Characterizations of a Novel 3D Trench-Column Sensor with Internal Gain

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Abstract

Over the last few years, 3D radiation sensors have been developed in High Energy Physics (HEP) experiments and other fields such as microdosimetry in proton and ion therapy. Due to their unique architectural design, 3D sensors offer radiation tolerance and fast signal response at relatively low bias voltages, making them one of the most promising sensor technologies for spatiotemporal (4D) tracking in extreme environments. Thin 3D sensors feature lower capacitance (and thus lower noise) and reduced material budget but suffer from limited charge collection. To address this, the IMECAS group has proposed a novel 3D trench-column sensor with internal gain, where charge multiplication is primarily enabled by the ultra-narrow radius of N+ columnar electrodes. These sensors were manufactured on 8-inch wafers using IMECAS CMOS processing technologies, achieving an aspect ratio of 70:1 via the deep reactive ion etching (DRIE) process. In this paper, we present the electrical characteristics, charge collection and time resolution of the sensor with a 35$×$35 m2 pixel cell. Through Current-Voltage ($I-V$) and Capacitance-Voltage ($C-V$) measurements, we investigate the depletion and breakdown characteristics of the sensors. Charge collection and time resolution have been evaluated using infrared transient current technology (TCT) and 90Sr-source measurements. The results confirm a substantial internal gain in the proposed sensor.

Full Text

Preamble

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Abstract

Over the last few years, 3D radiation sensors have been developed for High Energy Physics (HEP) experiments and other fields such as microdosimetry in proton and ion therapy. Due to their unique architectural design, 3D sensors offer radiation tolerance and fast signal response at relatively low bias voltages, making them one of the most promising sensor technologies for spatiotemporal (4D) tracking in extreme environments. Thin 3D sensors feature lower capacitance (and thus lower noise) and reduced material budget but suffer from limited charge collection. To address this, the IMECAS group has proposed a novel 3D trench-column sensor with internal gain, where charge multiplication is primarily enabled by the ultra-narrow radius of N+ columnar electrodes. These sensors were manufactured on 8-inch wafers using IMECAS CMOS processing technologies, achieving an aspect ratio of 70:1 via the deep reactive ion etching (DRIE) process. In this paper, we present the electrical characteristics, charge collection, and time resolution of the sensor with a 35$×35*m*^{2}$ pixel cell.

Through Current-Voltage (I-V) and Capacitance-Voltage (C-V) measurements, we investigate the depletion and breakdown characteristics of the sensors. Charge collection and time resolution have been evaluated using infrared transient current technology (TCT) and 90Sr-source measurements. The results confirm a substantial internal gain in the proposed sensor.

Keywords: 3D trench-column sensors, Charge collection, Internal gain

Introduction

3D radiation sensors were proposed by Sherwood Parker and his collaborators in 1997 [1], distinguished from planar sensors by vertical electrodes that are perpendicular to the wafer surface and extend into the substrate. The smaller interelectrode distance endows these sensors with advantages including low full depletion voltage, fast time response, and radiation hardness.

Pioneering research on 3D sensors initially focused on single-sided fabrication processes [2]; while groundbreaking, these early efforts faced challenges in electrode alignment and charge collection uniformity. “Active edge” technology was adopted in single-sided 3D sensors to minimize dead peripheral regions [3]. Subsequently, institutions such as CNM (Barcelona) [4] and FBK (Trento) [5] independently developed more streamlined double-sided 3D schemes, resolving earlier process bottlenecks and improving fabrication reproducibility. This technological advancement was notably applied in high-energy physics (HEP), with the ATLAS Insertable B-Layer (IBL) standing as the first HEP application of 3D sensor technology [6]. However, its deployment required overcoming challenges in scaling to large-area arrays for particle detection.

