Output characteristics of stacked CMOS-type active pixel sensor for charged particles

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A stacked CMOS-type active pixel sensor (SCAPS) for charged particles has been developed. The SCAPS is an integral-type detector that has several advantages over conventional systems, including two-dimensional detection, wide dynamic range, no insensitive time, direct detection of charged particles and a high degree of robustness. The output characteristics of the SCAPS for incident charged particles has been analysed both theoretically and experimentally. The relationships between the output voltage of the SCAPS and the number of incident charged particles were formulated by including corrections for the non-ideal characteristics of transistors in a pixel. The fluctuation of output characteristics of the SCAPS was evaluated experimentally by irradiation of secondary 4.5 keV Si⁺ ions generated by SIMS. The function was used to determine the number of incident ions into each SCAPS pixel within twice the statistical error. The SCAPS is useful as a two-dimensional detector for microanalysis, such as stigmatic SIMS. Copyright © 2001 John Wiley & Sons, Ltd.

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INTRODUCTION

An integral-type solid-state image sensor for charged particles, called the stacked active pixel sensor (APS), has been developed for charged particles. The operational principle of APS is based on detecting the change in the potential of a floating photodiode caused by the irradiation of charged particles. As the APS is composed of a rectangular array of 512 × 490 independent microdetectors named pixels, simultaneous two-dimensional detection for charged particles and for soft X-rays can be achieved. The capabilities of the APS have been demonstrated for ions, electrons and soft X-rays.

The APS has several advantages over conventional systems, including two-dimensional detection, wide dynamic range, no insensitive time, direct detection of charged particles, constant ion sensitivities among nuclides and a high degree of robustness. The characteristics of the APS are utilized in, for example, two-dimensional microanalysis, especially in isotope analysis using stigmatic SIMS. The isotope ratios of some elements range over six orders of magnitude, whereas the relative isotopic variation in nature is less than several per cent. Thus, two-dimensional detection of isotopes over six orders of magnitude under the same conditions is necessary for the determination of isotopic ratios in natural samples. Integral-type detectors are able to store charges suitable for precise, low-intensity measurements for sufficient time integration, thus reducing statistical errors. Because the APS has no insensitive time and is highly robust, it can also measure both the high and low intensity of incident charged particles simultaneously and with the same analytical conditions without mechanical or electronic damage. Normal pulse-count-type detectors have a limitation on beam intensity.

Recently, a CMOS-type APS having a non-destructive readout capability has been developed. The use of the non-destructive readout method results in a strong suppression of the level of APS readout noise. In spite of the attractive features of APS, it was found that the degree of non-linearity between incident ions and the APS output is not negligible in cases of high-precision analysis such as isotopic measurements. The aim of this paper is to demonstrate the output characteristics of APS for charged particles and to propose a method for restoration from non-linearity.

Figure 1(a) is a schematic cross-sectional view of a pixel of the stacked CMOS APS (SCAPS). Figure 1(b) is a diagram of the circuit configuration. Each pixel unit consists of a pixel capacitor, C_{PIX}, and three transistors (a readout transistor,
Three metallic layers are stacked on the pixel unit. The top layer, the ‘pixel electrode’, receives charged particles directly and protects the device underneath. The other two metallic layers are used for electric interconnection and to maintain a flat structure. Because of the separation of the irradiating part and the integrating unit of charged particles, the SCAPS can achieve a high fill factor and detect charged particles regardless of polarity. The SCAPS is designed with pixel dimensions of 14 µm (H) × 14 µm (V) and pixel electrode dimensions of 12 µm (H) × 12 µm (V), thus yielding a fill factor of 73%.

The charged particles irradiated on the pixel electrode release secondary electrons and ions by interacting with the pixel electrode. Some of the incident charged particles are implanted into the pixel electrode. The pixel electrode is thereby electrostatically charged through the interactions. The degree of charging of the pixel electrode is proportional to the number of charged particles. The generated carriers are integrated on the pixel capacitor, \( C_{\text{PIX}} \). Accordingly, the SCAPS can store the electrostatic charge until \( C_{\text{PIX}} \) reaches its maximum capacitance. The basic structure of the SCAPS is principally similar to the stacked amplified MOS intelligent imager (AMI) described by Matsumoto et al.\(^1\).
a row bus, which connects to M_{Rs}. Switching over from DRO operation to NDRO operation is controlled by an NDRO control signal. Column selection pulses generated by the horizontal scanner are applied to pixels during each horizontal scanning period. Thus, pixels are X-Y addressed by the horizontal scanner. A row bus, which connects to M_{Rs}, Switching over from DRO operation to NDRO operation is controlled by an NDRO control signal. Column selection pulses generated by the horizontal scanner are applied to pixels during each horizontal scanning period. Thus, pixels are X-Y addressed by the horizontal scanner.

