

Fabrication and characterization of two-dimensional pin-cushion position sensitive detectors

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Received January 13, 2004

In this paper, the fabrication and testing results of a two-dimensional pin-cushion position sensitive detector (PSD) are presented. The obtained pin-cushion PSD with an $8 \times 8 \text{ mm}^2$ effective area presents a maximum spectral response of 0.5 mA/mW at 850-nm wavelength, a 12-nA dark current at 5-V reverse voltage, a reverse breakdown voltage of 50 V , a nonlinearity of 2.175% , and a spatial resolution of $10 \mu\text{m}$. The spatial resolution is relatively low and the slight pin-cushion concave distortion is generated due to the incompletely satisfied relationship between sheet resistivity of the anode and the resistance per unit length. *OCIS codes:* 040.5160, 230.0040, 310.1860.

Position sensitive detectors (PSDs) are an important class of optoelectronic sensors which can be utilized to detect the position of a focused incident light beam using the lateral photoeffect^[1]. Compared with the discrete element detectors such as charge-coupled devices (CCDs) and quadrant detectors, the PSDs have many advantages including higher position resolutions, faster response speed, and simpler operating circuits. Furthermore, PSDs detect the centroid of light irradiating on the detector and are independent of the focus and the shape of the light spot. They are widely used nowadays in precision measurement applications such as optical position and angle sensing, remote optical controlling, displacement and vibration monitoring, laser beam alignment, and robotic vision.

To improve the linearity and resolution of position detection, different geometries of the sensitive area in the PSD, such as tetralateral, duo-lateral duo-axis and pin-cushion geometries, have been proposed. However, the tetralateral PSD has been found to have poor linearity over most of the sensitive area^[2,3]. The duo-lateral, duo-axis PSD has some disadvantages such as slow response speed and high fabrication cost, even though it exhibits superior linearity to tetralateral PSDs. Pin-cushion type, as shown in Fig. 1, was an idea of Gear^[4]. He pointed out in 1969 that when a current with uniform current density flowed through a circular arc border with radius a

and resistance per unit length R within an infinite sheet with homogeneous resistivity r , the border would not affect the current distribution within the sheet if the relationship $R = r/a$ was fulfilled. If $R > r/a$, there will be pin-cushion distortion, and if $R < r/a$, ballistic deficit will appear^[5].

Produced by following the Gear's rule, the pin-cushion PSD shows the merit of good linearity, and the distortion in the circumference has been greatly reduced. At the same time, it has other advantages such as small dark current, fast response, and easy bias application, which are advantages of the tetralateral type.

Here we demonstrate an $8 \times 8 \text{ mm}^2$ silicon pin-cushion PSD and its experimental performance. The fabricated pin-cushion PSD, as shown in Fig. 2, was Si pin structure with an effective sensitive area of $8 \times 8 \text{ mm}^2$, and the radius and width of border resistor were designed as 20 mm and $120 \mu\text{m}$ separately on a 3-inch n-type silicon (111) substrate. Ion implantation processes were used to introduce boron in the n-type substrate. The doping density and energy were separately $2.5 \times 10^{12} \text{ cm}^{-2}$ and 65 keV in sensitive area and $2.1 \times 10^{15} \text{ cm}^{-2}$ and 75 keV in border region. The tested capacitance of the p-n junction is about 400 pF under the 5-V reverse voltage and the sheet resistance is $5.86 \text{ k}\Omega$. Because the delay time arising from a diffusion process through which photo-generated carriers

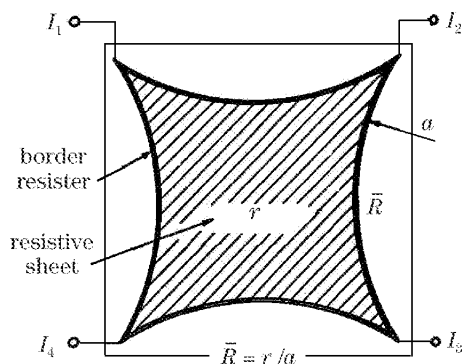


Fig. 1. Schematic diagram of a pin-cushion PSD.

