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A Silicon-Based Positive-Intrinsic-Negative Photodetector Double Linear Array on a Thick Intrinsic Epitaxial Layer *

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To measure small particles in clouds without the optical amplification system, a new type of p–i–n photodetector linear array with 128 diode units altogether is designed and realized. In each die, there are two rows of photodiode line array, and each row has 64 photodiodes. Every photodiode has a size of 100 μm × 100 μm with an individual output, and each of them is isolated by the trenches. The depth of them has the same thickness as that of the epitaxial layer, which is designed to be 30 μm to guarantee sufficient absorption of photons and leave a margin for the diffusion of p-type and n-type region. The detector has been tested with a laser whose wavelength was 650 nm and irradiance is 50 mW/cm^2. The achieved photocurrent is 2 μA. Hence, the current responsivity is about 0.4 A/W, and the external quantum efficiency is 76.45%. The dark current is less than 600 pA. Both of the sufficient absorption of photons and low dark current are achieved by utilizing the thick epitaxial intrinsic layer. Low interference of adjacent photodiodes is also guaranteed by the trenches around the photodiodes. With the obtained performance, the photodetector can be used to measure the diameter of precipitation particles in clouds. Therefore, rainfall can be judged based on the diameter of particles.

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It is well known that the p–i–n diode was invented by Nishizawa in 1950.[1] The p–i–n photodiode has an intrinsic layer between positive and negative diodes, which extends the depletion region where photons are absorbed, while excited electron-hole pairs generate the photocurrent.[2] Usually, p–i–n photodiodes are fabricated with a standard semiconductor process, and work at a low bias voltage. Due to their simple structure, they were widely used in the 1960s. Photodiode units that are used to form an array can be used in imaging fields, especially in the measurement of small particles.

In 1970, to determinate airborne particles in the cloud, Knollenberg *et al.* used fiber optics with a diameter of 100 μm and arranged them in a line to form the optical array probe (OAP).[3] The other ends of the fiber optics were connected to photodiodes that converted the optical signal to an electrical signal. They used a laser to illuminate the OAP. When a particle passes through the illuminated region, a shadow is cast on the OAP, and the signal in the output of the photodiodes changes. By counting the number of the photodiodes whose signal had changed, the number of fiber optics in the shadow was attained and thus the diameter of the particle could be figured out. Then Kollenberg *et al.* successfully used OAP to measure particle size in 1972.[4]

Also there have been compromised solutions. In 1984, Hauser *et al.* used only one photodiode instead of a diode array and a set of lenses to measure raindrops.[5] Löffler-Mang *et al.* also used a similar structure in 2000.[6] However, this was an indirect method, the size of the particle was determined by current values which did not reflect the real shape of particles.

Schönhuber *et al.* reported their 2D-Video-Distrometer in 1994.[7] This distrometer used two line scan cameras to measure raindrops to obtain information including raindrop size, shape, speed and quantity. However, a double line scan array mentioned by Knollenberg *et al.* could attain the speed of particles more easily.

There are some products of the silicon photodiode array, such as the S4111 series of Hamamatsu Photonics K.K. The current responsivity of them is from 0.39–0.43 A/W at a 633 nm wavelength, and dark current at 10 V bias voltage is from 25 to 300 pA. However, the photodiode element of them is 1.44 mm × 4.4 mm and the total number of I/O is less than 46. Hence, a common photodiode array may not meet the needs to measure small particles in clouds.

In this Letter, we design a double line photodiode array die with 128 photodiodes with a chip dimension of 6.8 mm × 3.8 mm. Every photodiode has a size of 100 μm × 100 μm with an individual output. The number of I/O almost reaches the technical limitation

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of wire bonding. The small size of the photodiode element is able to meet the measurement requirements of raindrops for the rainfall-prediction application.

In our design, an incident laser beam perpendicular to the photodetector surface covered the whole chip to measure the particle diameter. When a particle passes through the illuminated area, a shadow is cast onto the photodiode chip. Each photodiode in the shadow results in an electrical output change and thus is recorded. The diameter of the particle could be implied by the total number of the photodiodes in the shadow. The schematic diagram is shown in Fig. 1.

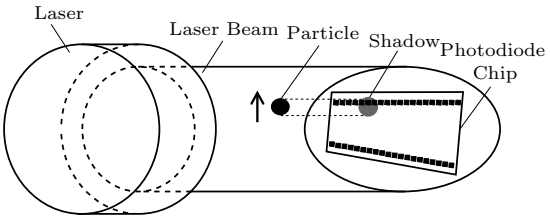

Fig. 1. Schematic diagram of the particle diameter detection.