**ANALYSIS OF OUTPUT SIGNAL INTENSITY GENERATED BY INCOMING CHARGED PARTICLES**

The output voltage, \( V_{\text{OUT}} \), relative to the pixel voltage, \( V_{\text{PIX}} \), is influenced by the characteristics of the readout transistor, \( M_{RD} \), and a source follower with an off-chip load resistor. In general, the output current, \( I_{\text{OUT}} \), of \( M_{RD} \) against the pixel voltage, \( V_{\text{PIX}} \), is expressed as

\[
I_{\text{OUT}} = k(V_{\text{PIX}} - V_{\text{TH}})^2
\]  
(1)

where \( k \) is a coefficient that depends on the pixel size, electron mobility and insulator capacitance per unit size, and \( V_{\text{TH}} \) is the threshold voltage of \( M_{RD} \).\(^{11} \) Because \( I_{\text{OUT}} \) is converted to the output voltage, \( V_{\text{OUT}} \), through a source follower with an off-chip load resistor, \( R_L \), in Fig. 3, the relationship between the pixel voltage, \( V_{\text{PIX}} \), and the output voltage, \( V_{\text{OUT}} \), in an ideal MOS transistor is expressed as

\[
V_{\text{PIX}} = V_{\text{OUT}} + V_{\text{TH}} + \sqrt{\frac{V_{\text{OUT}}}{kR_L}}
\]  
(2)

which shows that \( V_{\text{PIX}} \) and \( V_{\text{OUT}} \) do not have a linear relationship.

To apply the SCAPS to charge particle detection for analysis, it is essential to evaluate the non-linear relationship between the output voltage, \( V_{\text{OUT}} \), and incident charged particles, and to establish a method for correcting \( V_{\text{OUT}} \) to the incident charged particle numbers.

Because the SCAPS is an integral-type detector, the numbers of incident particles, \( N_i \), in a pixel from time \( t_0 \) to \( t_i \) is expressed as

\[
N_i = h(Q_i - Q_0) = h \int_{V_{\text{TH}}}^{V_{\text{PIX}}} C dV_{\text{PIX}}
\]  
(3)

where \( h \) is a transformation coefficient from incident ions to integrated charge in \( C_{\text{PIX}} \) and \( Q \) are the charge and capacitance of \( C_{\text{PIX}} \), respectively. Subscripts 0 and \( i \) indicate the parameters at \( t_0 \) and \( t_i \), respectively. If \( C \) can be assumed to be constant, the integrated charges, \( Q \), are expressed using Eqn (2)

\[
Q_i = C \left( V_{\text{OUT},i} + V_{\text{TH}} + \sqrt{\frac{V_{\text{OUT},i}}{kR_L}}\right)
\]  
(4)

Thus, an integrated charge in a pixel capacitor can be calculated from the output voltage, \( V_{\text{OUT}} \), using Eqn (4). To cancel the transformation coefficient, \( h \), we introduce a normalized parameter, \( \eta \), of incident charged particles on a pixel; \( \eta \) is defined as

\[
\eta = \frac{N_i}{N_R}
\]  
(5)

where \( N_i \) are the integrated ions from \( t_0 \) to \( t_i \), and \( N_R \) are the integrated ions from \( t_0 \) to \( t_R \), using Eqn (3), \( \eta \) is expressed as

\[
\eta = \frac{Q_i - Q_0}{Q_R - Q_0}
\]  
(6)

where \( Q_R \) is the integrated charge at \( t_R \). Because \( Q_0 \) and \( Q_R \) can be obtained experimentally, they are treated as constants. By substituting Eqn (4) into Eqn (6), \( \eta \) is expressed by \( V_{\text{OUT}} \) as

\[
\eta_i = \frac{1}{Q_R - Q_0} \left[ C \left( V_{\text{OUT},i} + V_{\text{TH}} + \sqrt{\frac{V_{\text{OUT},i}}{kR_L}}\right) - Q_0 \right]
\]  
(7)

