The performance of AC-LGAD with different N+ layer doping dose

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Abstract—AC-Coupled LGAD (AC-LGAD) is a new 4D detector developed based on the Low Gain Avalanche Diode (LGAD) technology, which can accurately measure the time and spatial information of particles. Institute of High Energy Physics (IHEP) designed a large size AC-LGAD with pitch of 2000 µm and AC-pad of 1000 µm, and explored the effect of N+ layer doping dose on the spatial resolution and time resolution. The AC-LGAD sensor with low N+ doping dose has good spatial resolution, the doping dose is from 10 P to 0.2 P, and the spatial resolution is from 32.7 µm to 15.1 µm. The lower N+ doping dose has a larger signal attenuation factor and the signal of AC-pad is more sensitive to the hit position. The time resolution does not change significantly at different N+ doping doses, which is about 15-17 ps.

Index Terms—AC-LGAD, 4D detector, Spatial resolution, Timing resolution

I. INTRODUCTION

LOW Gain Avalanche Diode (LGAD) is a thin N-on-P silicon sensor with a P+ layer inserted between N++ and p-type bulk. Due to such a high electric field of P+ layer, more electron-hole pairs are generated by the initial carriers when passing through the gain layer. The LGAD has a thin epitaxial layer of 30-50 µm, with fast rise time and high signal-to-noise ratio, and the time resolution can reach 30 ps [1]–[3]. The LGAD also has good radiation hardness performance and can withstand a irradiation fluence of $2.5 \times 10^{15} n_{eq}/cm^2$ [4]–[6]. One of the important applications of LGAD is the upgrade of the ATLAS experiments at the High-Luminosity Large Hadron Collider (HL-LHC) [7], [8].

AC-Coupled LGAD (AC-LGAD) is a new detector based on the LGAD technology. It can be used as a 4D tracker to accurately measure the time and spatial information of particles. AC-LGAD has a uniform and continuous N+ layer and P+ layer, and a very thin dielectric (SiO$_2$) is grown on the N+ layer, so that the segment AC-pad and the N+ layer form a coupling capacitor, as shown in Fig. 1. Compared to the LGAD array, AC-LGAD has a continuous P+ layer and a 100% fill factor. When a charged particle or laser pulse hits the AC-LGAD, electron-hole pairs are generated in the epitaxial layer, and electrons drift to the gain layer and generate a multiplication process. In the process of electron drift and multiplication, a coupling signal is generated on the AC-pad. The amplitude and charge of the coupling signal is influenced by several parameters, such as pitch size, AC-pad size, N+ layer resistivity, gain, etc.

Ref. [9]–[12] report AC-LGAD sensors produced by FBK, BNL, and HPK with square and strip AC-pad electrodes and pitch sizes in the range of 100-550 µm. Institute of High Energy Physics (IHEP) has designed AC-LGAD with a larger pitch size of 2000 µm, which means a smaller readout channel density in engineering applications. IHEP AC-LGAD sensors are produced by the Institute of Microelectronics (IME) on 8-inch wafers. In this paper, the IHEP AC-LGAD with a pitch of 2000 µm will be introduced in detail, and the effect of doping dose of the N+ layer on the spatial and time resolution will be explored.

II. DESIGN PARAMETERS OF IHEP AC-LGAD SENSORS

The IHEP AC-LGAD was fabricated on an 8-inch wafer with a 50 µm p-type epitaxial layer and a 725 µm P++ substrate. IHEP AC-LGAD has four square AC-pads for coupling signal readout, as shown in Fig. 2. The innermost ring is the DC electrode, the secondary inner ring is the guard ring, the AC-pad size of 1000 µm, and the pitch size of 2000 µm.
Fig. 2. The picture of IHEP AC-LGAD sensor with pitch 2000 µm.

TABLE I
PARAMETERS OF IHEP AC-LGAD.

| Sensors | N+ dose | AC-pad size [µm] | Pitch size [µm] |
|---------|---------|------------------|-----------------|
| 1       | 10.0 P  | 1000             | 2000            |
| 2       | 5.0 P   | 1000             | 2000            |
| 3       | 1.0 P   | 1000             | 2000            |
| 4       | 0.5 P   | 1000             | 2000            |
| 5       | 0.2 P   | 1000             | 2000            |

Table I shows the design parameters of the five IHEP AC-LGAD sensors. In order to study the effect of the N+ layer doping dose on the spatial resolution and time resolution, five N+ doping doses were designed, 10.0 P, 5.0 P, 1.0 P, 0.5 P, and 0.2 P. Here P is the unit of phosphorus doping dose defined in this paper.