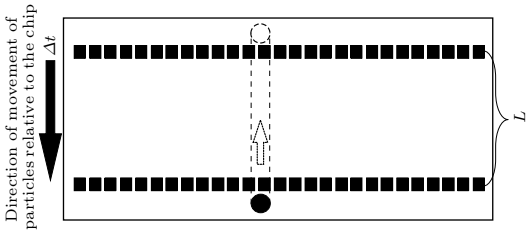

Fig. 2. Schematic diagram of a particle passing through the chip.

The particle velocity v relative to the chip could be determined by the interval Δt when it passed through the photodetector between two lines. The distance between two lines was a constant L, thus the speed of the particle could be solved by Eq. (1), where D was the diameter of the particle,

$$L + D = v \cdot \Delta t. \tag{1}$$

In fact, the particle was static and the measuring system was moving. The speed of the chip was equal to that of the particle which was measured by the photodiode array. When particles in clouds were detected one by one, the distance between two different particles could also be calculated by speed and time interval between two particles passing through the array. Hence the density of precipitation particles could be evaluated.

As stated above, the size of the photodiode could be used to calculate the particle's diameter and the size of one photodiode determined the minimal size of the particle that could be detected. Thus the area of a photodiode should be confirmed firstly. A particle in a cloud whose diameter is less than 100 μm is called a cloud drop, and a particle whose diameter is larger than 100 μm is called a rain drop.[8,9] When the rain drops are larger than 1000 μm, the probability of rainfall is very high.[10] In our project, we mainly focused on the droplet in the cloud from 100 μm to 1000 μm. Therefore, we chose 100 μm as the size of each photodiode.

To obtain a higher quantum efficiency and a larger photocurrent, the p–i–n photodiode was an appropriate choice. Thus we chose an epitaxial wafer which had a heavily doped n-type substrate and a 30 μm intrinsic epitaxial layer, its resistivity was larger than 100 Ω·cm. The thickness of the epitaxial layer was determined by the absorption length and the diffusion length of the p and n regions, which would be calculated in a technology simulation.

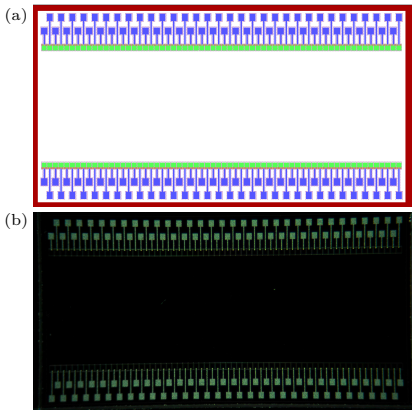

Fig. 3. Layout and the die.

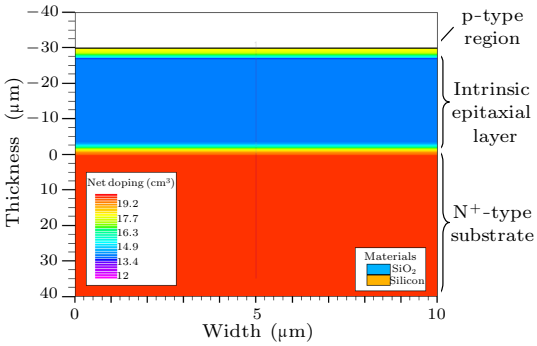

Fig. 4. Cross-sectional view of the photodiode.

Then we used ion implantation to form the p-type region, its size was 100 μm × 100 μm. The size of the p–i–n photodiode was determined by the size of the p-type region. Aluminum wires were used to connect each p-type region to the bonding pads, which were the anodes of the photodiodes. On the bottom of the substrate, an aluminum layer was evaporated to form the common cathode of all photodiodes. In the case of the interference between two adjacent photodiodes, inductively coupled plasma (ICP) etched a groove around each photodiode. Thus the current from one photodiode did not affect the current from the one next to it.

The layout and the die are shown in Fig. 3, where the green region is the photodiode and the blue one is the aluminum wire.

Figure 4 shows part of the structure of a photodiode. Technology simulation was performed in Silvaco software.