Small-pitch 3D pixels, tailored for high-luminosity LHC upgrades [7, 8], mitigate mechanical fragility via Si-Si direct wafer-bonded substrates [9]. Meanwhile, 3D-trenched detectors, developed under initiatives like INFN TIMESPOT [10], further enhance timing resolution by optimizing trench depth and electrode spacing [11, 12]. However, because of the low electric field regions between the same types of electrodes, the signal response of the 3D column sensor is not uniform. In addition, the capacitance of the trench sensor is much larger than that of planar sensors due to the depth of the electrodes and the small spacing between them [13, 14]. To mitigate these limitations, Zheng Li at BNL (USA) proposed a novel 3D device structure where a column electrode is surrounded by a trench electrode [15]. This design yields a much more homogeneous electric field with nearly pure radial dependence, eliminating potential saddle points and low-field regions in the sensor center—common issues in conventional 3D column sensors. Additionally, the capacitance of the BNL sensor is considerably lower than that of trench sensors because of its column collecting electrode. In particular, in all of the aforementioned studies, internal gain was not incorporated into the design stage due to manufacturing technology constraints.

Sensor Description and Simulation

We designed and fabricated a novel 3D trench-column sensor with internal gain by decreasing the widths of the column and trench electrodes and optimizing the doping strategy [16]. The basic structure consists of an N+ column electrode surrounded by a P+ trench electrode, as illustrated in Figure 1 Figure 1: see original paper. The P+ electrode penetrates the 30 µm epitaxial layer, while the tip of the N+ electrode is approximately 5 µm away from the highly doped substrate to prevent early breakdown.

In this work, we investigated a 5\$$\times 5arrayof3Dtrench-columnsensorswithapixelsizeof35m\times$\$35 µm and a trench width of 1 µm. To facilitate sensor characterization, a temporary metal layer was deposited to connect the electrodes. As shown in Figure 1(b), the gold-colored region in the layout represents the temporary metal layer: the large pad on the right is connected to the P+ trench electrode, the three small pads on the left are each connected to five N+ column electrodes, and the ten pads along the top and bottom are each connected to a single N+ column electrode.

The basic cell was simulated using Sentaurus TCAD, and the cross-sectional electric field distribution at a bias voltage of 80 V is shown in Figure 2 Figure 2: see original paper. Figure 2(b) presents the 1D electric field at depths of 15 µm and 25 µm for different bias voltages. The maximum electric field around the tip of the N+ electrode exceeds 200 kV/cm, where carriers can acquire sufficient energy to generate secondary electron-hole pairs through impact ionization. This process enables avalanche multiplication, serving as a gain mechanism for the sensor [17, 18].

Measurement Setup

Four types of measurements were performed: Current-Voltage (I-V), Capacitance-Voltage (C-V), infrared Transient Current Technology (TCT), and 90Sr-source measurements.

I-V measurements were conducted to characterize leakage current and breakdown voltage. The test system comprised a Keithley 2470 High Voltage SourceMeter and a Keithley 6482 Dual-Channel Picoammeter coupled to an Apollowave alpha-200CS probe station. During testing, the sensor was placed in a dark box on a Peltier-cooled thermal chuck maintained at 20 ± 0.01 °C. Negative high voltage was applied via a probe needle to the pad connected to the P+ trench electrode, while leakage current was measured through another probe needle on the pad connected to five N+ column electrodes.

C-V measurements were used to analyze the sensor depletion behavior. The setup included a Keithley 4200-SCS semiconductor characterization system paired with a PW-800 probe station. The sensor was housed in a dark box on an ordinary chuck at room temperature. Negative high voltage was applied to the P+ trench electrode pad, and capacitance was measured on the pad connected to five N+ column electrodes.

Charge collection and time resolution were evaluated using TCT and β-source measurements. As shown in Figure 3(a), the sensor was glued using double-sided conductive tape, and then electrodes were wire-bonded to the signal pad of the USTC amplifier board [19], which was designed to measure the time resolution of Low Gain Avalanche Detectors (LGADs) [20]. Here we improved the transimpedance on the readout board, so the gain of the amplifiers is increased by a factor of 1.7, which is high enough to measure the expected small signals from the 3D sensor.

