RESPONSE TIME OF SHALLOW JUNCTION SILICON PHOTODIODES

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There is a strong relation between the size, shape and location of the illuminated part of a shallow-junction photodiode, and its series resistance [1, 2, 3]. This relation creates an expectation for a big variation of the response time (the time for which the photo-generated charge will be removed from the photodiode) with the illuminated spot size. This is because the time constant of the photodiode, which is one of the main factors defining the response time, is a product of the series resistance multiplied by the junction capacitance.

In this work the dependence of the charge removal time of a shallow-junction photodiode on the size and location of the illuminated area, is studied. Simulation results, as well as measurement data, show that the response time is changing only slightly with the position and the size of the illuminated spot, when very short light pulses are used. After the incidence light is over, the discharging of the photodiode continues with a time constant, which is highly independent of the size and the location of the illuminated part of the photodiode.

Keywords: photodiode, deep ultraviolet, response time, and series resistance.

1. INTRODUCTION

Recently, the demand for radiation detectors in the spectrum range bellow 200 nm has noticeably increased. For example, the ever decreasing feature size of the projected on silicon wafers patterns has led to the development of deep ultraviolet (DUV, 193nm) lithography. The metrology and the dose control of the DUV pulsed sources require the use of fast and sensitive DUV radiation detectors. Photodiodes are good candidates for this type of applications. Due to the decreased penetration depth of DUV radiation in silicon, as shown in Fig. 1, the depletion zone of the photodiodes, where the photo-generated charge is collected, has to be made very close to the surface.

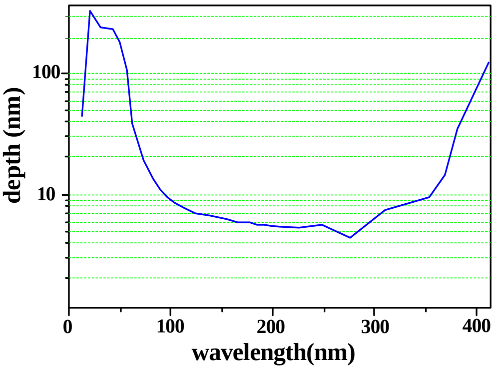

Fig. 1, penetration depth vs. incident radiation wavelength in Si

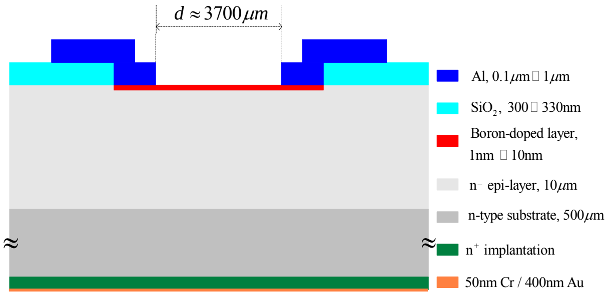

Fig. 2, cross section of a shallow junction photodiode

Further, the electrode cannot cover the active surface of the photodiode because it will absorb the radiation incidence. Instead, it is located at the edge of the active area, and is often called "ring" electrode. Base on these requirement, a DUV photodiode was developed. As shown in Fig. 2, it is the cross section of the photodiode that is used in this work. The diameter is about 3.7mm, and the thickness of the boron-doped layer is 1nm~10nm, which induce a large sheet resistance up to 10kΩ. As a result of this, the photo-current, which removes the photo-generated charge from the depletion zone, travels through a thin top layer with a relatively large sheet resistance. In fact, the series resistance of shallow photodiodes is dominated by the resistance of this thin top layer. The series resistance of the photodiode is of importance because it forms a time constant together with the photodiode junction capacitance, posing a lower limit to the response time of the photodiode. Equation (1) and (2) show that the series resistance of the active surface will be affected by the size and the location of the illuminated area, which is indicated in Fig. 3 [1].

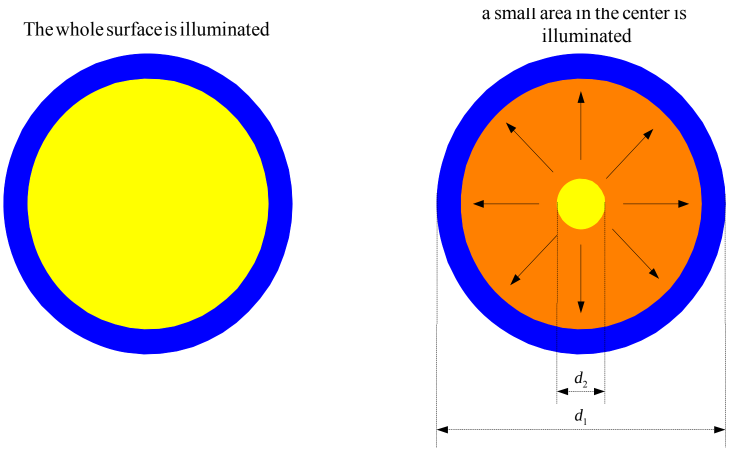

Fig. 3, different sizes of the illuminated area

$$R_s = \frac{R_{square}}{8\pi} \qquad \text{Equation (1)}$$

$$R_s = \frac{R_{square}}{8\pi}\left[1 + 4\ln\left(\frac{d_1}{d_2}\right)\right] \qquad \text{Equation (2)}$$

