A Novel Wavelength Detection Method Based on Wavelength Absorption in Silicon

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Abstract: This paper introduces a novel method to detect wavelength in silicon without the dispersing element. The light penetration depth depends on the wavelength for a specific semiconductor material, thus we can gain the wavelength spectral information by measuring the photon-generated electron-hole pairs as a function of depth. The MATLAB calculation results and COMSOL simulation results validate the idea.

Keywords: spectrometer, photon-generated carriers, absorption coefficient, life time

1. Introduction

Nowadays the modern spectrometers have indispensable dispersing elements, such as prism and diffraction grating [1]. A sensor is placed on the optical path after the dispersing element detects the monochrome light. CCD image sensors are usually the type of sensor that meets the requirement. This is the traditional and mature detection principle. A new filter-less method of detecting the spectrum based on wavelength absorption in silicon fabricated in CMOS technology without dispersing elements is proposed in this paper. It is well known that the light penetration depth depends on the wavelength for a specific semiconductor material, like silicon, and excess carriers are generated [2]. Wavelength-dependent absorption coefficient produces a unique excess carrier distribution as a function of depth. In these conditions, the wavelength spectral information can be obtained by measuring the photon generated electron-hole pairs as a function of depth. In this paper, the detection principle is presented and validated with an analysis and a finite element model.

2. Detection Principle

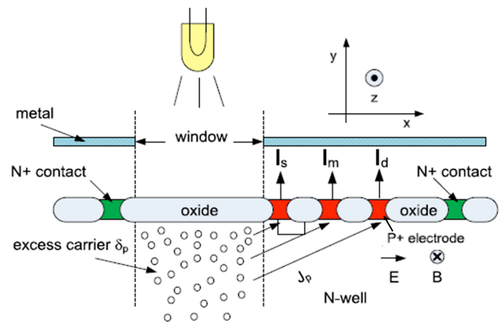

Figure 1. The schematic figure of the detection principle

As seen in the Figure 1, N-doped silicon is used as the substrate. A uniform electric field and an external uniform magnetic field are applied along the positive x direction and negative z direction respectively. The generated electron-hole pairs are separated by the electric field, and the electrons move along the negative x direction while holes move along the positive x direction. An external uniform magnetic field is applied, changing the trajectory of the hole current flows towards the electrode due to the Lorenz force effect. P+ electrode is a heavily doped region and forms a PN junction. For a specific electric and magnetic field, the angle of deflection of hole current is constant, so an electrode could collect the holes from a specific depth. Thus, the excess hole concentration profile along the incident depth could be achieved by varying the magnetic field. For a certain incident power, every wavelength has its unique excess carrier concentration profile, that can be use to determine the wavelength.

3. Theoretical calculation

We use the steady-state continuity equation to describe the carrier behavior under the constant incident illumination [3]. Considering the hole concentration variation along the depth, the equation becomes

$$D_p \frac{d^2 \delta_p(|y|)}{dy^2} - \frac{\delta_p(|y|)}{\tau_p} + g_p = 0$$

where the excess hole concentration, δ_P, the photo-generation rate, g_p, the diffusion coefficient, D_p, and the hole recombination lifetime, τ_P, are constants.

In order to collect the excess holes, we create an electric field and apply an external magnetic field to control hole transportation. As shown in Figure 1, the external electric field is parallel to the substrate surface and separates the electron-hole pairs which creates a hole current towards the positive x direction. Now applying a uniform external magnetic field, perpendicular to the electric field, deviates the hole current. According to the Lorentz force, the current obeys the equation [4]:

$$\mathbf{J}_p(\mathbf{B}) = \mathbf{J}_p(\mathbf{0}) - \mu_p^*(\mathbf{J}_p(\mathbf{B}) \times \mathbf{B})$$

where $\mathbf{J}_p(\mathbf{0})$ contains two components, the drift current and the diffusion current:

$$\mathbf{J}_p(\mathbf{0}) = \delta_p q \mu_p \mathbf{E} + q D_p \nabla p$$

Here we consider that the background hole density is negligible in the n-type silicon substrate, compared with photo-generated excess hole density, we only consider the excess hole concentration in this equation. $\delta_p q \mu_p$ denotes the electronic conductivity, μ_p and μ_p^* are the drift mobility and Hall mobility for holes, respectively, and q is the electric charge.

4. COMSOL Simulation Results

In this part, we will discuss some COMSOL simulation results. The semiconductor module is used to simulate the photo-generated excess carriers in silicon. Figure 2 shows the COMSOL model. Two N+ contacts and three P+ collectors are made in the N-silicon substrate, as indicated in Figure 1. The two N+ contacts are used to generate the electrical field.