III. THE EXPERIMENTAL SETUP

To study the time resolution and spatial resolution, the IHEP AC-LGAD sensors were tested with a transient current technique (TCT) platform. The four AC-pads are wire bonded to the four channels of the readout board, and the guard ring is grounded, as shown in Fig. 3(b). The four-channel readout board is developed with reference to the single-channel readout board designed by the University of California Santa Cruz (UCSC) [2]. It uses a broadband inverting trans-impedance amplifier of 470 Ω for each channel.

Figure 3(a) shows the laser TCT experiment setup, the accuracy of the three-dimensional translation platform is about 1 µm, and the laser spot size is focused to ∼ 10 µm (3 σ). The signal pulses from four AC-pads are recorded by a digital oscilloscope with a 20 GS/s sampling rate for offline analysis.

IV. ANALYSIS OF EXPERIMENTAL RESULTS

A. Attenuation of the signal

The amplitude of the AC-pad signal usually decreases with the distance of the laser spot. Figure 4(a) shows the signal amplitude of AC-pad changes with the laser spot distance. The signal amplitude decreases as the laser spot distance increases.

The decrease of the signal amplitude in the central area between the two AC-pads is very close to linear attenuation. Linear fitting is performed for signal amplitude and laser spot distance, and the slope is defined as the signal attenuation factor \( A \). The attenuation factor \( A \) of the IHEP AC-LGAD sensors is shown in Fig. 4(b). The attenuation factor increases with the decrease of N+ doping dose. The attenuation factor is 0.0074 mV/µm at 10.0 P and 0.018 mV/µm at 0.2 P. The N+ layer with low doping dose has high resistivity and larger signal attenuation factor, which also means that the signal is more sensitive to the change of laser position.

B. Position reconstruction and spatial resolution

In the diffusion of the signal generated by a laser, the sensor can be considered as a discretized positioning circuit (DPC) [9], as shown in Fig. 5. The N+ layer is equivalent to a resistive array, and the inductive charges on the four AC-pads are \( q_1, q_2, q_3, \) and \( q_4 \). The hit position \((X, Y)\) of laser or particle is determined by using the charge imbalance between AC-pads along the X and Y direction:

\[
\begin{align*}
X &= X_0 + k_x m \\
Y &= Y_0 + k_y n \\
m &= \frac{q_1 + q_2 + q_3 - q_4}{q_1 + q_2 + q_3 + q_4} \\
n &= \frac{q_1 + q_3 - q_2}{q_1 + q_2 + q_3 + q_4}
\end{align*}
\]

\[
\begin{align*}
k_x &= L \sum_{i}(m_{i+1} - m_i) / \sum_{i}(n_{i+1} - n_i) \\
k_y &= L \sum_{i}(n_{i+1} - n_i) / \sum_{i}(m_{i+1} - m_i)
\end{align*}
\]
where $k_x$ and $k_y$ are correction factors along X direction and Y direction respectively. Let the laser move along the X direction in steps of $L$ and calculate the $m_j$ for each position, then calculate the correction factor $k_x$ in the X direction according to the equation 2. Similarly, $k_y$ can also be obtained by a series of equidistant test positions along the Y direction. The above reconstruction method based on DPC model is mainly used for the central area of AC-LGAD, that is, the area where the signal is linearly attenuated.

TCT system is used to complete $6 \times 6$ laser test array in the central area of the AC-LGAD, and the step size of the laser is 100 $\mu$m. Each position in the $6 \times 6$ array has 1000 events recorded by the oscilloscope. The coordinates of laser hit position will be reconstructed by equation 1. The spatial resolution of each position is evaluated as the standard deviation of the difference between the reconstructed coordinates and the laser coordinates.

Figure 6 shows the X coordinate distribution of a reconstructed position, where mean value is used as the reconstruction coordinate of the point, and sigma value is used to evaluate the spatial resolution of the position in the X direction. Therefore, the reconstructed X coordinate is $-51.7 \mu$m, and the spatial resolution along the X direction is $14.6 \mu$m.