This has led to the concern that the response time of the photodiode is also affected by the size of the illuminated area. In order to optimize the design of the readout circuit for DUV photodiode, we need to know its worst case response time.

For this reason, a study of the response time of shallow-junction photodiodes is carried out. In the paper we present: (II) a finite element method (FEM) simulation was carried out based on the basic DUV photodiode structure shown above; (III) an experimental test set up is presented together with the achieved experimental results; (IV) for further analysis, an electrical model of the photodiode is introduced and SPICE simulation results of this electrical model are compared with FEM simulation results and experimental results, (V) conclusions are made finally.

2. FEM SIMULATION

To investigate the influence of the photon beam spot size on the response time of the detector a three-dimensional (3-D) device simulations performed with Synopsys MEDICI^{TM} software.

The results of the transient analysis in terms of photo-generated current are shown in Fig. 4[4]. First, only a spot with a 100μm diameter exactly in the center of the active area has been illuminated, and the second time – the whole active surface has been illuminated. From the result, we can see that the exponential decay curve of the photo-generated current, which indicates the time constant, does not depend on the spot size of the incident radiation.

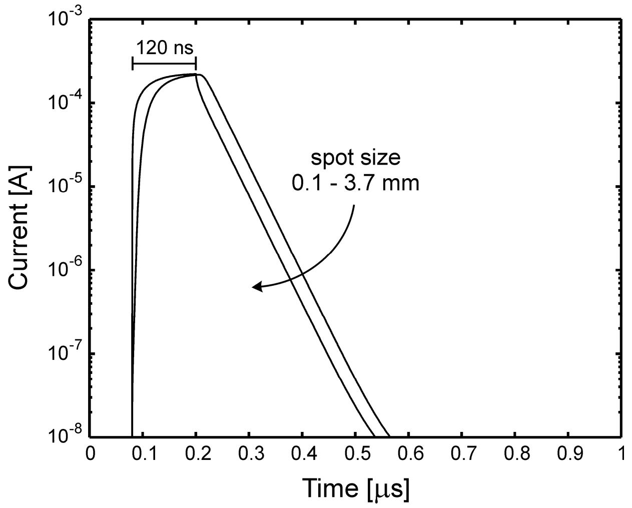

Fig. 4, Simulated photocurrents after a 120 ns pulse DUV radiation for different beam spot sizes by MEDICI^{TM}.

One thing to comment on is the fact that during the illumination time, the output current of the photodiode behaves differently when the illuminated area size is different. When only the center is illuminated, the output current rise time is longer compared to the situation when the whole active area is illuminated. This difference affects the total time needed for the generated charge to be removed from the diode. It is important to mention that this time difference is small compared to the total charge removal time, and it gets even smaller for shorter incident radiation pulses.

3. TEST SETUP AND EXPERIMENT RESULT

Next to the simulations results, the dynamic performance of a shallow p-n junction radiation detector has been experimentally verified. For this purpose a simple test setup for measuring the time constant of the photodiode has been created. In the test set up we used a green light emitting diode (LED). The penetration depth in silicon of green light (λ=520nm-565nm) is approximately 1 μm. The LED was driven by a pulsed signal whose frequency was 100kHz and a pulse duration 100ns. The experimental result is presented in Fig. 5. It shows again the exponential decay curve of the photo-generated current, consequently the time constant, does not depend on the illuminated area [4].

While it is not very easy to simulate the response time of a shallow-junction photodiode when the illumination spot is at an arbitrary position on the surface of the photodiode, this can easily be checked by experiment. The experimental results in Fig. 6 show the difference in the photodiode response when the illumination spot is at the center of the photodiode and when the same spot is moved near the edge of the photodiode. Again, the measured time constant in both cases, in the time interval after the light is switched off, is practically the same.

