the characteristic of CMOS-APD, layout of APD has changed. The sharper corners have stronger electric field concentrations and smaller breakdown voltages. In this CMOS process, the breakdown voltage can control by internal angles. These photocurrent and multiplication ratio characteristics are also depending on internal angles. This result indicated that the circle is best APD layout.

Acknowledgment

This work is supported by VLSI Design and Education Center (VDEC), the University of Tokyo in collaboration with Cadence Design System, Inc.

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