Circular single-photon avalanche diode with high premature edge breakdown and extended spectrum

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Abstract: This paper presents a 0.18 μm complementary metal-oxide-semiconductor (CMOS) technology high premature edge breakdown, extended spectrum and low dark count rate circular single-photon avalanche diode (SPAD) which together form a novel wide spectrum fluorescence correlation spectroscopy (FCS) detector. The circular device consists of a p+/deep n-well junction, a p-well guard-ring, and a poly guard-ring. Simulations on a Silvaco TCAD 3D device also show that the 10 μm-diameter circular p+/deep n-well SPAD device has high premature edge breakdown characteristics. Moreover, compared to the SPAD p+/n-well junction, the p+/deep n-well junction has a longer wavelength response and spectral expansion. The device achieves wide spectral sensitivity enabling greater than 40% photon detection probability from 490 to 775 nm wavelength at 0.5 V excess bias. The circular p+/deep n-well SPAD has fine avalanche breakdown (15.14 V) and a low dark count rate of 638 Hz at 25°C.

Key words: single-photon avalanche diode (SPAD), premature edge breakdown (PEB), dark count rate (DCR), spectral expansion

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高边缘击穿和扩展光谱的圆形单光子雪崩二极管

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摘要: 介绍了一种 0.18 μm 互补金属氧化物半导体 (CMOS) 技术的新型宽光谱单光子雪崩光谱探测器, 其为高边缘击穿, 扩展光谱和低暗计数率的圆形单光子雪崩二极管 (SPAD)。该器件由 p+/deep n-well 结, p-well 保护环和多晶硅保护环组成。通过 Silvaco TCAD 3D 器件仿真, 直径为 10 μm 的圆形 p+/deep n-well SPAD 器件具有较高边缘击穿特性。此外, p+/deep n-well 结 SPAD 比 p+/n-well 结 SPAD 具有更长的波长响应和扩展光谱响应范围。该器件在 0.5 V 过量偏压下, 可在 490 – 775 nm 波长范围内实现超过 40% 的光子探测率。该圆形 p+/deep n-well SPAD 器件在 25°C 时具有较好雪崩击穿为 15.14 V, 具有较低暗计数率为 638 Hz。

关键词: 单光子雪崩二极管 (SPAD); 边缘击穿; 暗计数率; 光谱扩展

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Introduction

Single-photon avalanche detectors (SPADs) are PN junction devices biased by Geiger-Mode, i.e., devices with bias voltage beyond their breakdown voltage. The electric field in the SPAD multiplication region is so intense that a single photon carrier is sufficient to begin a self-maintained avalanche by impact ionization due to the generation of photons, which creates high pulse signaling. A single photon can thus be detected by the associated electronic circuitry\(^1\). SPADs can detect the arrival resolution of individual photons in dozens of picoseconds time\(^2\). Photon-counting devices are widely used in quantum key distribution systems for the purposes of single molecule detection\(^3\)\(^4\). Researchers have developed solid-state SPADs as CMOS technologies suited to an array of science and engineering applications\(^5\)\(^6\). CMOS SPADs\(^6\) have been successfully applied in low-noise, high timing resolution, and high dynamic ranges\(^7\).

Recent scholars have focused on developing new SPADs with low DCR\(^8\)\(^9\), wide spectral response\(^10\)\(^11\), small pixel size\(^12\), and low breakdown voltage\(^13\). New CMOS SPAD designs tend to center on enhanced fill factor, reduced edge breakdown, and increased long-wavelength detection. The SPAD with a p+ /deep n-well junction of deep sub-micrometer CMOS technology produces high dark noise by tunneling while minimizing photon detection efficiency (PDE). However, the low doping concentration of the deep n-well makes the p+ /deep n-well junction deeper and the detected wavelength move towards a longer wavelength.

A variety of SPAD shapes (e.g., circular, octagonal, elliptoidal) have been proposed to improve the device performance\(^14\). In this work, we fabricated the proposed SPAD in a 0.18 \(\mu\)m CMOS process with a 10 \(\mu\)m active diameter. The SPAD’s circular structure effectively reduces the electric field concentration at corners, and thus effectively prevents edge breakdown and increases the fill factor.