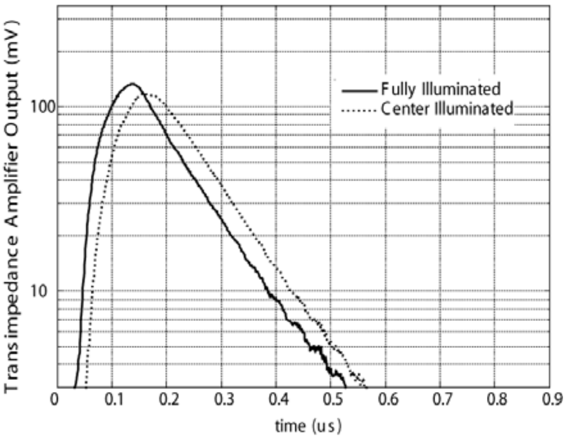

Fig. 5. Measured photodiode response to a pulse radiation input when the illuminated area sizes are different.

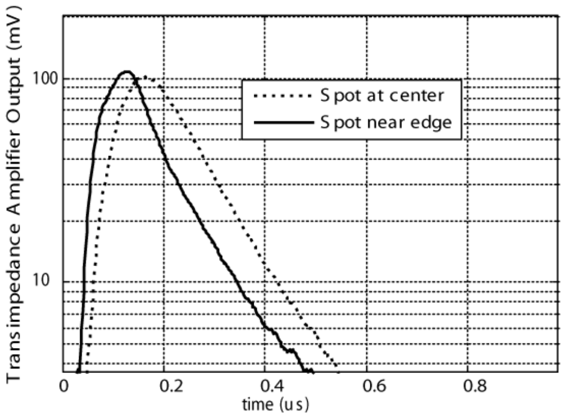

Fig. 6. Measured photodiode response to a pulsed radiation when the illuminated spot positions are different.

4. EQUIVALENT ELECTRICAL CIRCUIT

To better understand the obtained experimental results, a couple of SPICE simulations were carried out based on a distributed RC network shown in Fig. 7, which is believed to represent the photo-generated charge-transfer process in a much more accurate way than the lamped parameters model of the photodiode [4].

The RC network models the DUV photodiode used in the previous experiments. If the illuminated area is circular and concentric with the diode, the symmetry can help to simplify the model. Then the photodiode can be divided into a number of rings, each of which is modeled by a RC-network (Fig. 7). The values of resistances and capacitances are derived from the following formulas:

$$R_{ij} = \frac{R_{\square}}{2\pi}\ln\left(\frac{r_i}{r_j}\right) \quad \text{,with} \quad R_{\square} = 10k\Omega \qquad \text{Equation (3)}$$

$$C_i = C_{diode}\left(\frac{r_i^2 - r_{i-1}^2}{r_{diode}^2}\right) \quad \text{, with} \quad C_{diode} = 100\,pF \qquad \text{Equation (4)}$$

If a ring is illuminated, a current source is added to the node of the RC network of that ring. The value of the current is proportional to the area of the ring.

The simulation results of two cases are shown in Fig. 8. The duration of the current pulse in the simulation is 100ns. As can be seen from the plot in Fig. 8, with a logarithmic scale for the current, after a certain initial period the two current curves transform into straight parallel lines. This basically means that the time constants in both cases - when only the central diode area is illuminated, and when the whole diode area is illuminated, are the same. This result agrees well with the FEM simulation and experimental results.

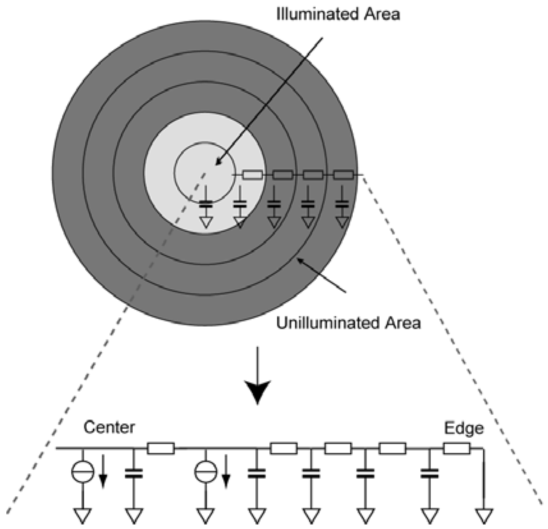

Fig. 7, The equivalent circuit when a shallow junction photodiode is partially illuminated