As shown in Fig. 4(a), Eqn (7) basically represents the relationship between \( \eta \) and \( V_{\text{OUT}} \), which was determined experimentally. The methods used for the experimental determination are described later. The errors between the calculated and measured \( \eta \) values are within 10%. The origin of error is due to non-ideal characteristics of the source follower and changes in the capacitance of a pixel caused by variation in the integrated charge.\(^5 \) By correcting for the non-ideal characteristics, the formula of Eqn (7) can be modified as

\[
\eta_i = a_1 V_{\text{OUT},i} + a_2 + (a_3 V_{\text{OUT},i} + a_4)^3
\]  
(8)

where \( a_i \) are the fitting parameters. From Eqs (5) and (8), the number of integrated ions from \( t_0 \) to \( t_i \) is expressed as

\[
N_i = N_R \eta_i = N_R [a_1 V_{\text{OUT},i} + a_2 + (a_3 V_{\text{OUT},i} + a_4)^3]
\]  
(9)
Figure 4. (a) Relationship between output voltage, $V_{\text{OUT}}$, and normalized accumulated ion number, $n_i$, of a pixel. Si$^+$ ions were irradiated onto the SCAPS and $n_i$ is determined by FC2 monitoring. The regression curves are derived by Eqsns (7) and (8). (b) Fitting error of Eqn (7). (c) Fitting error of Eqn (8). (○, □) 200 cps per pixel; (×) 60 cps per pixel; (△, ○) 30 cps per pixel.

EXPERIMENTAL

Determination of number of incident ions

The output characteristics of SCAPS for charged particles were evaluated by ion irradiation. A schematic configuration of the ion irradiation system and the SCAPS operating system is shown in Fig. 5. Si$^+$ ions accelerated at 4.5 keV were used as the irradiated charged particles onto the SCAPS. The Si$^+$ ion beam was generated by a Cameca IMS-3f SIMS instrument. The SCAPS device was placed in an ultrahigh vacuum of $<0.5 \mu\text{Pa}$. Secondary Si$^+$ ions were generated from a silicon wafer bombarded by 12.5 keV $^{16}\text{O}^+$ primary ions. To obtain a homogeneous distribution of the secondary ion emission, primary $^{16}\text{O}^+$ ions were rastered over an area of 250 $\mu\text{m} \times 250 $\mu\text{m}$, and the secondary Si$^+$ ions generated in the 60 $\mu\text{m}$ diameter central area were projected directly onto the SCAPS imaging area using stigmatic ion optics. The projected area covered $\sim40\%$ of the central field of the SCAPS imaging area, which corresponds to $\sim10^5$ pixels. The count rate of total secondary ions projected onto the imaging area was measured by insertion of a Faraday cup, FC1, in the IMS-3f instrument. The rate of incoming ions per pixel was calculated by dividing the FC1 intensity counts by $10^5$. The calculated rate per pixel includes errors of ion beam fluctuation between the measurement times of the SCAPS and of the Faraday cup as well as statistical errors of the incoming ions themselves.

During the experiments, the fluctuations of secondary ion intensities are often larger than the statistical errors of the ion intensities. The fluctuation of the secondary ion intensity is a serious problem because it adversely affects the precise determination of the integrated ions onto the SCAPS. To determine the count of integrated ions onto the SCAPS, we monitored the secondary ions that were trapped by a flight tube in the magnetic sector of the IMS-3f by a Keithley 6514 electrometer, as shown in Fig. 5. The flight tube, FC2, works as a Faraday cup because its length is long enough to trap charged particles. Therefore, except for the ions passing through the flight tube, the total number of secondary ions can be measured as current. Because the ion species irradiated onto the SCAPS or FC1 are different from the species trapped by FC2, the degree of correlation between the simultaneous measurements by FC1 and FC2 should be evaluated experimentally.

Operation of SCAPS

After ion irradiation, the ion signals from SCAPS were read at a 20 kHz scanning rate per pixel by adding driving pulses to the SCAPS from the APS driver (Fig. 5). The storage time of the ion signals can be selected from 20 s upwards. The signals read from each pixel were amplified and then converted to a digital signal by a 16-bit A/D converter for final processing in a personal computer. To reduce environmental noise, the communications between the SCAPS and the operation electronics were differential signals connected by shielded
twisted-pair cables through an ultrahigh vacuum electrical feed-through.

