Blue Selective Photodiodes for Optical Feedback in LED Wafer Level Packages

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Abstract— Recently applying an intelligent self-curing system to get a feedback from the LED light in order to control its intensity with driving current has attracted so much attention. This study presents a silicon stripe-shaped photodiode which is successfully designed and fabricated using a 2μm BiCMOS process. This process flow integrates simultaneously the photodiodes, the CMOS and BJT transistors all in just five masks. In this cheap and smart wafer level LED packaging, fabricated photodiodes demonstrated a very high selectivity to blue light. The maximum responsivity is at 480nm which is matched with the blue LED's illumination. The single-stripe photodiodes due to their higher rate of recombination caused by the dead layer formation at the recombination caused by the dead layer formation at the surface showed lower responsivity compared to multi-stripe ones. The fabricated devices presented a two-fold increase in the responsivity and quantum efficiency compared to previously published sensors.

Keywords—Blue selective photodiode, BiCMOS process, LED wafer level package

I. INTRODUCTION

With the development of GaN-based blue LEDs, high-power, brightness and white-color LED is getting more popular for wide range of applications[1]. However, high power LEDs suffer from reliability issues such as heat dissipation which is one of the core problems that will influence their performance[2]. The wafer level packaging (WLP) for LEDs using silicon substrates is a solution in terms of the cost and thermal design. It can provide batch fabrication and component integration, as it is compatible with CMOS technology and thus, can also include MEMS components[3], [4]. Applying these technologies, a smart LED package can be produced that resolves the brightness problems associated with LED lighting [5]. Despite, all advantages these LEDs have, they are suffering from Light intensity decay in stress tests. Their light intensity decays during a long operation time or due to high working temperature. Another drawback of such a device is color shifting [6].

Smart package with an output light feedback can compensate the brightness variation by changing the driving current of the LED. Light sensing can provide information both about light color and intensity. Employing a blue selective photodiode can be a promising solution.

Conventional Si photo detectors generally have a poor responsivity to blue and UV light. As these spectra absorbed very close to the surface while the active regions of these devices are usually situated at a certain depth below the crystal surface [7]. Different structures are used as selective silicon photodiodes. They all work based on wavelength-dependent absorption coefficient of light in silicon. The basic structure is a p-n-p dual-junction photodiode, the active region of a p-n photodiode is limited by another n-p junction situated under the first one[8]. In another detector, the doping profile of the photodiode is adjusted to have a sharp and high potential barrier[7], which makes a strong built-in drift fields in which photo-generated carriers are separated in a more efficient way. The structure is intrinsically selective but it is made in a dedicated sensor process, not compatible with CMOS standard process. Finally, another group proposed a stripe shaped photodiode, compromising shallow P layers implanted in a N-well[9]. The geometry was optimized for better UV/blue responsivity. The results showed a promising selectivity for blue light. We also used the same structure but the size and features was changed to better fit the process and application.

In this work, we developed a photodiode used in a LED WLP which can selectively detect the output blue light intensity in a very accurate way and can support the brightness information of a mounted LED in a package.

II. DEVICE STRUCTURE AND EXPERIMENTAL DETAILS

At present, the white LED dominantly uses blue chips and yellow phosphor to generate white light. In this case part of the blue light generated by the chip is converted into yellow light through phosphor while the other part directly comes out of the package and the mixture generate white light.

The target vertical LED in this study is a white LED which

<table>
<thead>
<tr>
<th>TABLE I. SPECIFICATION OF TARGET LED</th>
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<tr>
<td>Dimension</td>
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<tr>
<td>DC Forward current</td>
</tr>
<tr>
<td>Reverse voltage</td>
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<tr>
<td>Working temperature</td>
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<tr>
<td>Optical power (min)</td>
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<td>Dominant wavelength</td>
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is a combination of an InGaN-based blue color LED and a yellowish phosphor. Some of its specifications can be found in Table 1. These LEDs are useful in a broad range of applications such as general illumination, automotive lighting, and LCD backlighting.

Recently applying an intelligent self-curing system to get a feedback from the light has been attracting so much attention. This evaluation can help the driver for making a proper action by e.g. increasing the driver current.