The absorption length of incident light could be calculated by

$$I(d) = I(0) \times e^{-\alpha d}, \tag{2}$$

where $I(d)$ is the photo flux at a distance d from the surface and $I(0)$ is the incident flux entering the silicon. The absorption coefficient α at wavelength 650 nm at 300 K was $2.8 \times 10^3\,\mathrm{cm}^{-1}$.[11] When $I(d)/I(0)$ was less than 1%, the absorption length d was 16.45 μm. Thus the thickness of the intrinsic layer should be larger than 16.45 μm.

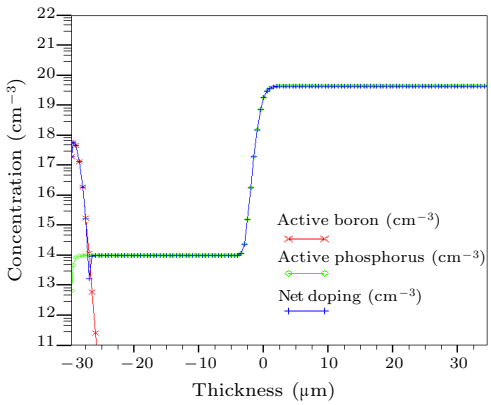

Fig. 5. Impurity distribution.

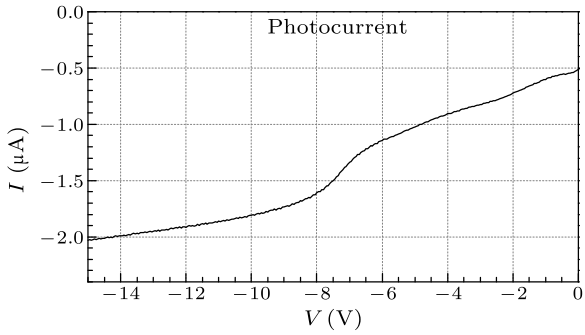

Fig. 6. Photocurrent (voltage is changed from −15 V to 1 V).

Impurity distribution after annealing is shown in Fig. 5. As shown in Fig. 5, the total diffusion length of the p and n regions was close to 10 μm. The thickness of the intrinsic layer, whose concentration is $1 \times 10^{14}\,\mathrm{cm}^{-3}$, is nearly 20 μm. Hence, an epitaxial layer of 30 μm ensures sufficient absorption of photons.

In the simulation through Silvaco, the light wavelength is 650 nm and the irradiance is $50\,\mathrm{mW/cm}^2$. When the bias voltage is −10 V, the simulation result of the photocurrent is 2.315 μA.

The current responsivity could be calculated by

$$R = \frac{I}{P} = 0.463\,\mathrm{A/W}, \tag{3}$$

where $P = 50\,\mathrm{mW/cm}^2 \times (100\,\mu\mathrm{m})^2 = 5 \times 10^{-3}\,\mathrm{mW}$.

The external quantum efficiency (EQE) can be calculated by

$$\eta = \frac{I/e}{P/h(c/\lambda)} \approx 88.50\%, \tag{4}$$

where elementary charge $e = 1.6 \times 10^{-19}\,\mathrm{C}$, speed of light $c = 3 \times 10^8\,\mathrm{m{\cdot}s^{-1}}$, Planck constant $h = 6.626 \times 10^{-34}\,\mathrm{J{\cdot}s}$, and wavelength $\lambda = 650\,\mathrm{nm}$.

After our die has been fabricated, we used a probe station for electrical measurements. A laser beam with a power density of $50\,\mathrm{mW/cm}^2$ and the wavelength of 650 nm was placed perpendicularly to the die. The photodiodes worked under reversed bias voltage, ranging from −15 V to 1 V. The photocurrent as the function of bias voltage is shown in Fig. 6. When the voltage was −15 V, the photocurrent was nearly saturated.

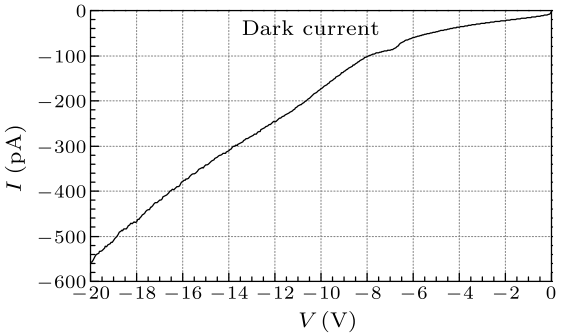

Fig. 7. Dark current (voltage is changed from −20 V to 0).