To reduce thermal noise in each pixel during ion irradiation and during the time waiting for the readout, the device was cooled by liquid nitrogen. The SCAPS temperature was held constant at ~77 K during operation. When the reset transistor, M_{RS}, is used to reset a pixel, a random noise, called the reset noise, is generated. The reset noise of the SCAPS at 77 K is estimated to be ~25 e⁻. To suppress the reset noise, the following NDRO sequence (Fig. 6) was applied:

1. For imager reset, each pixel is reset by a DRO operation.
2. For offset frame read, the reset signals of each pixel are read by an NDRO operation. A fixed pattern of noise among the pixels caused by variations of the threshold level of readout transistor, M_{RD}, and by the reset noise are included in the signal.
3. Charged particles are irradiated on the SCAPS.
4. For signal frame read, ion-integrated signals are repeatedly read by an NDRO operation during ion irradiation. Subtracting the output of the offset read from the output of the signal read extracts only the accumulated components of irradiated ions on each pixel.

RESULTS AND DISCUSSION

Correlation between incident ion intensity onto the SCAPS and total secondary ion intensity

Typical relationships between simultaneous measurements of ion intensities by FC1 and FC2 are shown in Figs 7(a) and 7(b). The FC1 monitored the $^{30}$Si⁺ ion and FC2 monitored other secondary ions. The ion intensities for each Faraday cup are normalized by the average currents through the run. The average currents for FC1 and FC2 are $5.0 \times 10^{-13}$ and $2.0 \times 10^{-11}$ A, respectively. The variations of intensities for FC1 are correlated to those for FC2 for $>1800$ s. Figure 7(c) shows the relative differences of the accumulated ions between the measurements. The relative differences of accumulated ions between the currents for $^{30}$Si⁺ by FC1 and for other ions, M⁺, by FC2 are expressed as

$$
\delta \left( \frac{30\text{Si}^+_{\text{accum}}}{M^+_{\text{accum}}} \right) = \left( \frac{\int_0^{1800} 30\text{Si}^+ \, dt}{\int_0^{1800} M^+ \, dt} \right) - 1 \times 1000
$$

where j is an integer from zero to 1800 s. Each point in Fig. 7(c) was calculated from the data shown in Figs 7(a) and 7(b) and plotted every 20 s. The $\delta$ values do not increase with time and the overall error for 1800 s is within ±0.15%, including an abrupt intensity shift at ~500 s. Accordingly, the fluctuation of incident secondary ions irradiated onto the SCAPS can be monitored by FC2 monitoring, i.e. $\delta$ calculated by FC2 monitoring was within an error of 0.3%.

Evaluation of output characteristics of the SCAPS pixel

The typical relationship between $V_{\text{OUT}}$ and $\eta$, which was determined by FC2 monitoring, is plotted in Fig. 4(a). The normalization number, $N_R$, for $\eta$ was given at $V_{\text{OUT}} = 0.85$ V. Therefore, the $N_R$ values among the pixels are different because $h$ in Eqn (3) and the characteristics of the readout transistor, M_{RD}, are slightly different among the pixels. The average $N_R$ among the pixels in this study corresponds to 72,000 ions; the variation of $N_R$ among the pixels is 1.1% (1σ). This means that the variation of ion sensitivity among the pixels is ~1%.

Five NDRO readout sets of a pixel with different Si⁺ currents on the SCAPS are plotted in Fig. 4(a). The average counts of Si⁺ in the five sets were $2 \times 10^7$ (two runs), $6 \times 10^6$ (one run) and $3 \times 10^6$ (two runs) counts per second (cps), which corresponds to the average Si⁺ intensities in each pixel of 200, 60 and 30 cps, respectively.

All data was plotted along a simple curve. Regression curves for the five sets, $\eta^*$, were calculated using Eqs (7) and (8) and are shown in Fig. 4(a). Both curves show good agreement with the output characteristics of SCAPS. To evaluate the fitting error quantitatively, the ratios of $\eta^*$...
calculated from Eqn (7) or Eqn (8) to observed \( \eta \) are plotted in Figs 4(b) and 4(c). The large errors below \( V_{\text{OUT}} = 0.1 \) V are due to statistical errors of the incident ions. The ratios between \( \eta \) and \( \eta' \) from Eqn (7) decrease systematically over 10%, depending on \( V_{\text{OUT}} \). The systematic changes were analysed as a non-linear response of the SCAPS. The ratios between \( \eta \) and \( \eta' \) from Eqn (8) are constant for \( V_{\text{OUT}} = 0\text{–}1 \) V to within 1%. Thus, Eqn (8) corrects the non-ideal output characteristics of the SCAPS within a 1% error for each pixel.