1 P+ /deep n-well versus p+ /n-well junction SPAD

The circular device consists of a p+ /n-well junction, a p-well guard-ring, and a poly guard-ring. A cross-section of the SPAD structure is shown in Fig. 1. The SPAD has a narrow depletion layer and a strong electric field, which raises the avalanche breakdown probability. The spectral response of the device is biased towards the blue band. The p-well, as a guard ring, merges with the depletion layer when the p+ /n-well SPAD is relatively small in size. As the breakdown voltage of the device increases, the p+ /n-well loses its efficacy as the diameter of the source area is 5 \(\mu\)m\(^15\). In this study, we used a source area of 10 \(\mu\)m.

![Fig. 1 P+ /n-well junction SPAD structure](image)

![Fig. 2 P+ /deep n-well junction SPAD structure](image)

The p+ /deep n-well junction SPAD has a wide wavelength response to suit the wide-spectrum detector, because electrons generated in the wide junction trigger the avalanche with high impact ionization possibilities. A cross-section of the SPAD structure is shown in Fig. 2. The deep n-well with a small doping concentration in the structure replaces the n-well, and the p+ /deep n-well forms an active multiplication junction. The device has a wide depletion layer which allows for extended spectrum response. The p+ /deep n-well and p+ /n-well junction of SPAD structure we tested are described in Table 1.

The two devices retain the STI around the protection ring to reduce the width of the protection ring. The Silvaco TCAD simulation of electric field are shown in Fig. 3, indicating that the protection ring prevents edge breakdown. Compared with P+ /deep n-well junction SPAD, the doping concentration of P+ /N-well junction SPAD has been increased, the depletion layer has been narrowed, and the breakdown voltage has been decreased.

As shown in Fig. 4, the photoreceptor depth of the p+ /n-well junction SPAD and p+ /deep n-well junction SPAD is 0.2-0.6 \(\mu\)m and 0.2-0.9 \(\mu\)m, respectively. Deeper junctions absorb photons at longer wavelengths providing improved PDE toward the red band of the spectrum. The 2D Silvaco TCAD simulation results show that the p+ /deep n-well junction SPAD has the wider spectral response between them.

2 Octagonal versus circular SPAD

Two shapes of SPAD were tested in this study as per

<table>
<thead>
<tr>
<th>Device name</th>
<th>D1 ((\mu)m)</th>
<th>D2 ((\mu)m)</th>
<th>D3 ((\mu)m)</th>
<th>D4 ((\mu)m)</th>
<th>D5 ((\mu)m)</th>
<th>D6 ((\mu)m)</th>
<th>D7 ((\mu)m)</th>
<th>Shape</th>
<th>PN junction</th>
</tr>
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<tbody>
<tr>
<td>Circular p+ /n-well SPAD</td>
<td>2.1</td>
<td>10</td>
<td>3</td>
<td>2.2</td>
<td>2.5</td>
<td>1.6</td>
<td>2.9</td>
<td>Circular</td>
<td>p+ /n-well</td>
</tr>
<tr>
<td>Circular p+ /deep n-well SPAD</td>
<td>2.1</td>
<td>10</td>
<td>3</td>
<td>2.2</td>
<td>2.5</td>
<td>1.6</td>
<td>2.9</td>
<td>Circular</td>
<td>p+ /deep n-well</td>
</tr>
</tbody>
</table>

Table 1 The size of p+ /deep n-well and p+ /n-well junction SPAD structure

表1 P+ /深n 阶和 p+ /n 阶 SPAD 结构尺寸表
their effects on the edge breakdown. As shown in Fig. 5, we used a Silvaco TCAD 3D device to simulate the octagonal and circular p+/n-deep n-well junction SPADs. The electric field of the octagonal SPAD edge is greater than that of the circular SPAD edge, which is mainly due to the large curvature of the p-n junction and sharp SPAD shape. The octagonal and circular SPAD structures we tested are described in Table 2.

We found that the electric field of the octagonal SPAD edge is greater than that of the circular SPAD edge (red circle, Fig. 6). The circular shape SPAD reduces the electric field concentration and prevents premature edge breakdown.