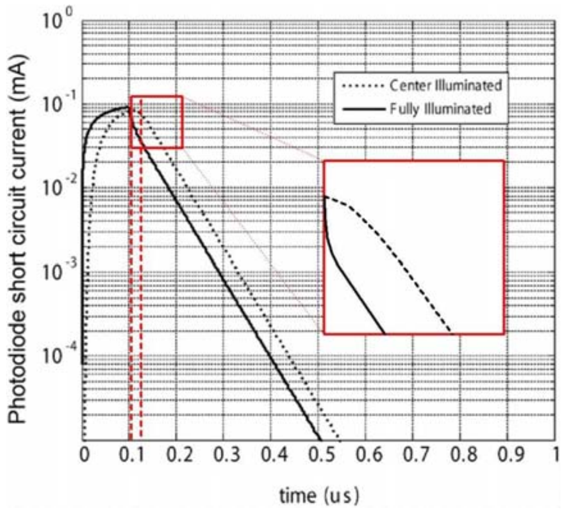

Fig. 8, Simulated photodiode short circuit output current with SPICE

This can be understood in the following way: When the illumination stops, the already generated charge tends to spread itself over the junction capacitance of the photodiode toward a “balance state”. To verify this process, an additional SPICE circuit simulation is performed, based on the same model shown in Fig. 7. In this simulation, for both case - central illumination and full illumination, the voltage of each node (shown in Fig. 9), is measured at different moments after exposure.

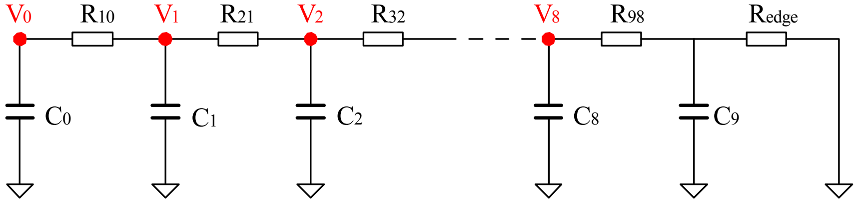

Fig. 9, circuit model for the SPICE simulation

Then, the voltage distribution on the photodiode at different moments after exposure is plotted in Fig. 10 and Fig. 11. Because the voltage value is proportional to the photo-generated charge, the voltage distribution described in Fig. 10 and Fig. 11 should keep the same trend with the photo-generated charge distribution.

As shown in Fig. 10, just after center illumination, the voltage is much higher in the center than at the edge. It means that most of the photo-generated charge is located in the central area at this moment. In the full-illumination case (Fig. 11), the voltage, consequently the photo-generated charge, is more evenly spread throughout the surface of the diode. Only 20 ns after illumination, the voltage distribution curves start to keep the same trend for both cases, which can be considered as the “balance state” mentioned above.

This analysis result agrees well with Fig. 8. As shown in Fig. 8, during the first about 20ns after illumination, the fully illuminated curve keeps a higher slope then the center illuminated one. It indicates that just after illumination, the fully illuminated surface has more photo-generated charge at the edge than the center illuminated case. So, this charge can be easily take away through the nearby ring electrode. After this 20ns, a "balance state" is achieved. The two curves are parallel with each other, which means the time constant for both cases now is the same. The only difference is that the full illumination case is actually one step further than the center illumination case during the following discharging process.

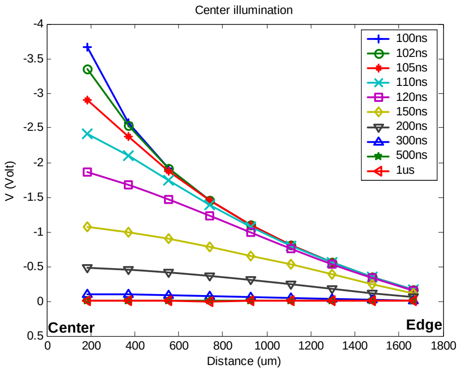

Fig. 10, Voltage distribution after center illumination

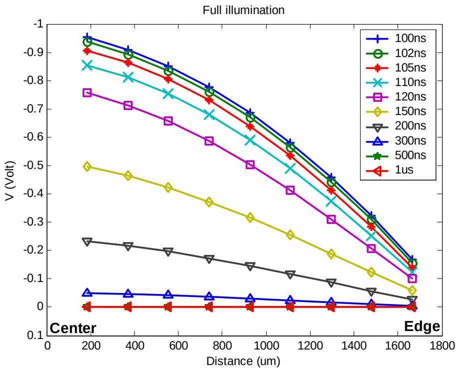

Fig. 11, Voltage distribution after full illumination

5. CONCLUSIONS AND DISCUSSIONS

It has been demonstrated by FEM simulations, and also verified by experiments, that the response time of shallow-junction radiation detectors to pulsed radiation, is only slightly dependent on the size and the location of the illuminated part of the detector active area.

By modeling the photodiode with spread R-C parameters and by simulation with P-spice, it has been shown that the photo-generated charge quickly distributes itself in a similar pattern, no matter the location and the size of the illuminated spot.

The existing difference in the response time is mainly a product of the electrical behavior of the detector during exposure, when it acts as a current source. After exposure, when there is no more charge generation, only the photo-generated charge is removed from the photodiode.

6. REFERENCES

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