The Fabrication and Test of 64-Channel Silicon Photomultipliers

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Abstract. A silicon photomultiplier (SiPM) is a highly sensitive photo sensor, and it consists of many micropixels that operated in Geiger mode. The SiPM has various preferable characteristics, such as low voltage operation compactness and lightweight. Additionally, the SiPM is robust and insensitive to magnetic fields, and it is capable of the counting of single photons due to the high gain of $10^5 \sim 10^6$. The developments of UV enhanced SiPMs and large area matrices of SiPMs have been actively pursued in the world. The technology can be utilized for applications such as radiation detection, medical science, cameras, and telescopes. In this study, we present the design, fabrication, and test result of the 64-channel SiPM sensor as the first step toward the development of a large matrix of SiPMs.

1. Introduction
The silicon photomultiplier (SiPM) consists of many micropixels and is a next-generation silicon photo sensor with high-speed, low power, low weight characteristics as well as a high sensitivity to light [1]. Each micropixel of the SiPM, called a Geiger mode Avalanche Photo Diode (APD), has the function of single photon counting, which is a characteristic of ultra-sensitivity [2]. As the micropixels of the SiPM are operated in Geiger mode, they have a higher gain ($10^6$) than a typical APD ($10^2$). The gain of the SiPM is approximately equal to a photomultiplier tube (PMT), which is frequently used as a photo detector of single photon counting [3]. The SiPM has a short rise time of about 1 ns, a short recovery time of about 20 ns, and a time resolution of about 30 ps/10 photon in a specific way. The sensor also has a low operating voltage of 20 $\sim$ 70 V. The photo detection efficiency (PDE) is at the maximum value of 50 % at peak wavelengths in 400 $\sim$ 900 nm [2]. With these advantages, the SiPM is spotlighted as a photo sensor to replace conventional PMTs. SiPM development throughout the world has been actively proceeding in UV enhancement for medical applications and radiation detection as well as large matrix for application in cameras and telescopes. The SiPM can be applied to all equipment using PMTs in fields of electronics, medicine, military, measurements, and space; they have a very wide range of uses [4-6]. In this paper, we present the design, fabrication, and results of the 64-channel SiPM sensor as the first step toward multichannel sensors.

2. The design and fabrication of the 64-channel SiPM sensor
The SiPM was simulated and designed with the PN junction of a high electric field into an epitaxial layer on p-type substrate, which works at a low operating voltage of about 25 V. The
vertical structure of the SiPM has an n+/p/p- diode configuration. Our design of the SiPM sensor is 8 × 8 arrays. Each SiPM consisted of 32 × 32 micropixels with the size of 35 × 35 m² in the space of 1 mm². We have designed and constructed the 64-channel SiPM sensor on a silicon substrate. Figure 1 (left) shows the designs of the 64-channel SiPM sensor. The multichannel sensor has the 64-readout pads arranged in an L-shape on two sides. Shown in Figure 1 (right) is a picture of the development prototype fabricated as designed.

![Figure 1](image)

**Figure 1.** The design (left) and the development prototype (right) of the 64-channel SiPM sensor. The multichannel sensor has the 64 readout pads arranged with an L-shape in two sides. Each SiPM has 32 × 32 micropixels in the size of 1 mm².

The large matrix is useful for covering a large area with the SiPM. An image sensor can be made by an array of the multichannel SiPM sensors on an electric board. The size of the multichannel sensor has to be in agreement with the yield of fabrication. As shown in Figure 1, the 64-channel SiPM sensor has been designed and fabricated with 8 × 8 arrays in the size of 1 cm². The sensor was made with the photo-masks of 8 layers and with approximately 150-step processes in complementary metal-oxide semiconductor (CMOS) fabrication technology. We had the final optimal parameters in the design and fabrication of the multichannel SiPM sensor to make the PN junctions with a high enough electric field for Geiger mode operation. In addition, using 4 × 4 arrays of the 64-channel SiPM, we have also made an image sensor of 1024 channels. The image sensor had the test to take a picture at very low density light, which we will present in another paper.

3. The results of the fabricated 64-channel SiPM sensor

The I-V characteristics of the 64-channel SiPM sensor were measured. The reverse biasing voltage (V) over each SiPM channel was increased up to 40 V in increments of 0.2 V. Only one channel was biased at a time and other channels were unbiased. The I-V characteristics of the sensor are shown in Figure 2 (left). The average leakage current of the 64-channels was about 1 ~ 5 pA before the breakdown voltage. The avalanche breakdown voltages (BV) of all the channels in the sensor were about 24 V, which has very uniform BV characteristics. The leakage current increased rapidly after the BV. The sensor can be operate up to Δ 5 V.

Multiplication process in the SiPM does not discriminate avalanche breakdowns by incident light or thermal excitation. The dark noise in the sensor is caused by thermally generated charge carriers in the silicon. The dark rate of the 64-channel SiPM sensor is 300 ~ 800 kHz at Δ 3 V from the BV. Figure 2 (right) shows the ability of single photon counting of the sensor with low-intensity light in an oscilloscope. As shown in the picture, the single photoelectron (PE) peaks
are clearly separated from the pedestal. The single, double, and triple PE peaks are separated from each other in the pulse height histogram. The height of the single PE peak increased with the gain increased by bias voltage. The typical gain in the sensor is $2 \times 10^5 \sim 5 \times 10^5$ at $\Delta 2 \sim 5$ V. The PDE is about 10% at a wavelength of 490 nm. Our plan is to study the SiPM improvement of a high PDE at 300$\sim$400 nm.

4. Conclusion
The 8$\times$8 array sensor of SiPMs was designed with the PN junction of a high electric field on a p-type epitaxial layer for working at low voltage operation. We had the final optimal parameters in the design and fabrication of the SiPM to establish a high electric field enough for Geiger mode operation PN junction. Finally, we fabricated the 64-channel SiPM sensor as a first step toward the fabrication of a large area matrix of SiPMs. We measured dark rate, gain, light response, and PDE on first product of the 64-channel SiPM sensor. The SiPMs turned out to have the capability of single photon counting, the dark rate of 300$\sim$800 kHz, the gain of $\sim 10^5$, and the PDE of 10% at 490 nm. The next plan is to improve the PDE of the SiPMs in the wavelength of 300$\sim$400 nm.

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