3 Experiments and discussion

To optimize the structural shape and junction doping concentration of the SPAD device, we fabricated different SPADs in 0.18 µm CIS technology. A photomicrograph of the chip is shown in Fig. 7. The circular p+/n-well junction SPAD, circular p+/deep n-well junction SPAD, and octagonal p+/deep n-well junction SPAD are shown from left to right in Fig. 7.

A passive quench circuit was used to measure the dark count rate (DCR) of the SPADs; the measurement circuit is shown in Fig. 8. The cathode of the SPAD was connected to the voltage source $V_{Excess} + V_{Breakdown}$ and the anode to the ground at a 51 kΩ quenching resistance. The SPAD test platform and quenching circuits (Fig. 9) were measured for DCR in darkness.

Figure 9 shows a test platform which consists of three templates representing a DC power supply, digital oscilloscope, and the proposed SPAD plus quenching circuits, respectively.

The inverse I-V characteristics of the three SPADs were measured as shown in Fig. 10. The breakdown voltage of the circular p+/n-deep n-well junction SPAD, the octagonal p+/deep n-well junction SPAD, and the circular p+/n-well junction SPAD are approximately 15.14 V, 15.12 V, and 10.62 V, respectively (Fig. 10). The breakdown voltage of the circular p+/deep n-well junction SPAD is approximately 15.14 V, which exceeds the 13.9 V reported in the literature circular device, due to the 0.13 µm CMOS technology, in which the doping concentration is relatively large and the breakdown voltage is small. Under the same bias voltage and non-break-

<table>
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<th>Device name</th>
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down edge condition, the photocurrent of the circular p +/n-well junction SPAD is particularly large.

The DCR and bias voltage have linear relationship at room temperature (Fig. 11) due to the probability of avalanche breakdown and the generation of tunnel carriers. An excess bias voltage ranging from 0.1 V to 1 V was applied with a 0.1 V step. The DCR of the circular p+/n-well junction SPAD is much greater than that of the circular p+/deep n-well junction SPAD at the same excess bias voltage to the photosensitive junction concentration and high avalanche breakdown probability. At room temperature, the octagonal and circular p+/deep n-well junction SPAD DCRs are 112 Hz and 105 Hz, respectively, when the excess bias voltage is 1 V.

The photon detection probability (PDP), which is the ratio of the quantity of detected photons over the quantity of incident photons, was measured over a wavelength range from 400 nm to 1100 nm at room temperature with an excess bias voltage of 500 mV. As shown in Fig. 12, the p+/n-well junction SPAD detected a wavelength range with maximum PDP of 565 nm, or 16%.
The circular p+/deep n-well junction SPAD has longer wavelength response with a peak value wavelength up to 775 nm. The device achieves spectral response sensitivity with above 40% PDP from 490 to 775 nm wavelength, and the spectral response is enlarged.

The proposed circular SPAD device with p+/deep n-well junction allows active multiplying junctions with deep n-well shallow n-type doping, increases the depletion layer width compared to the other SPADs, and detects light over a wide spectrum and long wavelength; however, its PDP is relatively low. As shown in the diagram, the loss region is relatively thick and it is to some extent beneficial to enhancing the spectral response.

4 Conclusion

A circular p+/deep n-well junction SPAD implemented in a 0.18 μm CMOS technology was introduced in this paper. The circular device consists of a p+/deep n-well junction, a p-well guard-ring, and a poly guard-ring. The circular p+/deep n-well junction SPAD, octagonal p+/deep n-well junction SPAD, and circular p+/n-well junction SPAD were compared to find that the p+/deep n-well junction SPAD has extended spectrum response characteristics relative to the p+/n-well junction SPAD; the former device achieves wide spectral sensitivity with above 40% PDP from 490 to 775 nm wavelength at 0.5 V excess bias. Theoretical analyses, simulation via Silvaco TCAD 3D device, and measurements together indicated that the avalanche breakdown voltage of the circular SPAD device with 10 μm diameter is 15.14 V. It also shows high premature edge breakdown and low DCR of 638 Hz at 25°C.

References