There are two categories of the silicon-wafer-based wafer level packaging (WLP) LEDs; the surface-mount type, in which electrodes are formed on the silicon wafer and the LED chip is then attached to the wafer; and the cavity type, in which cavities are formed prior to the electrodes [5]. Generally, the cavity is fabricated using KOH wet etching with a (100) silicon wafer. The cavity acts both as a reflector and a holder for filling phosphor and resin. In this study, we would like to develop a photo sensor appropriate for the target wavelength (470nm) and compatible to the cavity type WLP process.

The first photodiode structure is composed of a stripe-shaped geometry in which shallow P⁺-doped regions are connected together as the anode implanted in a N-well and biased with a sweeping voltage (i.e. V-stripe). A shallow N⁺-doped region as the N-well contact and a shallow P⁺-doped region as the substrate contact are short-circuited in order to get only the photocurrent produced by the top shallow junction. The contacts at the anode and cathode electrodes were checked to be ohmic. Fig. 2 shows the schematic of the device and equivalent circuit.

In the second photodiode just a single anode but with very large area was used. In this device, the anode geometry is simply a shallow P⁺-doped region with the same width as all stripes and the distances between them together. The doping profiles for the N⁺, N-well contact and P⁺ substrate contact are the same as the multi-stripe shaped structure, but the anode is a wide P⁺ region.

For the stripe-shaped structure the width (W) of the stripes is 2μm and the distance (D) between two adjacent stripes is 5μm. The stripe length is 235 μm. According to these dimensions the shallow P⁺-doped region for the single anode geometry is 35μm.

The photodiodes were fabricated by a 5 mask 2μm BiCMOS process which allows us make different functional devices such as sensors and logical circuits for a wafer level package for LEDs.

These configurations of single and multi-stripe photodiodes were also simulated using COMSOL Multiphysics to check all physical aspects of the investigation. In order to achieve this goal, Electromagnetic waves (Frequency domain) and Semiconductor physic interfaces were coupled. The light illumination was simulated by solving the Helmholtz equations. This was achieved by analyzing the electromagnetic waves when it enters the device.

The Fresnel equations were also employed to take multiple reflections of the propagating electromagnetic wave at each interface into account. The transverse mode of electromagnetic wave, which is a particular electromagnetic field pattern measured in a plane perpendicular to the propagation direction of the beam, was applied to solve the mentioned equations. The solution to these equations is the electric field which is needed for calculating the generation term. This electric field was used to calculate the Poynting vector, and hence the optical power. Finally, the generation term, which will be added to the final continuity equation, would be derived from the optical power as shown below:

$$G = -\frac{\partial P_{op}}{\partial y} \times \frac{1}{h}$$

Where h, f, y and P_{op} are respectively Plank’s constant, frequency of the incident beam, depth and optical power. As the simulation results demonstrated, blue light ray optical power (470nm) decays dramatically as it enters the silicon (Fig. 3). So for getting better blue responsivity the active junction should be at a few hundred nanometers depth inside the substrates. Making the shallow P⁺-doped area through Boron ion implantation results in a dead layer on top, very close to the Si surface. This layer is one of the high doping effects and boron redistribution. In other words, dopant pileup occurs in an interfacial layer between SiO₂ and Si. This layer act as a sink for inactive dopant atoms in this region[10].

The presence of this dead layer on top acts as the recombination sites for the generated electron-hole pairs. As a result, recombination with a very high rate occurs at the surface which creates an electric field toward the substrate. This dead layer can be also observed in electron concentration profile
extracted from simulation as shown in Fig. 4a. Fig. 4b illustrates the doping profile of the P⁺-doped/N-well area measured by electrochemical capacitance-voltage profiler (ECVP). Due to the fact that the ECVP measures the active carrier concentration, the dead layer cannot be observed in this figure. The minimum at 330nm is the P⁺/N-well junction and N-well is extended for 1.5μm into the substrate.

As illustrated in Fig. 3, because the blue and UV spectrum is basically absorbed near the surface regarding the penetration depth, the dead layer formation decreases the responsivity. Electron-hole generated by target photons can recombine in the dead layer which is not desired so by making stripe shaped junction we can minimize the problem. Therefore, by using multi striped structure, the dead layer in comparison to single anode structure is down scaled to W/(W+D) [9] which will improve the blue spectra responsivity.