The TCT setup is shown in Figure 3 Figure 3: see original paper, where a customized infrared laser with a wavelength of 1060 nm was used and the full width at half maximum (FWHM) of the well-focused laser spot was less than 11 µm. The laser passes perpendicularly through the sensor from the top side, and the center of the laser was adjusted to be between the trench and column electrodes.

The setup for beta-particle measurement using a 90Sr radioactive source is the same as described in detail elsewhere [21]. A Hamamatsu Photonics K.K. (HPK) Type 3.1 LGAD [22, 23] was used as the trigger and reference, whose timing resolution is 60.62 ps (20 °C, 180 V) and 49.71 ps (-30 °C, 150 V). The amplifier boards with the sensor and the mechanical tools, providing precise alignment of all components, are placed in an environmental chamber. The measurement is completed at 20 °C and -30 °C. The low temperature is necessary to reduce noise.

On the other hand, the charge collection at different temperatures when the bias voltage is the same can also indirectly estimate whether gain occurs, because the impact ionization coefficient depends on temperature. In this measurement, multi-pixels are wire-bonded, including the 15 pixels of rows 2, 3, 4 and the 2 pixels in the bottom right corner in Figure 1(b).

Results and Discussion

A. Leakage Current and Capacitance

The measured I–V curve at 20 °C is shown in Figure 4 Figure 4: see original paper. The leakage current increases rapidly at a few volts, then flattens at the level of several tens of nA. After 82 V, the current begins to increase significantly, and the sensor eventually breaks down. Figure 4(b) displays the C–V curve at room temperature. The C–V test is performed using an AC signal amplitude of 30 mV and frequency of 1 MHz. The C–V curve demonstrates two slopes which relate to two different depletion regions: the trench-column region depletes at 2 V, whereas the under-column region depletes at around 10 V.

B. Results of TCT Measurements

Figure 5(a) shows the averaged waveforms at different laser intensities when the bias voltage is 84 V. The numbers after "Laser" in the legend represent different laser intensities, where smaller numbers correspond to larger laser intensities. The amplitude of averaged waveforms increases with intensity because of greater energy deposition in the sensor. The averaged waveforms at different bias voltages are shown in Figure 5(b), and the amplitude increases obviously with bias voltage.

The collected charge of each event is calculated by the integration of the waveform divided by the calibration constant of the amplifier board. Then, the distribution of charge is fitted with a Gaussian function to extract the most probable value (MPV) as the collected charge under the corresponding measurement conditions. Figure 6 Figure 6: see original paper shows the distribution of the collected charge at 84 V and Laser50, and the red line is the Gaussian fitting curve. The relationship between collected charge and bias voltage is shown in Figure 6(c). When the bias voltage is in the range of 5–20 V, the slope of the curves increases slowly because the sensor is gradually becoming fully depleted and, in the meantime, the velocity of carriers also increases with electric field ($<$ 20 kV/cm). Next, the charge remains almost stable until 40 V because the drift velocity of carriers is saturated and no longer increases with electric field. When the bias voltage is above 40 V, the charge increases more and more rapidly. Figure 6(d) shows the collected charge scaled to the collected charge at 20 V. It has an exponential dependence on bias voltage, which indicates that gain occurs before breakdown.

Regarding time resolution, the time-of-arrival (TOA) of the sensor and the synchronization signal of the laser are extracted using the Constant Fraction

Discriminator (CFD) method (30% for 3D sensor and 50% for laser), which is an efficient way to minimize the effect of time walk. A Gaussian function is applied to fit the TOA difference (ΔTOA). The time resolution (σ_3D) can be calculated by equation 1 and is equal to the "Sigma" of the Gaussian fitting function regardless of the time resolution of the laser.

