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A novel CMOS spectrometer based on wavelength absorption

Kai Zhang*, Pascal Burasa, Yves Audet

Génie électrique, École Polytechnique de Montréal, Université de Montréal, Canada

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ABSTRACT

This article reports on a novel spectrometer without dispersing elements fabricated in standard CMOS technology. The spectrum detection principle is based on the wavelength absorption mechanism in silicon. A finite element model confirms the excess holes' detection principle as a function of depth where moving holes' trajectory is deviated under the Lorentz force towards a set of collectors. In the case of high excess carrier concentration, experimental results confirm the theoretical analysis that wavelength becomes indistinguishable because the Auger recombination mechanism is dominant, which should be avoided to realize a spectrometer. For the low excess carrier concentration case, the concentration profile is determined by the incident irradiance and the wavelength and can be additive since the Shockley-Read-Hall recombination mechanism prevails, where the excess carrier life time is constant, and hence suitable for wavelength discrimination. In order to realize a spectrometer, a light spectrum detection method is developed, which requires a linear equation set where coefficients of the matrix coming from the measurement of the current density as a function of the irradiance for different wavelengths and magnetic fields. The proposed miniature and integrated spectrometer with a pixel array can be used as a spectral imager.

1. Introduction

Spectroscopy analysis is a powerful tool to investigate materials and structures. The current research-grade spectrometers and spectral imaging sensors are bulky equipment composed of a dispersing element, lenses, photo-detectors, electromechanical components and electronic circuits. The commonly used dispersing elements can be categorized into three main groups according to the mechanism involved in the extraction of spectral information from optical signals: spatial dispersion, interferometer, and resonance [1]. The latter group encompasses spectrometers using materials having properties of absorption, transmission, and reflection that are dependent on the wavelength. Recently a lot of interest has emerged in employing new structures and new materials such as photonic crystals, metamaterials [2,3] and quantum dots [1] as the detecting component of a spectrometer. In that respect, a color image sensors design to exploit the wavelength dependent absorption properties of silicon has been developed where the three primary colors employed in digital imaging, blue, green and red are extracted without thin film filtering. Recently, efforts have been made to miniaturized spectrometers and a handful of new products have emerged on the market to provide compact spectrometry solutions [4–8]. Traditional spatial dispersion elements, such as lens and gratings, are still employed. However, exquisite optical path designs allow the spectroscopic systems to be accommodated in small containers.

In this paper, we propose a new method of detecting the spectral content of luminous signals by exploiting the absorption properties of semiconductors. The method enables compact and cost effective spectrometer solution for a wide range of applications. Using silicon has the main advantage of having a detector compatible with some advance bipolar or CMOS integrated circuit fabrication processes, meaning that on the same substrate, the detector, signal conditioning circuits and digital processing can be implemented. The proposed principle employs the Lorentz force applied to moving charged particles in the presence of a magnetic field in order to relate wavelengths to the depth of photo-generated carriers. The paper is divided as follows: in Part 2, an overview of the underlying physics of carrier generation in semiconductor is described, followed by a description of the carrier concentration profiling method using the Lorentz force; in Part 3, a wavelength detec-

Abbreviations: COMSOL, A multi-physics finite element method software; CMOS, Complementary Metal-Oxide-Semiconductor; FEM, Finite Element Method; MATLAB, Matrix Laboratory a numerical computing software; MOSFET, Metal-Oxide Semiconductor Field-Effect Transistor; NMOS, N-channel MOSFET; SRH, Shockley-Read-Hall recombination; WAS, Wavelength Absorption Spectrometer.

* Corresponding author at: École Polytechnique, C.P. 6079, Succ. Centre-ville, Montréal, Québec, H3C 3A7, Canada.

E-mail address: zhangkai0313@gmail.com (K. Zhang).

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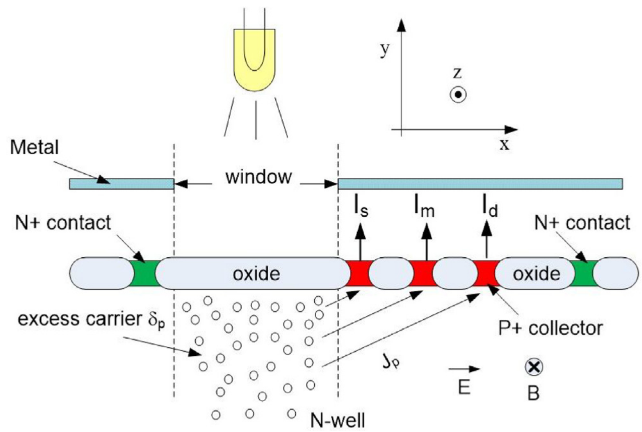

Fig. 1. Schematic diagram of a pixel of the spectrometer prototype.

tion method is developed and also verified experimentally. It relies on a linear system of equations where the coefficients have been obtained from electrical measurement as a function of the optical irradiance for different wavelengths and magnetic fields. Finally, concluding remarks are presented.

2. Detection principle

A monochrome light beam generates a unique excess carrier distribution along the incident depth due to the absorption coefficient. Hence, the wavelength information can be obtained by measuring the photon generated carrier concentration as a function of depth, and the proposed spectrometer is named the Wavelength Absorption Spectrometer (WAS).