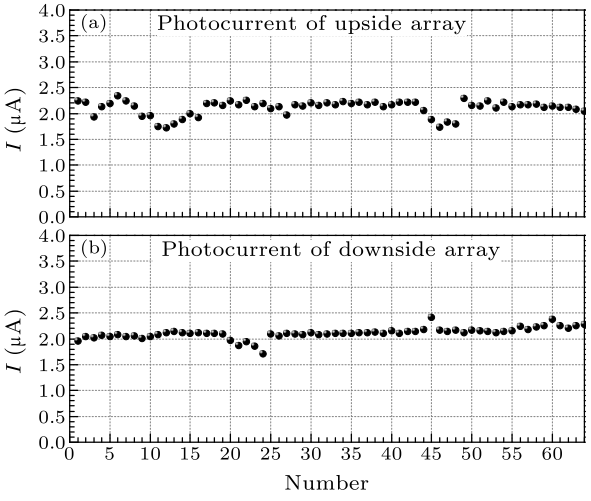

Fig. 8. Photocurrent of all photodiodes of two linear arrays (voltage is −10 V).

Due to the fact that dark current is mainly relative to the thermal factor, the dark current shown in Fig. 7 is nearly proportional to bias voltage. The

dark current is less than 600 pA even under −20 V bias voltage.

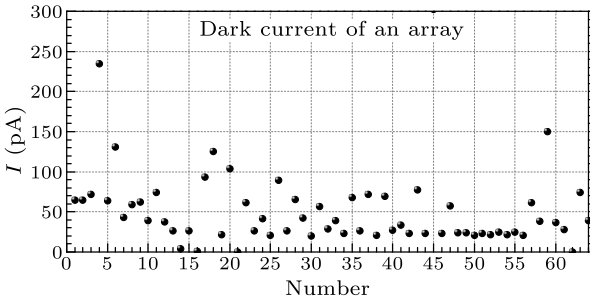

Fig. 9. Dark current of all photodiodes of one line array (voltage is −10 V).

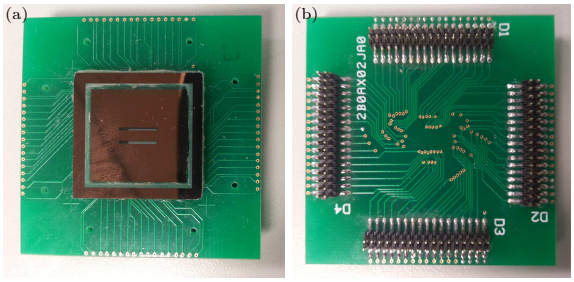

Fig. 10. Picture of die after packaging: (a) top view of chip, (b) bottom view of chip.

We also tested all photodiodes on a die to confirm whether there was a broken unit. The photocurrent test results are shown in Fig. 8.

Due to the fact that the light beam of the laser might not be accurately perpendicular to the die in every test, the consistency was not calculated. However, we could see that the average photocurrent is about 2 μA under −10 V bias voltage. Thus the current responsivity and EQE could also be calculated by Eqs. (3) and (4),

$$R = \frac{I}{P} = 0.4\,\mathrm{A/W}, \tag{5}$$

$$\eta = \frac{I/e}{Ph(c/\lambda)} \approx 76.45\%. \tag{6}$$

The dark current of a one line array is shown in Fig. 9. The consistency of the dark current was not good. A possible explanation was that the resistivity of the epitaxial layer was non-uniform. Due to the fact that in the epitaxial process, impurities from the heavily doped substrate may be doped into the epitaxial layer. That would result in the resistivity being changed. However, the current of every photodetector was less than 350 pA, which was nearly 5700 times less than the photocurrent. The effect of the dark current could be ignored.

The experimental results agree well with the simulation results, especially the photocurrent.

Then we bonded dies directly to a printed circuit board (PCB) by wire bonding. A glass board with two narrow slits covered the whole die to protect it. Two photodiode arrays were illuminated separately through the two slits. After packaging, the device can be used in an airplane.

In summary, we have implemented a silicon-based photodiode double array. It has a high quantum efficiency of up to 76% and a current responsivity of 0.4 A/W. With a PCB package and laser-assisted operation, this device can be used to measure the density of particles in air. Meeting the electrical and optical requirements, it is applied to a rainfall-prediction system.

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