$$\sigma_{3D} = \sqrt{\Delta TOA - \sigma^2_{Reference}}$$

Figure 6(e) shows the time resolution as a function of bias voltage, and there are also three stages in the curve. First, the time resolution decreases with bias voltage because the sensor gradually becomes fully depleted and the velocity of carriers increases with electric field at low bias voltage. After the carrier velocity becomes saturated in almost all areas of the sensor, the time resolution stabilizes. Due to gain occurring above 40 V, the time resolution decreases further and can reach around 31 ps. In this test, the laser is focused at a fixed position, so the time resolution is mainly dominated by jitter, excluding the contribution of the impact location within the cell [24]. The rise time (10%-90%) of the averaged waveforms is also calculated. Figure 6(f) shows the rise time as a function of bias voltage, and it varies around 1300 ps. The larger rise time and the shape of averaged waveforms indicate that the bandwidth of the amplifier board is not high enough.

C. Results of 90Sr-Source Measurements

The 3D trench-column sensor is measured at 20 °C and -30 °C when the bias voltage is 84 V. The distributions of charge in Figures 7(a) and 7(c) are fitted with a Landau function convoluted with a Gaussian function to extract the most probable value (MPV) as the collected charge at 20 °C and -30 °C, respectively. Considering that the most probable value (MPV) energy loss of the minimum ionizing particle (MIP) in 30 µm silicon is about 0.3 fC, the gain is about 4.17 at 20 °C and 6.37 at -30 °C, respectively. At the same bias voltage, the charge is higher at low temperature, which is related to the larger impact ionization coefficient [25].

The time-of-arrival (TOA) of the 3D trench-column sensor and the reference are also extracted by the constant fraction discriminator (CFD) method (30% for 3D sensor and 50% for LGAD). The distributions of ΔTOA are fitted by a Gaussian function and are shown in Figures 7 Figure 7: see original paper and 7(d). The time resolution of the 3D trench-column sensor is 231.89 ± 10.18 ps (20 °C, 84 V) and 182.45 ± 7.07 ps (-30 °C, 84 V), respectively. With about 1.5 times larger gain at -30 °C, the time resolution improves by about 49.44 ps. Therefore, better time resolution is expected in the second batch of 3D trench-column sensors with a thicker active thickness. Besides, the present amplifier board needs to be optimized for time measurement of 3D sensors with shorter internal rise time than LGADs.

Conclusion

In conclusion, both the TCT measurements with the infrared laser (1060 nm) and the beta-scope measurements with 90Sr electrons confirm that internal gain occurs as predicted by TCAD simulation. The TCT tests show that the largest collected charge at 84 V, scaled to the collected charge at 20 V, is 28.68 ± 0.07, and the time resolution at the fixed measurement position is 30.72 ± 0.71 ps. The 90Sr-source tests show that the gain for the minimum ionizing particle (MIP) is about 4.17 at 20 °C, 84 V and 6.37 at -30 °C, 84 V. The gain is larger at low temperature, which is related to the larger impact ionization coefficient. However, the time resolution for the minimum ionizing particle (MIP) needs to be investigated further. Nevertheless, the development of novel 3D trench-column sensors in this study provides a feasible technology to achieve internal gain without adding an extra gain layer, like LGADs, promising advances in spatiotemporal (4D) tracking with low material budget in extreme experimental environments.

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Author Contributions

Manwen Liu and Kuo Ma contributed equally to this work. Device concept, design, and manufacture were performed by Manwen Liu, Huimin Ji, Zheng Li, Zhihua Li, and Jun Luo. Measurements and data collection were conducted by Kuo Ma and De Zhang. Huimin Ji carried out the TCAD simulation. All authors contributed to the data analysis. The first draft of the manuscript was written by Manwen Liu and Kuo Ma. Yanwen Liu, Zheng Li, Zhihua Li, and Jun Luo participated in draft writing, review, and editing. Manwen Liu, Zhihua Li, and Jun Luo were responsible for draft editing, supervision, project administration, and funding acquisition.

Declarations

The authors declare that they have no conflict of interest.

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