III. RESULTS

The anode current of the photodiode was simulated using the continuity equation consisting drift-diffusion, generation and recombination rates. Both single- and multi-stripe structures were analyzed w/o 470nm radiation (see Fig. 5a). The resulted I-V shows no significant variation in the current under the dark condition. However, multi-stripe device showed a 2.5 times improvement in the output current compared to single-stripe one which is another proof for the significance of the dead layer. The spectral responsivity of photodiode was measured by a solar cell simulator using a monochromatic light with sweeping wavelength in 300-1200nm range. The responsivity plot shows a peak at λ=480nm with 342mA/W. Fig. 5b shows the responsivity of two different photodiodes vs. wavelength for 0 volt bias condition. Comparing to the single anode structure, an improvement in responsivity is observed for the multi-stripe photodiode as was predicted in the simulation results. IR range responsivity shows a dramatic fall which indicates a high selectivity for the target wavelength. Fig. 5b shows the responsivity of two different photodiodes vs. wavelength for 0 volt bias condition. A selectivity can be defined as a ratio of responsivity for different wavelength, that is 42 for λ=470nm and λ=1000nm. It was seen that for high bias voltage, the responsivity can also go higher while because the depletion area extension selectivity would be less.

The measurement was also performed for integrated package. The package was consisted of array of 4 LEDs which can be turned on separately or with different combinations. Fig. 6 shows the package picture with off and on LEDs and photodiode positions.

Each LED chip is consisted of 2 parallel p-n junction which we just use one of them in the package. The light intensity of

![Fig. 4: (a) Electron concentration in photodiode structure in Zero volt bias condition. (b) ECVP profile of shallow P⁺ area implanted in the N-well. P⁺-N junction is formed at depth of 330nm where the doping profile is first crossing N-well doping level.](image)

![Fig. 5: (a) Simulated IV current for both single anode and multi-stripe structures w/o 470nm radiation (b) Responsivity vs. wavelength for multi stripe and single anode photodiodes.](image)

![Fig. 6: Photodiodes in LED package. For each LED two sets of photodiodes were used to get output light measurement.](image)
LED was measured with the photodiodes for different driving currents. The results are shown in Fig. 7. When LED is off, the reverse current value is $10^{-12}$A. It shows almost 6 orders of magnitude difference compared to when the LED is on. This difference is governed by the generation of electron-hole pairs in the active part of the device and the recombination dominantly close to the surface. By normalizing the output current and fitting to the datasheet amounts a remarkable consistency can be achieved (see Fig. 8).

The devices also were examined by some sort of stress test. Relative luminous intensity decays 0.9% within 2 hours (constant input $i_f=350\text{mA}$). This effect is caused by the temperature raising during the Lighting on period. This is a proof of sanity for the importance of such an intelligent control system for these LEDs. It is worth mentioning that the ambient light rarely affects the performance of photodiode due to its remarkable blue light selectivity.

Fig. 9 compares the spectral responsivities of the fabricated photodiodes and a calibrated UV-enhanced photodiode from Hamamatsu, S1226-18BQ. The commercial UV-enhanced device with an antireflection coating exhibits an almost non-selective behavior. However, our photodiode and the one manufactured in [9] demonstrate slightly lower responsivity for the deep ultraviolet spectral range. The device fabricated in [9] has a peak at 400nm, while the photodiode in this study has shown a peak at exactly 480nm which is amazingly matched with the illuminated waves from the LED. A rapid decreasing trend is observed for the VIS and IR ranges. Moreover, a two-fold increase in quantum efficiency and comparable selectivity are evaluated for the LEDs fabricated in our work compared to the previously published devices.

IV. CONCLUSIONS

A silicon stripe-shaped photodiode was successfully designed and fabricated using a 2μm BiCMOS process which integrates simultaneously the photodiodes, the Bipolar and CMOS transistors all in just five masks. This IC includes several functional devices such as sensors and primary logical circuits for a smart wafer level LED packaging. These silicon technology compatible photodiodes, with junction at 330nm, demonstrated a very high selectivity to blue light. The maximum responsivity was at 480nm which is matched with the blue LED's illumination. The single-stripe structure due to higher rate of recombination caused by the dead layer formation showed lower responsivity compared to multi-stripe

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**REFERENCES**