The parameter range of Eqn (8) for 11 \times 11 pixels in the centre area of the Si irradiation field is shown in Table 1. Although parameter \( a_5 \) in Eqn (8) is ideally 0.5, the calculated value of \( a_5 \) is 0.22 \( \pm \) 0.13. This shift is due to the non-ideal characteristics of a source follower and the changing capacitance, depending on the integrated charges in a pixel. The variation of \( a_5 \) shows how the degree of non-ideal characteristics changes among pixels. Other parameters for the 121 pixels also varied from pixel to pixel, depending on the non-ideality of the pixel output.

Equation (8) for each pixel determined by the five data sets was applied to another set. The average Si\(^+\) count of the experimental set was \( 6 \times 10^6 \) cps, corresponding to the average Si\(^+\) intensity for each pixel of 60 cps. To analyse the cause of the discrepancies between \( \eta' \) determined by \( V_{\text{OUT}} \) and \( \eta \) determined by FC2 monitoring of Eqn (8) among the 121 pixels, we introduce \( \delta \eta \) as follows

\[
\delta \eta_i = \left( \frac{\eta_i' - \eta_i}{\langle \eta - \eta_i \rangle} - 1 \right) \times 1000
\]  

(11)

where \( \langle \eta_i - \eta \rangle \) is the average of \( \langle \eta_i - \eta \rangle \) among the 121 pixels. Each plot of \( \delta \eta \) in Fig. 8 is the average value among the 121 pixels of SCAPS; the error bar shows the standard deviation among the 121 pixels. The horizontal axis of Fig. 8 corresponds to the accumulated ions from zero to 72,000 because the average \( N_\text{SCAPS} \) is 72,000. The average value of \( \delta \eta \) is constant within \( \pm 0.5\% \) over the entire range of \( \langle \eta_i - \eta \rangle \). The curves in Fig. 8 indicate the theoretical errors of the accumulated ions for a pixel estimated from the counting statistics. The observed standard deviations are nearly equivalent to the statistical errors, but are systematically larger. The components of the standard deviations larger than the statistical errors are considered to be statistical fluctuations of emissions of secondary electrons on the pixel electrodes among the pixels, and the variation of ion sensitivities among the pixels. Although spatial heterogeneity of irradiated ions on the SCAPS is also a possible candidate for an error component, heterogeneity is not likely because the 121 pixels correspond to the centre of the ion-irradiated field and the area is small (140 \( \mu \text{m} \times 140 \mu \text{m} \)) when compared with the size of the total irradiated field of the homogeneously adjusted beam (4400 \( \mu \text{m} \times 4400 \mu \text{m} \)).

The ratios between the observed and statistical errors among the pixels are shown in Fig. 8(b). The ratios increase with \( \langle \eta_i - \eta \rangle \). This increase is primarily caused by the variation of ion sensitivities among the pixels because the relative variation of sensitivity is constant to \( \langle \eta_i - \eta \rangle \) and the other relative errors described above decrease with \( \langle \eta_i - \eta \rangle \). Instead of the raw signals, if the signal ratios of each pixel are useful, the differences of ion sensitivities among the pixels can be cancelled. Therefore, the performance-corrected output characteristics are suitable for producing a two-dimensional distribution map of isotope ratios using stigmatic ion optics.

**CONCLUSIONS**

1. The variation of accumulated ions on SCAPS was monitored within a 0.3% error range by the measurement of ions trapped in a flight tube in the magnetic sector.
(2) The output signal of a pixel for the SCAPS was corrected to accumulated ion numbers within a 1% degree of uncertainty using the output characteristics

\[ \eta = a_1 V_{OUT} + a_2 + (a_3 V_{OUT} + a_4)^n \]

(3) Application of the correction method from output signal to ion numbers is suitable for ion accumulation at least up to $10^5$ per pixel. Therefore, the SCAPS is applicable for detectors of two-dimensional quantitative analysis using charged particles.

REFERENCES