Figure 7 shows the reconstruction results of the $6 \times 6$ laser test array of sensor 5. The red marks are the laser position, and the blue marks are the reconstruction coordinates. The reconstructed array has a small deviation from the laser test array. By reconstructing 36 positions of $6 \times 6$ laser array, we can obtain the spatial resolution of 36 positions along X and Y directions, with a total of 72 spatial resolution values. Fig. 8 shows the distribution of the 72 spatial resolution values, with an mean value of 15.12 $\mu$m and a small standard deviation of 1.46 $\mu$m. The mean value is taken as the spatial resolution of the AC-LGAD sensor directly measured.

The blue marks in Fig. 9 are directly measured spatial resolution in different N+ layer doping doses. The sensor with low N+ doping dose has good (small) spatial resolution, the
The lower the phosphorus doping dose or concentration in the N+ layer, the higher the resistivity, the greater the attenuation factor of the AC-pad signal, the bigger the amplitude change of the signal when the hit position moves, which is more conducive to the reconstruction of better spatial resolution. If the N+ doping dose is too small, it will make the signal attenuation factor too large, resulting in a smaller coupling range of AC-pad and a worse signal-to-noise ratio, and thus a worse spatial and time resolution. The optimal N+ doping dose or resistivity needs further exploration.

C. The timing resolution

The arrival time of particle or laser $t_{\text{arrived}}$ is defined as the mean value of the cross-threshold time of four AC-pad signals:

$$ t_{\text{arrived}} = \frac{t_1 + t_2 + t_3 + t_4}{4} \quad (4) $$

where $t_1$, $t_2$, $t_3$, $t_4$ are the cross-threshold time of four AC-pads obtained according to the constant fraction discriminator (CFD) method. The spread of arrival time is mainly composed of the time resolution of AC-LGAD ($\sigma_{\text{AC timing}}$) and the jitter of the start time $t_0$ ($\sigma_{t_0}$):

$$ \sigma^2_{(t_1+t_2+t_3+t_4)/4} = \sigma^2_{\text{AC timing}} + \sigma^2_{t_0} \quad (5) $$

To avoid the jitter of $t_0$, $(t_1 + t_2 - t_3 - t_4)/4$ is used to calculate the time resolution of AC-LGAD sensors:

$$ \sigma_{\text{AC timing}} = \sigma_{(t_1+t_2-t_3-t_4)/4}. \quad (6) $$

Figure 10 shows the distribution of $(t_1 + t_2 - t_3 - t_4)/4$, with a time resolution of 15.6 ps. The time resolution of the AC-LGAD is evaluated by the mean value of the time resolution of 36 test positions. Figure 11 shows the timing resolution (laser test) of AC-LGAD with different N+ doping doses. The time resolution does not change significantly at different N+ doping doses, which is about 15-17 ps. The signal-to-noise ratios of these AC-LGAD sensors in the experiments were all greater than 30, so they all had good time resolution and did not show large differences.
Fig. 11. The time resolution with different N+ doping doses.

V. Conclusion

The IHEP AC-LGAD sensors were designed by IHEP and fabricated by IME with 2000 µm pitch size and 1000 µm AC-pad size. Five AC-LGAD sensors with different N+ doping doses (10.0 P, 5.0 P, 1.0 P, 0.5 P, and 0.2 P) were designed to study the effect of N+ doping dose on the spatial and time resolution. The time resolution does not change significantly at different N+ doping doses, which is about 15-17 ps. The sensor with low N+ doping dose has good (small) spatial resolution, the doping dose is from 10 P to 0.2 P, and the spatial resolution is from 35.2 µm to 15.1 µm. The spatial resolution is positively correlated with the signal attenuation factor $A$ and negatively correlated with the noise $N$. Reducing the noise level and increasing the signal attenuation factor appropriately is an effective way to improve the spatial resolution. The lower the phosphorus doping dose or concentration in the N+ layer, the higher the resistivity, the greater the attenuation factor of the AC-pad signal, the bigger the amplitude change of the signal when the hit position moves, which is more conducive to the reconstruction of better spatial resolution.

Acknowledgement

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