Fig. 1 illustrates the schematic diagram of a WAS pixel. An N-well region is made in a P-type silicon substrate. Three P+ electrodes (red in Fig. 1) are heavily doped regions and forms PN junctions with the N-well. The junctions are reversed biased to collect holes only. A uniform electric field along the +x direction is produced by the voltage difference between the two N+ contacts. Light penetrates into silicon through a window area and the oxide layer. Other regions are covered by metal to block the illumination. The light-generated electron-hole pairs are separated by the electric field, and electrons move along the −x direction and holes move along the +x direction. In this first WAS prototype, an external uniform magnetic field is applied along the −z direction, thus, the holes' current flows towards the three P+ electrodes due to the Lorenz force. For a specific electric and magnetic field combination, the angle of deflection of holes' current density is constant, so that the electrodes could collect holes from a specific depth. Holes are collected by the middle P+ electrode and form the hole current I_m, while the left and the right P+ electrodes collect holes above and below that specific depth, and form current I_s and I_d, respectively. As a result, excess holes' concentration profile along the depth (-y direction) could be achieved by varying the magnetic field, hence, the current density angle of deflection.

In the theoretical analysis, we firstly derive the equation giving the photon-generated excess holes' concentration distribution along the −*y* direction, and secondly, the excess holes' transportation mechanism from the window area to the P+ collectors is validated with a finite element model implemented in the software tool COMSOL™ [9] and experimental result.

2.1. The excess holes' generation and recombination

The steady-state continuity equation describes the carrier behavior under the constant incident illumination [10]. Considering the holes' concentration variation along the depth under the window area, the equation becomes

$$D_p \frac{d^2\delta_p(|y|)}{dy^2} - \frac{\delta_p(|y|)}{\tau_p} + g_p = 0 \tag{1}$$

where δ_p is the excess holes' concentration, D_p, the diffusion coefficient [11], and, $|y|$, the depth from the surface ($y = 0$). For an illumination irradiance, P, at a specific wavelength, λ, the generation rate, g_p, is defined as [12]

$$g_p = \frac{P\lambda}{hc}\alpha_\lambda (1 - Re)\, e^{-\alpha_\lambda |y|} \tag{2}$$

where α_λ is the absorption coefficient and Re is the reflectivity at the Si/SiO_2 interface.

The hole recombination lifetime, τ_P, is not constant and is determined by the Auger and the Shockley-Read-Hall (SRH) recombination mechanisms

$$1/\tau_p = 1/\tau_{\text{Auger}} + 1/\tau_{\text{SRH}}. \tag{3}$$

The SRH recombination mechanism is active where there are impurities or defects in the semiconductor material while Auger lifetime is independent of the impurity and defect densities. In silicon, the Auger recombination mechanism dominates when either the doping density or the excess carrier concentration is very high, and the SRH recombination mechanism prevails at lower concentration [12]. Auger lifetime is a function of carrier concentration, while SRH lifetime is independent of excess carrier density.

At high concentration in N-type silicon as in the scenario of Fig. 1, the Auger recombination mechanism dominates and the hole lifetime becomes

$$\tau_p = \tau_{\text{Auger}} = 1/\left[C_n\left(n_0^2 + 2n_0\delta_P + \delta_P^2\right) + C_p\left(p_0^2 + 2p_0\delta_P + \delta_P^2\right)\right] \tag{4}$$

where C_p and C_n are the Auger recombination coefficients for holes and electrons respectively [11]. For holes' excess concentration δ_P of $10^{20}\ \text{cm}^{-3}$, which is much larger than the equilibrium concentration of electrons, n_0, and holes, p_0, Eq. (4) becomes

$$\tau_p = \tau_{\text{Auger}} = 1/\left[\delta_P^2\left(C_n + C_p\right)\right] \tag{5}$$

and the lifetime decreases rapidly to reach approximately 1 ns [12]. In these conditions, the recombination term in Eq. (1) is dominant and the continuity equation becomes

$$D_p \frac{d^2\delta_p(|y|)}{dy^2} - \frac{\delta_p(|y|)}{\tau_p} = 0 \tag{6}$$

Consider the boundary conditions $\delta_P(0) = g_P(0)$, where $\delta_P(0)$ is the surface excess hole density and $\delta_P(\infty)$, the analytical solution of Eq. (6) is:

$$\frac{1}{\delta_p(y)} = \frac{|y|}{\sqrt{2D_p/\left(C_n + C_p\right)}} + \frac{hc}{p\lambda a_\lambda (1 - Re)} \tag{7}$$

and reveals that the slope of the reciprocal of photon-generated holes' concentration versus depth is wavelength-independent at high carrier concentration condition. A high incident illumination induces a high carrier concentration, and Eq. (7) indicates that high illumination and the Auger recombination regime must be avoided for the spectrometer application.

At lower photon generated carrier concentrations, for example, when the concentration can be compared to the equilibrium concentration or smaller, SRH recombination mechanism prevails, and g_p can't be ignored in Eq. (1). g_p is wavelength-dependent, therefore, the carrier concentration distribution along depth provide the spectrum information of the incident light. However, given the relationship of τ_P and g_p, Eq. (1) is a non-linear non-homogenous differential equation that doesn't have an analytical solution. The