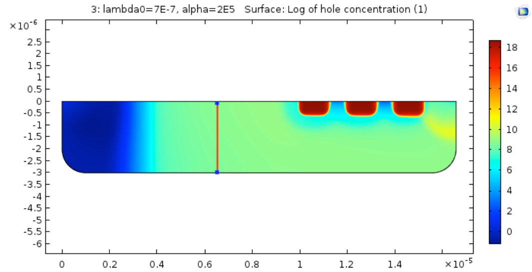

Figure 2. Finite element model of the proposed wavelength detector.

4.1 The Excess Carrier Concentration Profile without an Electrical Field

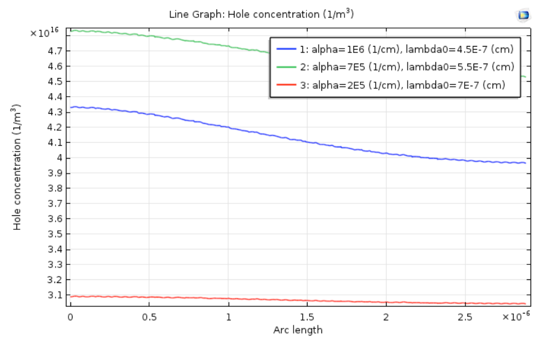

Figure 3. COMSOL modeling of the excess hole concentration along depth for three wavelengths without electrical field.

Figure 3 shows the hole concentration without electrical field nor magnetic field as a function of depth in silicon. Excess photo-generated electron-hole pairs, recombine to reach equilibrium between generation and recombination.

4.2 The Excess Carrier Concentration Profile with an Electrical Field

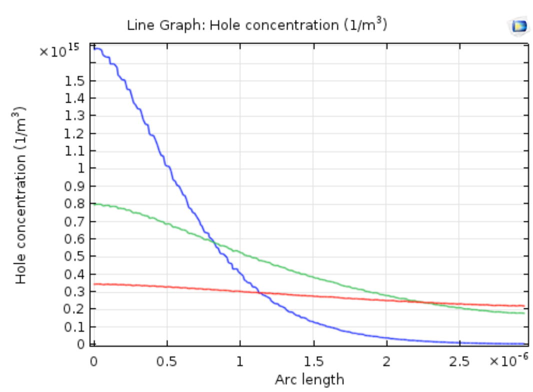

Figure 4. COMSOL modeling of the excess hole concentration along depth for three wavelengths with the electrical field.

A potential difference of 5V is applied on the two N+ contacts. In this case, generated electron-hole pairs are separated by the electrical field and form a current. The excess electrons go towards the leftmost N+ contact and the excess holes are collected by the three P+ electrodes.

In this case, we also use MATLAB to calculate the hole concentration along depth.

$$D_p \frac{d^2\delta_p(|y|)}{dy^2} - \frac{\delta_p(|y|)}{\tau_p} + g_p = 0$$

Here the continuity equation has two boundary conditions, $D_P \nabla \delta_P = S\delta_P$ at depth=0 (at surface), and δ_P =0 at infinite depth. S is the surface recombination velocity. In the small approximation with a constant lifetime, the solution of the continuity equation is

$$\delta_P = \frac{gL^2}{D_P\,(1\text{-}\alpha^2L^2)}\left[e^{-\alpha x} \text{-} e^{-x/L}\left(\frac{\propto + S/D_P}{1/L + S/D_P}\right)\right]$$

Comparing Figure 4 and Figure 5, the curves for three wavelengths are highly similar. However, the value of hole concentration and the intercross points are different. MATLAB model reflects an ideal situation and the lifetime is constant, which may be the reasons of the difference.

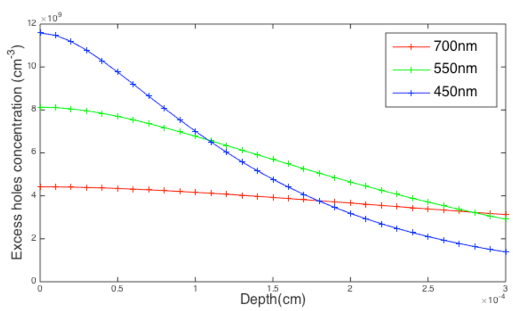

Figure 5. The calculated excess carrier concentration along depth for three wavelengths by MATLAB.