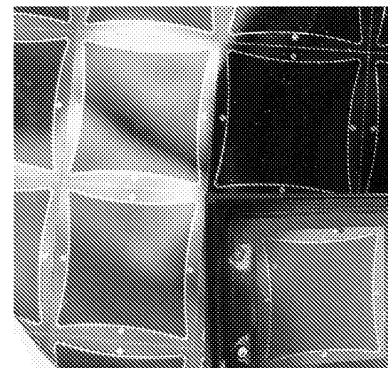


Fig. 2. Unpackaged 8×8 PSD silicon chips. Inset: a packaged PSD detector.

move to the depletion region is about several nanoseconds and can be neglected, the time constant of this PSD is determined by the distributed RC characteristic of the PSD, and is equal to 2.38×10^{-6} second. In order to reduce the contact resistance, a p^+ shallow diffused region was made in the contact windows and an n^+ layer was diffused before evaporation of aluminum contact metal. After testing the device on the wafer, each qualified device was separated for packaging using a dicing saw. A typical reverse breakdown voltage of the device was 50 V and the dark current is 12 nA at 5-V reverse voltage. The spectral range is from 300 to 1150 nm and the peak of photosensitivity reaches 0.5 mA/mW at 850-nm wavelength, as shown in Fig. 3.

The experimental measurement result of the position mapping is shown in Fig. 4. A 1.2-mW He-Ne laser beam with the diameter of about $200 \mu\text{m}$ was incident on a fully reverse-biased PSD (5 V) mounted on an x - y translation stage, which was accurate to $1.25 \mu\text{m}$ and driven by a manually controlled stepping motor at room temperature.

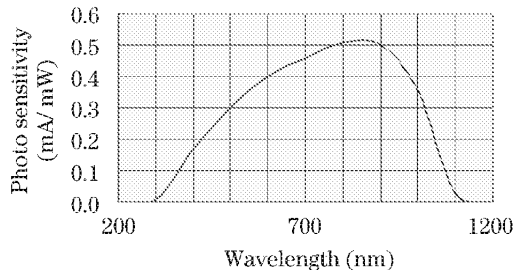


Fig. 3. Spectral response of the fabricated $8 \times 8 \text{ mm}^2$ PSD.

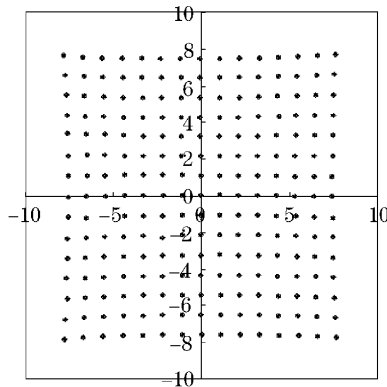


Fig. 4. Measured position patterns of a pin-cushion PSD with a step of $500 \mu\text{m}$.

The nonlinearity indicates the deviation between the real position and the PSD yielded position, it is usually defined as $\delta = 2\sigma/F$, where σ is the root mean square deviation from a regression line fit to the measured position and F is the full length of the sensitive area. We also measured the PSD spatial resolution, which is defined as the minimum detectable beam displacement. Scans were performed with a decreasing positional step size until δ exceeded 15%. Typically, $\delta < 15\%$ is sufficient for many applications^[6]. The experiments resulted in a nonlinearity factor of 2.175% with a step distance of $500 \mu\text{m}$ and a spatial resolution of about $10 \mu\text{m}$.

The distortion between the obtained position response and actual light spot location was caused by the nonuniformity of resistance sheet introduced during the doping process. There is also a pin-cushion distortion in the position pattern in Fig. 4 because actually the resistance per unit length is a little bigger than the designed quantity. This can be rectified in the future by methods such as decreasing the annealing temperature of the sensitive area or reducing the energy and/or the concentration during ion implantation doping.

In conclusion, we have demonstrated a high-resolution two-dimensional pin-cushion silicon PSD with a time constant of less than $2.5 \mu\text{s}$. The $8 \times 8 \text{ mm}^2$ device has a wide spectral range from 300 to 1150 nm and a peak sensitivity of 0.5 mA/mW at 850 nm, and exhibits a nonlinearity of about 2%. All these merits make it very suitable in precision measurements that require high resolution, fast device response, and large detection area.

The authors wish to thank Hamamatsu Photonics K. K. for finishing part of the testing work. D. Chen's e-mail address is patown@163.com.

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