4.3 The Excess Carrier Concentration Profile with an External Magnetic Field

In the previous part, the excess carrier concentration along depth is achieved by COMSOL and MATLAB. In this part, an external magnetic field is used to improve the device sensitivity because the measured current could be increased under the Lorentz force.

To simulate the Hall Effect, some factors of the magnetic field are added by hand in the global equations in semiconductor module. J_X, the total current along x direction, and J_Y, the total current along y direction, are multiplied by some expressions to reflect the magnetic field effect. The simulation result is in Figure 6.

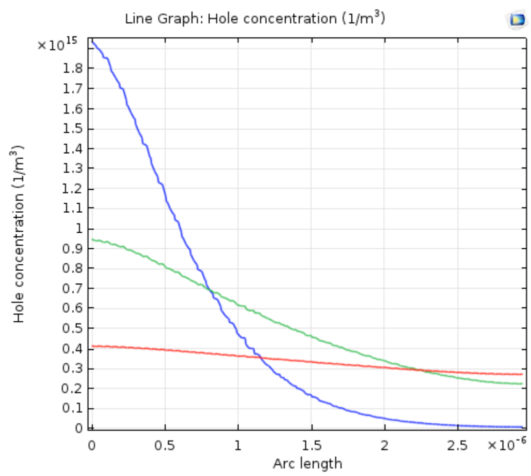

Figure 6. The simulated excess hole concentration along depth for three wavelengths with the electric and magnetic field. Simulation by COMSOL.

Comparing Figure 5 and Figure 6, the external magnetic field doesn't change the curve shape, but increases the concentration a little. The external magnetic field will make the hole current deflect up, so that the concentration at the same depth will increase.

The effect of magnetic field also appears in the electrode current. Figure 7 and Figure 8 are the current that is collected by the middle electrode of the three P+ electrodes, as shown in Figure 1.

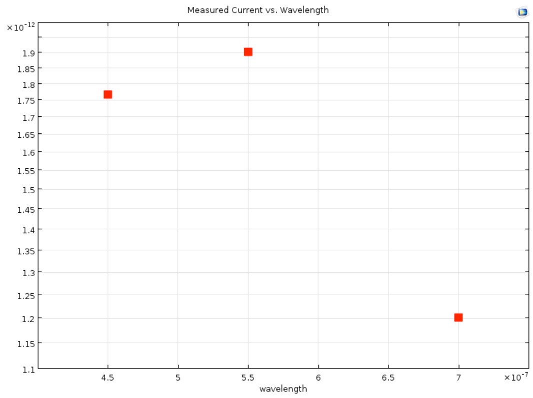

Figure 7. The simulated current that is collected by the middle P+ electrode, under magnetic field.

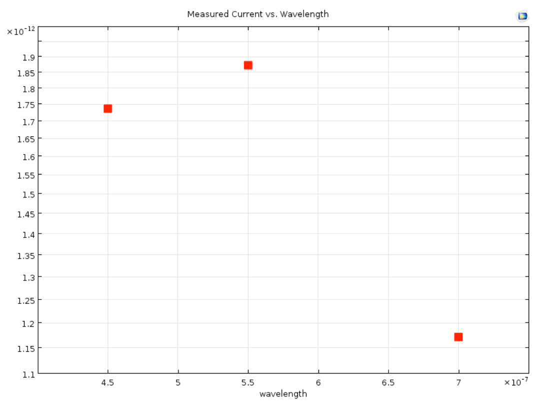

Figure 8. The simulated current that is collected by the middle P+ electrode, without the external magnetic field.

The largest current comes from the 550nm wavelength. This is because the collected current is formed by the carriers around 1um depth, not the carriers near surface, because the surface current is collected by the leftmost P+ electrode. Figure 9 gives the electrical field, and it clearly shows that the middle P+ electrode collects the carriers coming from the depth around 0.9um. At this depth in Figure 6, the green curve indeed has the largest value.

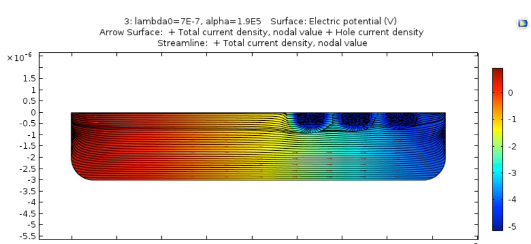

Figure 9. The simulated electrical field and the streamline.

5. Discussion and Conclusion

In this paper, we proposed a novel method to detect the wavelength without the dispersing elements. A COMSOL model and MATLAB calculations validate the detection principle. More modeling results need to be compared to experiments before concluding on the performance of this novel highly integrated spectrometer device.

6. References

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